SPATIAL AND TEMPORAL ASSESSMENT OF SOIL NITROGEN AVAILABILITY AND RELATIONSHIPS TO BIOPHYSICAL VARIABLES IN A HIGH ARCTIC WETLAND

By

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Abstract

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Increased soil nutrient availability, and associated increase in ecosystem productivity, could create a negative feedback between Arctic ecosystem and the climate system, reducing the contribution of Arctic ecosystems to future climate change. This study explores the environmental controls over spatial patterns of soil nitrogen availability in a High Arctic wet sedge meadow and how they influence carbon exchange processes to predict whether this feedback will develop. Ion exchange resin membranes measured available inorganic nitrogen throughout the growing season at a high spatial resolution, while environmental variables and carbon flux measurements were taken at frequent intervals during the 2016 field season. Environmental measures correlated highly with total and late season nitrate with soil temperatures having the greatest effect. The results suggest that finer scale processes altering nitrogen availability may influence the C balance of wet sedge meadows in the High Arctic and how these ecosystems may respond to changes in climate.

Co-Authorship

The following list provides the names and institutions of the people who contributed to the manuscript that is the basis for this thesis:

Hung, J.K.Y.[1], Atkinson, D.M.[2], Scott, N.A.[3] (2017). Spatial and temporal assessment of soil nitrogen availability and relationships to biophysical variables in a High Arctic wetland.

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The candidate is the primary author of the thesis and manuscript. Author 2 is the candidate's supervisor who contributed to the experimental design development, assisted with data collection, provided guidance on analysis methods, and reviewed and edited the manuscript. Author 3 also reviewed the manuscript and provided comments.

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List of Abbreviations

ACIA	Arctic Climate Impact Assessment
AL	Active Layer
ANOVA	Analysis of Variance
AT	Air Temperature
C	Carbon
CBAWO	Cape Bounty Arctic Watershed Observatory
CNNRO	Canadian Network of Northern Research Operators
CH_4	Methane
CO_2	Carbon Dioxide
ER	Ecosystem Respiration
GPP	Gross Primary Production
IER	Ion Exchange Resin
IPCC	Intergovernmental Panel on Climate Change
IRGA	Infrared Gas Analyzer
M	Mean
NEE	Net Ecosystem Exchange
N	Nitrogen
NH_4^+	Ammonium
NO_3^-	Nitrate
N_2O	Nitrous Oxide
OLS	Ordinary Least Squares
P	Phosphorus
PAR	Photosynthetic Active Radiation
ppm	Parts Per Million
PRS	Plant Root Simulator
SD	Standard Deviation
SE	Standard Error
SOM	Soil Organic Matter
SM	Soil Moisture
ST	Soil Temperature
SZ	Saturation Zone

Chapter 1: Introduction

The onset of climate warming has been introducing numerous problems to our environment, and in recent decades, Arctic regions have been most notably affected (IPCC, 2013; Stocker *et al.*, 2013). The last three years – 2014, 2015, and 2016 – have been the warmest years on record (NASA, 2017). In 2016, global temperatures were 0.99°C above the 1951-1980 average, with the region north of 60°N warming by 0.94°C alone in the past year (NASA, 2017). Changes in the High Arctic regions include decreasing sea ice extents and the melting of perennial snowpacks as a result of warming temperatures (IPCC, 2013; Woo and Young, 2014). Ecosystems adjacent to these snowpacks therefore experience changes in patterns of water inputs (Callaghan *et al.*, 2011b). With increased snowmelt contributing greater amounts of runoff to wetland areas of Arctic environments (e.g. wet sedge meadows), changes to the spatial and temporal patterns of microbial activity and soil nutrient availability could occur (Biederbeck and Campbell, 1973; Jonasson and Shaver, 1999). These wet sedge meadows can have a significant impact on landscape-scale carbon (C) exchange. Environmental responses of higher ecosystem respiration (ER) will release more carbon dioxide (CO_2) into the atmosphere, contributing to the positive feedback loop of global warming, while increased nutrient availability could increase plant growth, storing more C and creating a negative feedback (Elberling *et al.*, 2008; Chae *et al.*, 2015; Christiansen, 2016). In this climate change narrative, Arctic ecosystems play a large role in its contribution or sequestration of CO_2 into the atmosphere (Grogan and Jonasson, 2005). As such, understanding controls on soil nutrient availability in these ecosystems can provide insight into their future contribution to C storage rates in the High Arctic (Grogan and Chapin, 2000).

At the Cape Bounty Arctic Watershed Observatory (CBAWO), scientists have been studying hydrological, biogeochemical, and permafrost dynamics since 2003 (CNNRO, 2015). There is extensive literature published on the findings from research conducted on the processes occurring across different environments at the CBAWO. While the controls on C dynamics in wet sedge meadows have been studied (Gregory, 2011; Atkinson, 2012; Beamish *et al.*, 2014; Ramsay, 2015; Blaser, 2016; Luce, 2016), the nutrient availability as a control on C dynamics has not been investigated in this setting. A knowledge gap still exists within some of the individual micro-environments within the watersheds, specifically in relation to High Arctic wetlands.

At Ryerson University, the Polar Regions Spatial and Environmental Analysis Laboratory (Polar SEAL) has been examining the biophysical variables within Low, Mid, and High Arctic ecosystems. Specific studies in the High Arctic out of Polar SEAL have looked at modelling environmental variables (e.g. active layer depth, soil moisture, soil temperature, and snowmelt) in High Arctic wetlands (Ramsay, 2015) and the examination of the relationship between C cycling and environmental variables (Luce, 2016). Building on this previous research and existing knowledge, the objective of this study is to examine and evaluate the spatial and temporal distribution of available soil nitrogen (N) in a High Arctic wetland.

The following three research questions were investigated in this study:

1. *How does active layer depth, soil moisture, and soil temperature affect nitrogen availability of a High Arctic wetland throughout the growing season?*

With the known changes that are occurring in High Arctic environments (IPCC, 2013), it is expected that as the growing season progresses, the active layer will thaw and deepen, resulting in an increase in the mean soil temperature within the High Arctic wet sedge tundra

(Grogan and Chapin, 2000; Hill and Henry, 2011). Prior research has shown that increases in soil temperature will promote microbial activities like net N mineralization (Biederbeck and Campbell, 1973; Jonasson and Shaver, 1999).

2. *What relationships exist between carbon flux and the concentration of available nitrogen in a High Arctic wetland throughout the growing season?*

If N limits net primary production, increased N availability could increase photosynthesis and, therefore, net ecosystem exchange (NEE). Previous research has found that that an increase in soil N significantly increased net CO_2 uptake (Billings *et al.*, 1984; Shaver *et al.*¸ 2000). This reverse relationship of increased net CO_2 uptake promoting soil available N will likely be seen in the wetland as the growing season progresses; however, this will depend on whether respiration or production is the dominant process in flux at the time of the season.

3. *What effect does proximity to the perennial snowpacks have on spatial patterns of nitrogen availability of a High Arctic wetland as the growing season progresses?*

The melt of the perennial snowpack adjacent to many wet sedge meadows will alter the water availability and microbial activity within the wetland (Nobrega and Grogan, 2008; Christiansen, 2016). As productivity within the meadow is directly linked with moisture (Reynolds and Tenhunen, 1996), it can be hypothesized that areas with higher water content in wet sedge meadows will display higher NEE, greater ER, and more photosynthetic activity compared to dry tracks. As the snowpack disappears, areas beyond the lateral extent of the snowpack will likely see the rates of the linked processes slow down.

Chapter 2: Literature Review

2.1 High Arctic Wetlands

High Arctic wetlands play an important role in the hydrological and C dynamics of Arctic environments (Grogan and Jonasson, 2005). Wetlands require a constant, sufficient water supply and are found where water gains exceed losses (Woo, 2011). Consequently, the availability of water in the arid, desert environment of the Arctic is a determining factor in the location and productivity of these wetlands (Woo and Young, 2006; Woo and Young, 2012). Wetlands consist of hydric soils characterized by saturated surfaces promoting hydrophyte growth (National Wetlands Working Group, 1988). In the Arctic, their growing season is limited to a maximum of three months each year, during which an adequate supply of water is needed to sustain them as wetlands. These areas of significant moisture within the otherwise dry polar desert provide sustenance for Arctic fauna and play an important role in ecological function (Woo and Young, 2006; Woo and Young, 2012). Their role in the global climate system is often understated: covering 346-500 Mha of the Earth's surface, northern wetlands play an important role in regulating dynamic processes that affect the entire planet (Gorham, 1991; Zoltai and Martikainen, 1996; Sullivan *et al.*, 2008).

In the Canadian Arctic, wetlands cover 3.4% of the northern land area (Environment and Climate Change Canada, 2016). Arctic wetlands currently act as important regions of long-term C storage and sequestration. These wetlands contain a disproportionate amount of subterraneous C (Post *et al.*, 1982; Grogan and Chapin, 1999) and will contribute significantly to global C changes. For example, it is expected that increased C losses from the terrestrial environment into the atmosphere will result from increased permafrost degradation as a result of a changing global climate (Tarnocai *et al.*, 2009). Land cover in the High Arctic is typically classified as being dry, mesic, or wet (Gregory, 2011; Atkinson, 2012). Within the wet land cover class in the CBAWO, wet sedge meadows are the most productive and photosynthetically active environments (Henry *et al.*, 1990; Henry, 1998; Atkinson, 2012; Atkinson and Treitz, 2013). Seasonal and perennial snowpacks, which are frozen for 9-10 months throughout the year, provide runoff during the short growing season, resulting in nival-driven wetlands (Woo and Young, 2006). Thawing of the active layer in these environments is promoted by the clay substrate that underlies the organic layer, which helps decrease the amount of moisture loss through vertical percolation (Woo and Young, 2006). Preliminary research has predicted that the wetland cover in Arctic regions have the potential to increase with increased temperatures and precipitation inputs (Nobrega and Grogan, 2008; Hill and Henry, 2011). These increases in wet sedge meadow biomass can help offset the projected increases in C losses through C uptake during photosynthesis. However, global climate models by Avis *et al.* (2011) have also projected the opposite, with permafrost degradation leading to a decrease in the areal extent of wetlands. As such, more research is needed to understand the relationship between climatic warming and Arctic wetlands to determine the reaction these regions will have with increased temperatures.

2.1.1 Climate Warming and High Arctic Wetlands

An earlier onset of snowmelt and consequent vegetation growth is expected to increase water storage in the subsurface (Young, 2006; Woo and Young, 2012; Lafrenière *et al.*, 2013). Warmer climate years can quickly diminish the extents of permanent snowpacks that feed into wetlands, but to accumulate a snowpack back up to its former extent takes a considerable time and winter precipitation (Woo and Young, 2006). Consequently, the water supply to High Arctic wetlands in the latter part of the growing season will see a shift in its water source in years to come due to the declining extent of permanent snowpacks. Global climate models project significant regional temperature increases in the High Arctic, with precipitation inputs expecting to increase in response (IPCC, 2013; Bintanja and Andry, 2017). Subsequent changes in the water balance and expected degradation of permafrost will help maintain a high water table but may lead to a decrease in the extent of wetlands that are fed by meltwater (Woo and Young, 2006). Similarly, permafrost thaw is also thought to decrease wetland extent due to drainage (Avis *et al.*, 2011; Grosse *et al.*, 2011; Beermann, 2016). Thus, the effects of changes in environmental variables on these ecosystems needs to be further investigated to project the future reactions of northern wetlands to warming.

Within the permafrost and frozen soil layers of Arctic wetlands are thousands of years of stored C that can be released through melt. In saturated environments like wetlands, the anaerobic conditions (oxygen limited) are favourable for methane (CH_4) and nitrous oxide (N_2O) production and release over CO_2 (Elberling *et al.*, 2008; Schuur *et al.*, 2009). The impact of CH_4 and N_2O release in the atmosphere is much more detrimental than CO_2 release, as the global warming potential of CH_4 is 28-36 over 100 years and N_2O has a GWP of 265-298 (US EPA, 2017). Because these trace gases are favoured in anoxic conditions like High Arctic wetlands, there is a need to understand the dynamics in these wetlands that warrant their potential release in warming conditions.

2.2 Climate Warming and Carbon Shifts

There has been a 40% increase in atmospheric CO_2 concentrations since pre-industrial times (1920-2017), and concentrations continue to increase more rapidly each year (IPCC, 2013; Stocker *et al.*¸ 2013). Atmospheric CO_2 concentrations were measured at greater than 400 ppm at the National Oceanic and Atmospheric Administration’s (NOAA) Mauna Loa in September 2016, at a time when CO_2 concentrations are typically at their lowest of the year (Kahn, 2016).

Comprehensive data from NOAA's Barrow station indicated that early winter CO_2 emissions have risen 75% since 1975 (Commane *et al.*, 2017). Arctic tundra soils contains 14% of the global C pool (Post *et al.*, 1982; Grogan and Chapin, 1999) and their potential release into the atmosphere could be detrimental to terrestrial and hydrological systems. Nobrega and Grogan (2008) have found in their study of mid-Arctic wetlands that net C gain was largest in an Arctic wetland setting when compared to other Arctic ecosystems. Short-term studies of Arctic tundra environments are suggesting that Arctic permafrost regions currently act as sinks of atmospheric and terrestrial C (Nobrega and Grogan, 2008; Lafleur *et al.*, 2012; McGuire *et al.*, 2012); however, the comprehensive C study by McGuire *et al.* (2012) also determined that the tundra has been neutral in recent decades. Generally, long-term C studies are still lacking across the High Arctic tundra (Euskirchen *et al.*, 2016). A long-term study by Euskirchen *et al*. (2016) found that increases in air and soil temperatures at multiple depths may trigger a new trajectory of CO_2 release. As such, the need to understand both the physical processes as well as the environmental variables that influence these processes is necessary, particularly in ecosystems like wetlands that can have the most dramatic change and impact on global systems.

2.2.1 Arctic Carbon Fluxes

The terrestrial C cycle is composed of two dynamic components – gross primary production (GPP) and ER – that together make up NEE. GPP accounts for C gained through processes like photosynthesis, while ER is the C lost through respiration in plants and soils. Several variables influence C exchange processes: Sullivan *et al*. (2008) found that in Greenland fen environments, the terrestrial C balance is dependent on the surrounding microtopography. Natali *et al.* (2011) found that a 1.5°C increase in soil temperature resulted in a 10% increase in thaw depth. Additionally, the water table depth can have an influence on ER through higher evapotranspiration resulting in drier soils (Billings *et al.*, 1982; Weller *et al.*, 1995; Welker *et al.*, 2004).

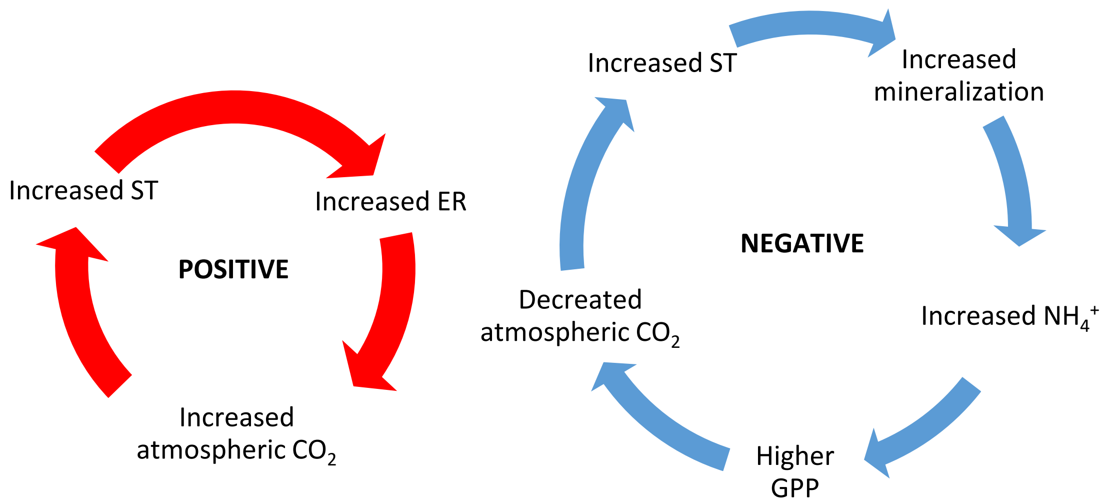

Figure 1: Positive and negative feedback loops between carbon fluxes and environmental variables

The balance between ER and GPP is an important determinant of net C storage. High Arctic wetlands have long been regarded as C sinks due to the dominance of GPP over ER (Mikan, *et al.*, 2002; Nobrega and Grogan, 2008; Lafleur *et al.*, 2012; McGuire *et al.*, 2012; Blaser, 2016). However, experimental warming research near the Alaska Range has shown that organic C near the surface of these Arctic environments is very vulnerable and susceptible to release, contributing to a positive feedback loop (Figure 1) (Post *et al.*, 1982; Natali *et al.*, 2011; Commane *et al.*, 2017). Warming temperatures are expected to increase ER in the Arctic regions, which could lead to a shift in the C balance depending on the response of GPP. This could lead to decreased net C storage and make permafrost regions long-term net C sources (Welker *et al.*, 2004; Commane *et al.*, 2017).

2.2.2 Environmental Controls of Arctic Carbon Fluxes

The northern circumpolar permafrost region accounts for approximately 16% of the global soil area with 1672 Pg of organic C stored (Tarnocai *et al.*, 2009). Belowground CO_2

release is season-dependent and strongly influenced by climate (Grogan and Chapin, 1999). Historically, the Arctic's frozen soils were considered strong C sinks due to low temperatures and poor drainage (Grogan and Chapin, 1999; Mikan, *et al.*, 2002). However, some Arctic areas like the Alaskan North Slope have consistently been acting as C sources during the growing season (Oechel *et al.*, 1993). More recently, studies have determined that the Alaskan Arctic has been a net CO_2 source from 2012 to 2014, with particularly high emissions in the early winter months (Commane *et al.*, 2017). Similarly, a study that included a Canadian High Arctic wetland at Alexandra Fiord on Ellesmere Island showed that the wet sedge was a net CO_2 source until switching to a sink closer to the end of the growing season (Welker *et al.*, 2004). Studies at Toolik Lake, Alaska found that simulated warmer climate made wet sedge tundra plots a weak sink for CO_2 at the peak of the growing season but only for a short period of time (Johnson *et al.*, 2000). The study of C cycling in Arctic wetlands by Sullivan *et al.* (2008) found C fluxes to be temperature-sensitive, concluding that with future warming trajectories. High Arctic wetlands may respond more rapidly due to their smaller temperature ranges.

Bunnell *et al.* (1977) quantified the temperature response of microbial respiration (Q_{10}) in the Arctic as 3.7 for soils between 0 and 10°C (Robinson, 2002), which is the average temperature range of wet sedge soils in the growing season. When Billings *et al.* (1984) increased soil N through fertilization, a significant increase in CO_2 uptake was recorded in the harvested tundra soil cores. Past research has shown that a relationship exists between available soil N and measured environmental variables; this study aims to determine the spatial and temporal extents of these relationships in the CBAWO wetlands.

2.3 High Arctic Soils

In Canada, High Arctic soils are generally cryoturbated and permafrost-affected, therefore classifying them as cryosols. Cryosols in Canada's High Arctic account for 35% of soil area in the country (Tarnocai *et al.*, 2009; Jones *et al.*, 2010). High Arctic soils fall under the hypergelic soil temperature regime (Jones *et al.*, 2010), meaning their mean annual soil temperature falls below -10°C. Processes like cryoturbation explain irregular soil horizons or lack of definitive horizontal soil layers; the thorough mixing of soil material is frost-induced, and as such, below the organic layer, High Arctic soils see a perennially frozen layer known as the I horizon (Jones *et al.*, 2010). According to the *Soil Atlas of the Northern Circumpolar Region*, compiled as an initiative under the International Polar Year, CBAWO soils are turbic cryosols (Jones *et al.*, 2010). Arctic cryosols have a high quantity of recalcitrant organic material because of thousands of years of accumulation (Stark, 2007).

Arctic soils store large quantities of organic matter due to the frozen storage of decayed matter. In soils, competition for nutrients between microorganisms and plants is expected to shift with the changing climate; for example, reductions in soil microbes could greatly increase the amount of plant-available nutrients for uptake (Schmidt *et al.*, 1997; Stark, 2007). As the climate warms, environments like the High Arctic are susceptible to increased ground ice thaw and the subsequent degradation of permafrost through the formation of ground slumps and thermokarst depressions (Woo *et al.*, 2013). In 2007, which was an unseasonably warm year at the CBAWO, active layer detachments occurred that have direct disturbances on the watersheds (Lamoureux and Lafrenière, 2009); these permafrost disturbances are only expected to increase as warming is amplified (Jorgenson *et al.*, 2006; Fortier *et al*. 2007; Isaksen *et al.*, 2007). Because Arctic soils are particularly sensitive to climatic changes (Oechel *et al.*, 1993), Arctic permafrost environments are expected to be some of the largest C contributors through CO_2 and CH_4 release as the climate warms (Oechel *et al.*, 1993; Euskirchen *et al.*, 2016). These permafrost environments are also expected to contribute large quantities of N_2O. An experiment in the High Arctic research facility in Zackenberg, Greenland by Elberling *et al*. (2010) found that after thaw and rewetting, 31% of the N_2O in a 10-cm permafrost core was released into the atmosphere. Another study in Northern European Russia found the first evidence of increasing N_2O emissions with warmed temperatures (Voigt *et al.*, 2016). Relevant to this study of Arctic wetlands is that saturation is expected to increase N_2O emissions (Callaghan *et al.*, 2011a; Chen *et al.*, 2016); as such, the saturated nature of High Arctic wet sedge meadows and the forecast of increased precipitation with temperature increases the potential for greenhouse gasemissions of CH_4 and N_2O.

2.4 Nutrient Cycling in High Arctic Ecosystems

The nutrient regime in Arctic plant growth is typically characterized by slow growth rates that are N and P-dependent (Shaver and Jonasson, 1999). However, relative to more active, nutrient-rich temperate environments, tundra environments are more responsive to short-term (1-10 year) changes in nutrient availability (Shaver *et al.*, 2000). Due to the interconnected nature of the physical and microbial processes of Arctic wetlands, it is expected that changes in nutrient availability will be reflected in processes such as C flux. In a tundra microcosm experiment by Billings *et al.* (1984), authors found that an increase in soil N significantly increased CO_2 uptake. With the ongoing changes to climate that are affecting the High Arctic regions, it is expected that the increased soil temperatures will deepen active layers, lowering the water table to allow for nutrient release from decomposing organic matter (Biederbeck and Campbell, 1973; Billings *et al.*, 1982; Nadelhoffer *et al.*, 1991; Johnson *et al.*, 2000; Natali *et al.*, 2011). Environmental variables that have influence on the distribution of nutrients include soil temperature (ST), water availability and flow pathways, topography, and precipitation (Stewart *et al.*, 2014). All these factors in turn affect abiotic characteristics such as ST, soil moisture (SM), and pH.

2.4.1 Arctic Nitrogen Cycling

The N cycle involves the steps of fixation, mineralization, nitrification, and denitrification to convert N into various chemical forms (Figure 2). Terrestrial inputs of N occur through fixation, which is the conversion of atmospheric N into ammonium (NH_4^+) or reduced N through microorganisms like cyanobacteria. There is a large quantity of atmospheric N, however this form is unavailable to plants (Chapin *et al.*, 2002). The input of N into the soils through N_2 fixation plays a large role in accounting for half of the external annual input into Arctic soils, with atmospheric deposition contributing the remainder (Chapin and Bledsoe, 1992).

Mineralization is the conversion of organic N into NH_4^+ for uptake by plants. This process is heavily dependent on the C to N balance of the decomposing material in the soil (Chapin *et al.*, 2002; Stark, 2007). Net mineralization encompasses gross N mineralization, soil adsorption, and immobilization (Robinson, 2002) and ranges from 0.1 to 0.6 g m^{-2} $year^{-1}$ in Arctic soils (Van Cleve and Alexander, 1981; Robinson, 2002), although it is highly variable across different soil types and plant groups. Soil organic matter and decomposing litter fuel mineralization, and as the process is reliant on enzymes and bacteria, the presence of NH_4^+ can be indicative of microbial activity. Furthermore, it is hypothesized that with climate change and warming temperatures, higher rates of ecosystem respiration will decrease C storage, creating more favourable conditions for mineralization to occur in the High Arctic (Shaver *et al.*, 2000; Schmidt *et al.*, 2002).

NO_3^- is another form of inorganic N that is available for plants. Nitrification converts NH_3^+ or NH_4^+ to NO_2^-, which can then be oxidized to form nitrate that plants can take up through assimilation. The rate at which microbial processes like the N cycle operate depends on several factors within the specific environment (Stark, 2007). The low temperature and acidic nature of tundra soils slows processes like nitrification (Giblin *et al.*, 1991), which can only occur when nitrifying microorganisms are present (Stark, 2007). Mineral N forms can be lost to soil through leaching, as shown in Figure 2.

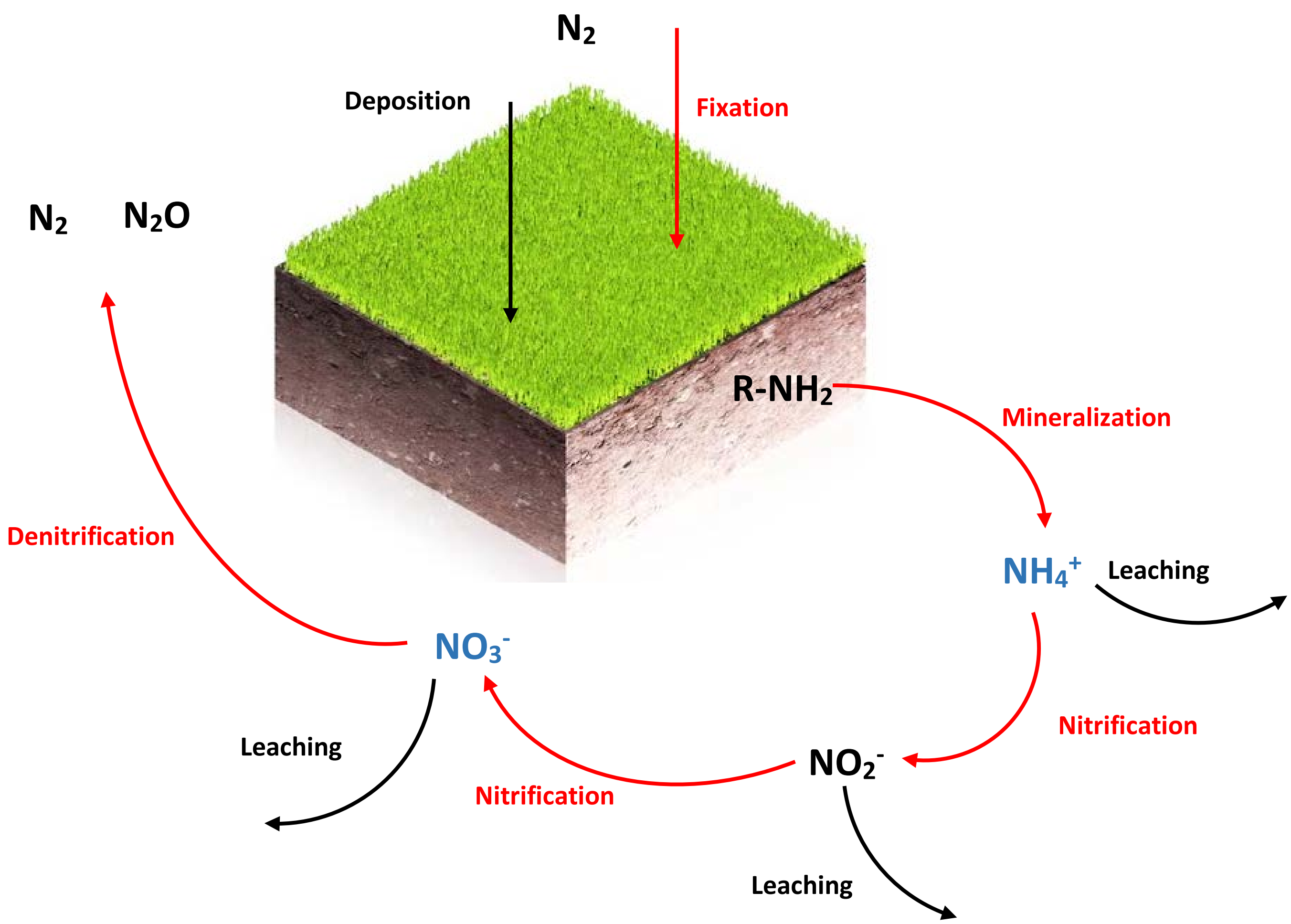

Figure 2: A conceptual diagram of the terrestrial nitrogen cycle, with red portions representing microbial processes and blue portions representing plant available N forms.

Denitrification is the last step of the N cycle when NO_3^- is converted back into N_2 for release into the atmosphere. Low oxygen, high NO_3^- concentration, and a labile organic C supply are required for high denitrification (Del Grosso *et al.*, 2000); as such, denitrification is a dominant process in anoxic environments like wetlands, since the high water availability limits oxygen (Chapin *et al.*, 2002). Larose *et al.* (2013) found N cycling to be sustainable in water-limited environments like the base of snowpacks through the work of microorganisms; the microbial communities were able to shift their functional potential to allow for several pathways of the N cycle to continue despite the low temperatures and limited water. These processes may be important in the wet sedge meadow of the study presented here, which is located at the base of a perennial snowpack. Research from field studies has also shown soil decomposition by microbes may be limited by N (Mack *et al.*, 2004; Lavoie *et al.*, 2011). Understanding the role N plays in Arctic ecosystems will help in future predictions of decreasing soil C storage and microbial decomposition as the environments continue to change (Chapin *et al.*, 2002; Mack *et al.*, 2004).

2.4.1.1 Biotic Nitrogen Fixation in High Arctic Wetlands

N sources in Arctic wetlands are largely brought in through fixation (Chapin and Bledsoe, 1992), much of which comes from biotic sources like cyanobacteria and mosses (Lennihan *et al.*, 1994; Griffith, 2014; Leppänen *et al.*, 2015). These organisms fix atmospheric N, transforming it into plant-available N forms. Cyanobacteria in terrestrial High Arctic ecosystems play an important role in N cycling. One genus, *Nostoc*, are associative phototrophic N fixers (Chapin *et al.*, 2002), and while their role in the wetland environment is known to be important, the relationship between fixation from *Nostoc* and consequent uptake into plants in the High Arctic has never been quantified (Griffith, 2014). In the CBAWO, *Nostoc commune* cover is quite high in undisturbed, exposed soil (Atkinson, 2012). In response to elevated temperature, Griffith (2014) found boreal N fixation by *Nostoc* to be decreased. Furthermore, with higher levels of plant-available N in the soils, *Nostoc* slowed down or ceased N fixation (Griffith, 2014). While these findings represent the response of *Nostoc* in a non-tundra environment, their role in nutrient cycles are the same, which could warrant similar responses in tundra environments.

Sphagnum is a genus of moss that has high water retention associated with N_2 fixation in Arctic environments (Leppänen *et al.*, 2015). This genus is typically found in fens and bogs with low-pH soils (Verhoeven *et al.*, 1990; Jonasson and Shaver, 1999); a variety of *Sphagnum* species are present in the CBAWO (Atkinson, 2012). In a warming treatment study, Chapin *et al.* (1995) found *Sphagnum* species to respond positively (increased height growth) to increased light exposure. As such, one can expect that with increased temperature leading to increased N availability, species richness may shift to favour more suitable N fixers in these wetland environments (Mellinger and McNaughton, 1975; Tilman, 1982; Jonasson and Shaver, 1999)

2.4.2 Environmental Factors Affecting Nitrogen Availability

Several factors explain the limitation of nutrient cycling in the Arctic; the short growing season with low temperatures and harsh climactic conditions are the main factors accounting for the limited microbial processes of the Arctic as compared to boreal environments. Plant decomposition rates are limited by temperature (Nadelhoffer *et al.*, 1991), as the nature of the climate in the Arctic regions allows decay to be slowed down by the cold temperatures (Woo and Young, 2006). These decomposition rates are directly related to nutrient release rates and their subsequent availability to plants (Jonasson and Shaver, 1999). With the changing climate, it is expected that the rate of microbial processes will change in response to higher soil temperatures.

However, the magnitude of this change is unknown, as the effect that warmer air temperatures will have on soil temperatures is uncertain (Robinson, 2002). An incubation study by Clein and Schimel (1995) did find that a wet sedge soil from Arctic Alaska showed a shift from net mineralization to immobilization of N as temperatures decreased.

Nutrient deposition into soil can occur through several pathways. Atmospheric C and N inputs can be deposited into soils through precipitation (Chapin *et al.*, 2002). Dry deposition delivers compounds like nitric acid by sedimentation, while cloud-water deposition leaves compounds onto plant surfaces as water droplets in fog (Chapin *et al.*, 2002). Generally, atmospheric N deposition in the Arctic regions tends to be low as compared to southern ecosystems, but can be highly variable. Studies have placed this number anywhere from 0.03 to 0.56 kg N ha^{-1} $year^{-1}$ (Gunther, 1989; Shaver *et al.*, 1992; Woodin, 1997; Hodson *et al.*, 2005; Aren *et al.*, 2008), to 1 to 10 kg ha^{-1} $year^{-1}$ (Lagerström *et al.*, 2007), to as high as 50 kg ha^{-1} $year^{-1}$ (NADP, 2002). Leaching through groundwater from surrounding watersheds also provide an input for loading of nutrients (Jonasson and Shaver, 1999). However, N gained through this process is generally low; for example the nature of the topography of the wet sedge meadow of interest at the CBAWO generally prevents groundwater input and promotes groundwater output.

Water availability is high in High Arctic wetlands due to the soil composition and its water supply (Chapin *et al*., 2002). The CBAWO is underlain by steeply dipping sandstone and siltstone of the Devonian Weatherall and Griper Bay Formations; the weathered material is fine sand, silt, and clay mixed with gravel (Hodgson *et al.*, 1984; Atkinson and Treitz, 2013). As clay substrate soils have a high surface area-to-volume ratio, the relatively high soil moisture of the CBAWO promotes nutrient availability. Topography is also important in influencing the direction of flow and areas of deposition for nutrients. Spring snowmelt run off and a heavy rain after a drier season can introduce pulses of nutrients into an environment (Chapin *et al.*, 2002; Thompson and Woo, 2009); the flow pathways and input of these nutrients are dependent on elevation.

Microbial controls on nutrient cycling are important processes to consider in High Arctic environments. Mikan *et al.* (2002) found that warming in laboratory incubation studies stimulated microbial activity and increased nutrient turnover in thawed soils. Microbial activity is known to remain active throughout the winter season and can have significant contributions to nutrient budgets during spring thaw (Hobbie and Chapin, 1996; Schmidt and Lipson, 2004; Edwards *et al.*, 2006). Because the insulating snow layer prevents Arctic mid-winter soils from falling below -10°C (Clein and Schimel, 1995), the occurrence of freeze-thaw events allows microorganisms to remain active as long as pockets of liquid water are still present as a result of the snow insulation (Edwards *et al.*, 2006). The activity of these microorganisms will mobilize N stores that can help mitigate the current nutrient limitation in High Arctic ecosystems (Beermann, 2016). This conforms to Mikan *et al.*'s (2002) findings that thawed soils display increased microbial activity. In High Arctic wetlands where microbial metabolism is primarily anaerobic due to the anoxic conditions, changes to drainage, precipitation, or evapotranspiration patterns will be the primary driver of microbial activity changes in the future (Mikan *et al.*, 2002).

While soil nutrient availability in High Arctic wetlands can be associated with C flux, C flux cannot necessarily be used as an indicator of nutrient stores as plants metabolize nutrients at different rates (Jonasson and Shaver, 1999). More available nutrients to plants promotes plant metabolism and subsequent respiration and photosynthetic activity. These mineralization and metabolic rates of plants are heavily dependent on variables such as temperature and moisture;

Schmidt *et al.* (2002) found that increases in soil temperature (ST) by 2°C increased net N mineralization in Low Arctic dwarf shrubs.

2.5 Summary

In the High Arctic, wetlands are the most productive ecosystems with high rates of C storage (Henry *et al.*, 1990; Henry, 1998; Blaser, 2016) and will have great influence on the C balance of the northern regions as the climate warms. These ecosystems have a large quantity of stored subterraneous carbon (Post *et al.*, 1982; Grogan and Chapin, 1999, Tarnocai *et al.*, 2009). As such changes to wetlands can drive changes in the fluxes of CO_2 and trace gases in these systems. Changes to environmental variables like ST, SM, and active layer (AL) depths will affect the processes and dynamics within Arctic soils, including key processes like N cycling. Available N in the forms of NH_4^+ and NO_3^- is a major limiting factor for plant growth in the High Arctic (Nadelhoffer *et al.*, 1992; Shaver and Chapin, 1995) and concentrations are usually relatively low. However, the factors causing this shortage of plant-available N are not fully understood (Beermann, 2016) and the circumpolar N pool needs to be further investigated. Biotic N fixers like cyanobacteria and moss play important roles in the Arctic tundra environments (Lennihan *et al.*, 1994), and their role in response to environmental change is expected to increase (Griffith, 2014). Many factors determine the levels of plant-available N that fuel N cycling and C flux (Nadelhoffer *et al.*, 1991; Clein and Schimel, 1995; Chapin *et al.*, 2002), and the need to understand the relationship between the environmental variables and these processes is more important than ever in this climate change narrative.

Chapter 3: Spatial and temporal patterns of soil nitrogen availability and carbon exchange in a High Arctic wetland

3.1 Abstract

Increased soil nutrient availability, and associated increase in ecosystem productivity, could create a negative feedback between Arctic ecosystem and the climate system, reducing the contribution of Arctic ecosystems to future climate change. To predict whether this feedback will develop, it is important to understand the environmental controls over nutrient cycling in High Arctic ecosystem, and how they vary over space and time. This study explores the environmental controls over spatial patterns of soil nitrogen availability in a High Arctic wet sedge meadow and how they influence carbon exchange processes. Ion exchange resin membranes measured available inorganic nitrogen throughout the growing season at a high spatial resolution, while environmental variables (e.g. active layer depth, soil temperature, and soil moisture) and carbon flux measurements were taken at frequent intervals during the 2016 field season. Environmental measures correlated highly with total and late season nitrate (total season dry tracks NO_3^- R^2 = 0.533, total season wet tracks NO_3^- R^2 = 0.803, late season NO_3^- R^2 = 0.622), with soil temperatures at 10 cm depth having the greatest effect. Soil available nitrogen correlated highly with total and early season gross primary productivity (total season wet tracks R^2 = 0.685, early season dry tracks R^2 = 0.788, early season wet tracks R^2 = 0.785). Higher ammonium concentrations coincided with greater CO_2 uptake. Nitrate concentrations correlated strongly to soil moisture, but nitrate levels were much lower than ammonium concentrations, suggesting low rates of nitrification vs. mineralization. Similar patterns were observed regardless of whether the wet-sedge meadow was classified as wet vs. dry, but the relationships were always stronger in areas classified as wet, indicating the importance of moisture and water availability on abiotic processes in High Arctic wet sedge meadows. Topography played an

important role in the movement and transport of water, which influenced how nutrients were cycled and moved within the wetland. Generally, the low-lying areas had the highest inorganic nitrogen concentrations. These results suggest that finer scale processes altering nitrogen availability may influence the C balance of wet sedge meadows in the High Arctic, and how these ecosystems may respond to changes in climate.

3.2 Introduction

Warming temperatures in the High Arctic are expected to exceed global rates by 40% (IPCC, 2013). Changes to seasonal weather patterns may also influence ecosystem-level abiotic factors, which in turn will influence biogeochemical processes (e.g. C and N cycles) in complex ways. The IPCC (2013) projects a 10-28% increase in mean Arctic precipitation by the end of the 21st century. Some of the changes to Arctic regions are already being seen with amplified warming (Bintanja and Andry, 2017) and further changes are expected. These changes could lead to the development of negative feedbacks, potentially stabilizing the climate system.

Some of the consequences of Arctic warming include increased air temperatures leading to earlier snowmelt onset (Young, 2006) and precipitation increase leading to permafrost degradation and the release of previously unavailable soil C (Oechel *et al.*, 1993; Schuur *et al.*, 2009). Warming is expected to accelerate the decomposition of soil organic matter (SOM) (Chapin *et al.*, 1995; Aerts *et al.*, 2005; Bell *et al.*, 2013), potentially altering rates of nutrient cycling. N fixation by key ecosystem species like *Nostoc commune* and *Sphagnum spp.* will also change with air temperature increases (Chapin *et al.*, 1995; Schmidt and Lipson, 2004; Griffith, 2016), potentially altering available nutrient pools. In turn, higher nutrient availability could alter species composition within High Arctic ecosystems (Aerts *et al.*, 2005), plant productivity (Shaver *et al.*¸ 2000), and the net C balance (Welker *et al.*, 2004). Given the number of changes and potential responses, an ecosystem-level understanding of these interactions is critical to understand how they will respond to future changes in climate.

High Arctic plant growth is typically limited by N availability (Nadelhoffer *et al.*, 1992; Shaver and Chapin, 1995; Shaver *et al.*, 2000). As such, this study looked at the spatial patterns of plant-available inorganic N to see how these patterns shift as the growing season progressed. A wetland was selected as the study site for its characteristics as the most productive and photosynthetically active ecosystem in the High Arctic environment. N fixing organisms in wet Arctic environments like wet sedge meadows are primarily mosses and lichens (Robinson and Wookey, 1997; Stark, 2007), which are dominant in wet sedge meadows in the Cape Bounty Arctic Watershed Observatory (CBAWO). With changes anticipated in the High Arctic regions, land classes such as wet sedge meadows will likely respond dramatically, and changes in these wetlands will have cascading effects on terrestrial and hydrological features around them.

This study explores the spatial and temporal patterns of available soil N in a wet sedge meadow in the Cape Bounty Arctic Watershed Observatory of the Canadian High Arctic, and how they relate to C exchange processes. In the High Arctic, the wet sedge meadows are generally saturated year round, resulting in relatively high net primary production (NPP), but productivity is limited by the harsh polar environment and poor drainage (Gebauer *et al.*, 1995; Hill and Henry, 2011). Wet sedge meadows at CBAWO occupy slightly less than 10% of the land area at CBAWO and have the highest rates of net ecosystem exchange (NEE) compared to the other dominant plant communities at CBAWO (Gregory, 2011). Previous studies in this wet sedge meadow have looked at the seasonal variability of C flux and environmental variables (Ramsay, 2015; Luce, 2016) and C fluxes across wet and dry areas within wet-sedge meadows (Blaser 2016). To date, however, no one has assessed the relationships between available N and

C exchange and never assessed the spatial patterns of these interactions. While nutrients have been examined in CBAWO wetlands (Gregory, 2011), spatial and temporal extent of the sampling was much more limited than used in this study.

3.3 Methods

3.3.1 Study Site

The CBAWO (Figure 3) is located on the southern coast of Melville Island, Nunavut (74°54'N, 109°35'W), near the Nunavut-Northwest Territories border. The area contains two watersheds (East and West Lake), and the entire area covers approximately 150 km^2. The area is continuous permafrost with a 0.5 to 1-metre thick active layer (Atkinson and Treitz, 2013). The climate in the area is cold throughout the year with the summer melt and growing season running from June to August (Atkinson and Treitz, 2013). Strong winds are typical during the growing season, clocked at up to 80 km/h in 2008 (Gregory, 2011). January 2016 minimum and maximum temperatures were -33.7°C and -21.5°C respectively, while July 2016 minimum and maximum temperatures were 1.7°C and 10.9°C respectively.

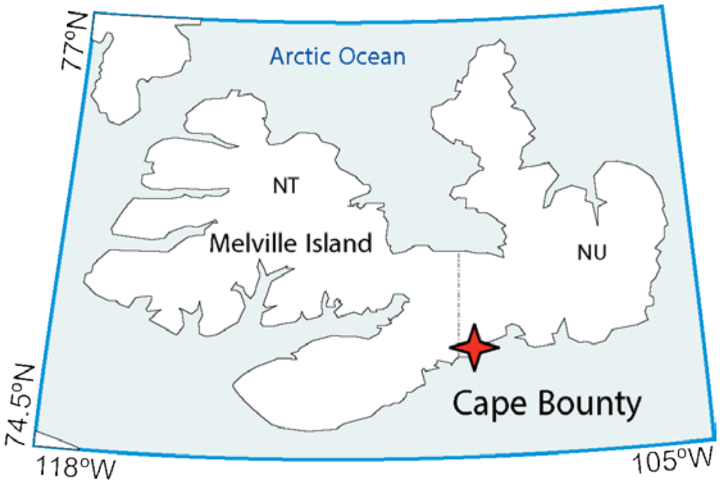

Figure 3: Map showing Melville Island with the Cape Bounty Arctic Watershed Observatory (red star).

Figure 4: WorldView-2 imagery of the Cape Bounty Arctic Watershed Observatory in July 2016.

The CBAWO (Figure 4) was selected as the area of interest due to its availability as a High Arctic research area and the longevity of hydrological and biogeochemical research that has been conducted. This study was carried out from June 25 to July 28. Sampling regimes were established once on site and depended to some extent on equipment availability and weather.

The CBAWO is dominated by three land cover classes: polar semi-desert, mesic tundra, and wet sedge meadows (Gregory, 2011; Atkinson, 2012; Atkinson and Treitz, 2013). The polar semi-desert often occur on upland sites and contains patches of vegetation interspersed with dry, rocky ground. These vegetation patches are characterized by a mix of dwarf shrub, forbs, grasses, and mosses (Gregory, 2011; Atkinson, 2012). The mesic tundra is characterized by a thin vegetation layer interspersed by exposed mineral soil (Gregory, 2011; Atkinson, 2012). Wet sedge meadows are the least abundant cover type in the CBAWO (Atkinson and Treitz, 2013). These areas tend to be in lower-lying locales near a continuous water supply during the growing season (Woo and Young, 2006; Thompson and Woo, 2009; Woo, 2011).

The wet sedge meadow of interest within the CBAWO, “Muskox”, is a 200 metre by 200 metre plot that is saturated year round (Figure 5). Water is provided to the site from a perennial snowpack located at the north end of the area (Figure 6). Walker *et al.* (2005) give the Cape Bounty area a G2 vegetation classification of moist tundra covered with low-growing forbs, grasses, mosses, and lichens. The Muskox site slopes downward away from the snowpack from north to south as well as from east to west and has a south-facing aspect. Within Muskox, there are variations in dryness and wetness across the sites (Atkinson, 2016; Blaser, 2016). Wet tracks are characterized by standing water in some areas and higher soil moisture, while dry tracks are still wet but lack pools of standing water (Blaser, 2016). The partitions for these moisture tracks are small longitudinal hummocks that were likely formed from cryogenic events (Hodgson *et al.*, 1984).

Figure 6: North-facing image of the wet sedge meadow study area “Muskox”.

Figure 5: Topographic map of the Cape Bounty Arctic Watershed Observatory, highlighting the study area “Muskox”.

The sampling area is dominated by *Carex*, *Gramineae*, and *Sphagnum spp.* (Figure 7), with the occasional bedrock outcrop. The dwarf shrub *Salix arctica* and flowering *Eriophorum*, *Ranunculus rivalis*, and *Papaver radicatum* are also present in the wet sedge meadow. *Salix arctica* was most dominant in the wet tracks of the meadow, while herbaceous flowering plants tended to be found in dry tracks. Sharing the ground with the *Sphagnum* mosses were various lichen, including *Cladonia* and *Stereocaulon* genus. As the melt season progressed, the drainage of standing pools of water in the western portion of the meadow revealed the N-fixing cyanobacteria *Nostoc commune*.

Figure 7: Wet sedge meadow vegetation type.

3.3.2 Experimental Design

The sampling methodology was designed to sample the variations in soil moisture within the meadow. The actual sampling sites were determined using *in situ* site reconnaissance with the aid of satellite imagery to discern between moisture tracks.

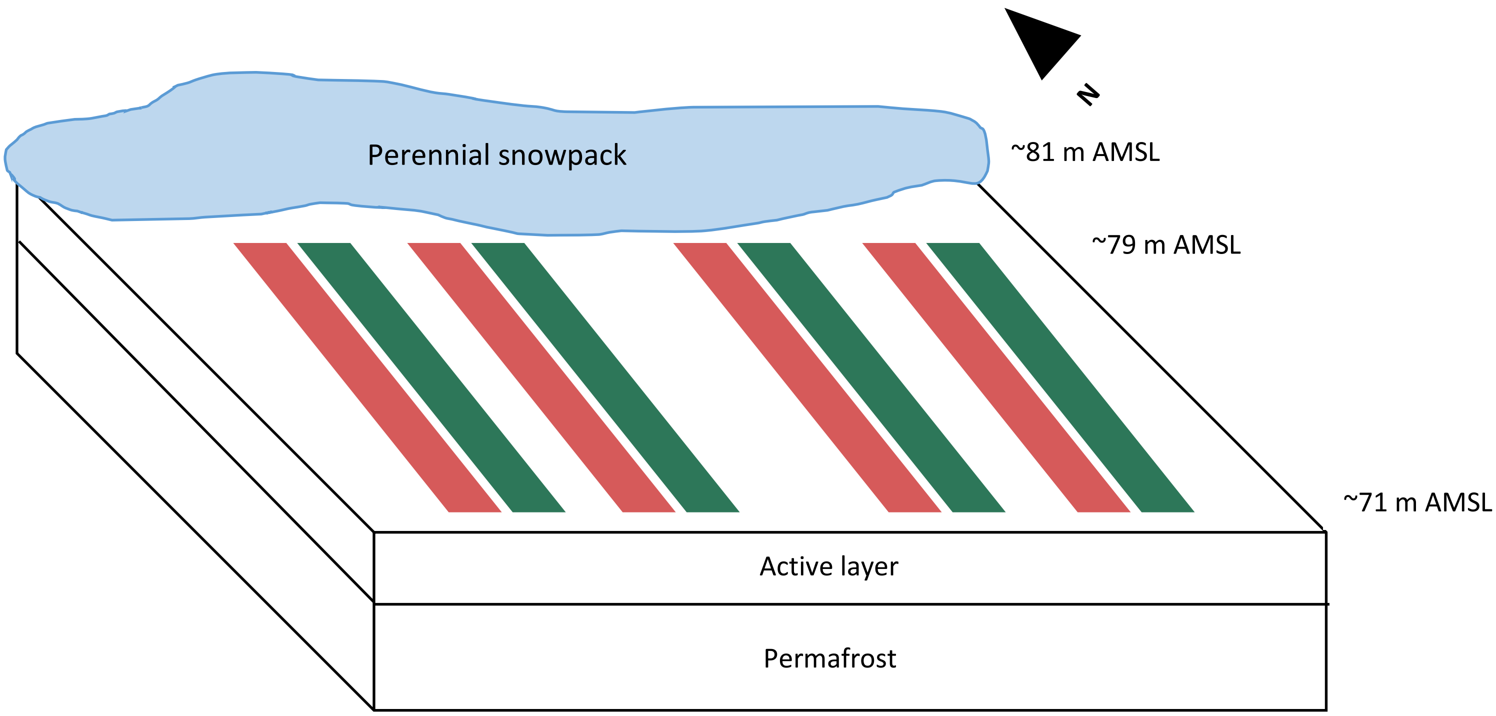

Figure 8: Conceptual diagram of the sampling plot, with wet tracks represented in red and dry tracks represented in green. Elevations of the snowpack, northern-most sampling plots, and southern-most sampling plots are displayed as metres above mean sea level (AMSL).

A total of 64 sites were established on alternative wet and dry strips sampled using ion exchange resin strips (Figure 8 and Figure 9); these sites represent an 8 row by 8 column grid that encompasses 4 wet and 4 dry transects within the meadow. The aim with this sampling design is to test the effects of proximity to snowpack and its water input (e.g. differences in soil moisture) on nutrient availability within the wet sedge meadow. A prior study at CBAWO sampled soil nutrients randomly in wet-sedge meadows, and did not account for soil moisture variability (Gregory, 2011). The results from this design give insight into the spatial variability within the meadow.

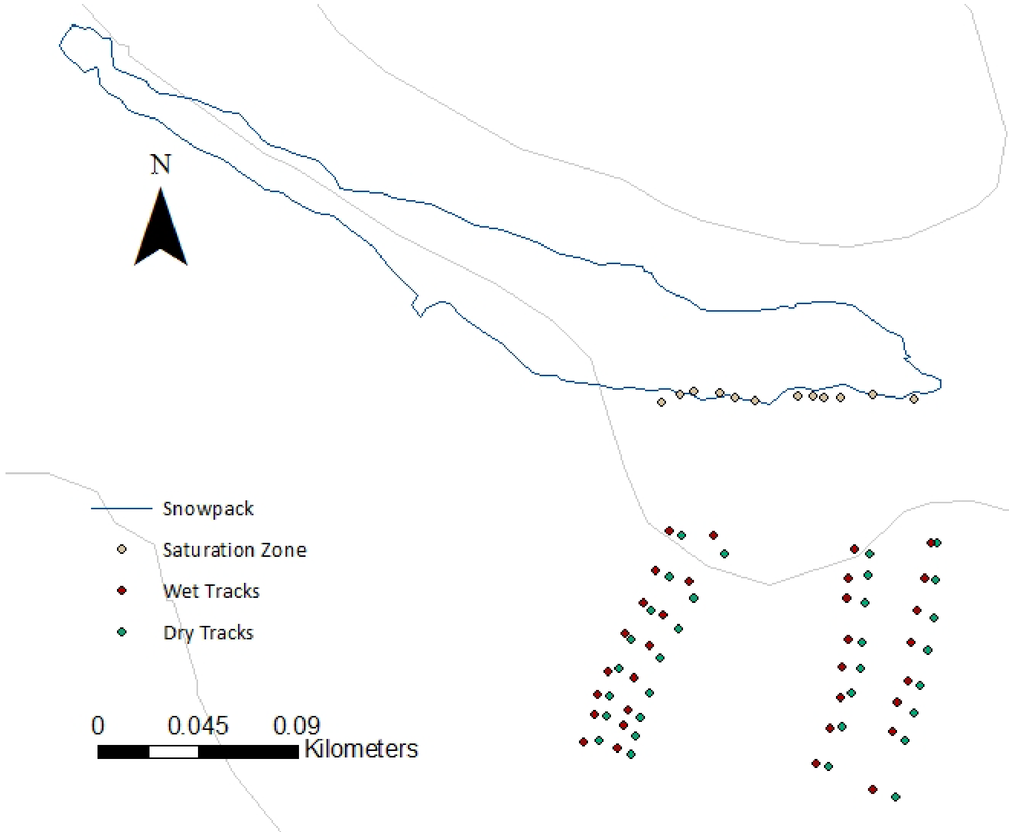

Figure 9: Topographic map depicting the layout of the experimental design

Directly south of the snowpack, a saturation zone (SZ) exists that is characterized by standing water above the vegetation in some areas (Atkinson, 2016). The SZ exists as the snowpack retreats due to the melt, exposing an area that is not quite developed as a wetland due to a lack of exposure from under the snowpack that has a very high moisture content. Consequently, vegetation in this area does not develop as it is typically limited in nutrients (Woo and Young, 2006). This area was also sampled with 12 sites of ion exchange resins to determine the effects of the perennial snowpack on soil characteristics. Overall, 76 sampling sites were staked out in the wetland.

3.3.3 Soil Nutrient Availability Evaluation

Ion exchange resin (IER) membranes (Qian and Schoenau, 2005; Milligan, 2010) were employed to determine soil N availability within the Muskox meadow at CBAWO. The methodology for soil nutrient assessment in the watershed were determined from literature, as soil nutrients have never been examined or quantified in the watershed wet sedge. Traditionally, soil nutrient assessment studies in literature have employed the use of the soil sample collection and wet chemical analysis to determine the nutrient availability on site (Binkley and Matson, 1983). However, these traditional methods can be costly and time consuming, depending on the environment of interest. A method of assessing soil nutrient availability that can complement traditional methods of soil sampling is the use of resin strips (Qian and Schoenau, 2005). These resin membranes work by adsorbing nutrients that are attracted to the resident ions on the resin membranes, which are placed onto the resins through pre-burial preparation techniques (Jasrotia and McSwiney, 2009).

IER membranes are polymers that have charged sites that can exchange ions with other substances; bicarbonate-form anion resins were selected as they are preferable to hydroxyl-form resins (Lajtha, 1988). Resin membranes were prepared using the ion exchange resin protocols created at the Kellogg Biological Station at Michigan State University (Jasrotia and McSwiney, 2009). Cation and anion exchange resins measuring 2.5 cm by 10 cm were made from membrane sheets obtained from Membranes International Incorporated (Membranes International Inc., Ringwood, New Jersey, United States). Cation and anion resins were pre-loaded with a 0.5M hydrochloric acid (HCl) solution for 24 hours with agitation to allow for the acid to strip the resin of any ions currently present, after which they were soaked in 0.5M $NaHCO_3$ for 5 hours with agitation to saturate sites for sodium and bicarbonate ions (Qian and Schoenau, 2005; Western Ag, 2012). The anion probes were also soaked in a 0.01M ethylenediaminetetraacetic acid (EDTA) solution for one hour with agitation to help increase its adsorption of phosphorus (Western Ag, 2012). The resins were deployed at 10 cm soil depth remained in the field for the allotted burial time of either 2 weeks or 4 weeks. When removed from site, the resins from each experimental plot were cleaned and rinsed with deionized water, bagged, refrigerated, kept dark, and brought back for analysis. In each sampling plot, 5 anions and 5 cations were deployed and eluted concurrently to obtain one concentration value of the nutrients of interest. Batch elutions were done for each sampling plot do to the nutrient-limited nature of the study area that may be below detection limits if eluted individually and averaged. Resin extracts were then run through an Astoria2 Analyzer automated colourimetric system (Astoria-Pacific, Clackamus, Oregon, United States) to quantify nitrate and ammonium concentrations.

Two sampling regimes were employed: in one method, the resins were deployed for the duration of the study period for nutrient adsorption from June 30 to July 27 (Resin A). In the second method, resins were deployed at the beginning of the study period from June 30 to July 13 (Resin B1) and switched out for new resins halfway through from July 13 to July 27 (Resin B2) to test for the robustness of the resins when comparing the total nutrients adsorbed to the resins deployed for the entire season. This sampling methodology also helps account for the seasonal variation of soil nutrient availability.

3.3.4 Carbon Flux Sampling

NEE and ER measurements were conducted using closed, static chambers, according to methods in Beamish *et al.* (2014). A PVC collar (20 cm diameter) was inserted into the ground (at roughly 5 cm depth) at half of the resin sampling sites and transparent chambers (Figure 10) were attached to the collars using a rubber gasket to create a seal. Instantaneous CO_2 concentration was measured using a portable infrared gas analyzer (IRGA) (Vaisala GMP343 Carbon Dioxide Probe; ± 3ppm) (Vaisala, Vaanta, Finland) in sites adjacent to the resin sampling area. A relative humidity (RH) and temperature probe (Vaisala HMP75 Relative Humidity and

Temperature Probe; ±1% RH, ±0.2°C) in the chamber measured these parameters simultaneously. Changes to CO_2 concentrations were measured in the chamber at five second intervals for five minutes. After the light measurement, the chambers were removed from the collars and aired out return to ambient conditions, after which an opaque shrowd was used to cover the chamber and prevent photosynthesis for the ER measurement. A Kestrel 3500 weather metre was used to determine atmospheric pressure which was needed for the gas flux calculations (Kestrel, Birmingham, Michigan, United States).

Figure 10: CO_2 flux static chamber light measurement and ion exchange resin strips *in situ*

3.3.5 Environmental Measurements

Environmental measurements (soil moisture, soil temperature, and active layer depth) were taken twice per week. Sampling sites were adjacent to the locations of the ion exchange resins. SM was measured at 0-5 cm depth using a ML-3 Theta probe with data stored in a data logger. ST was measured at 10 cm depths using a standard soil temperature probe. AL depth was measured using a steel rod that was inserted into the ground until reaching frozen ground. A local meteorological station set up by Queen's University, "West Met" provided hourly on temperature and precipitation.

3.3.6 Post-Field Processing

3.3.6.1 Ion Exchange Resin Sample Processing

The ion exchange resins were eluted in groups of 10 strips (5 per cation and anion) to analyze each sampling plot; consequently, single values for each ion of interest were generated for each of the 76 sampling areas. The concurrent elutions to produce one sample for analysis was done to avoid nutrient readings below the detection limit, as Arctic environments are nutrient-limited to begin with. The eluates were extracted by soaking the resins in a 400 mL 0.5M HCl solution for one hour with 40 rotations per minute (RPM) agitation. The elution for each sampling site were down-sampled into two sets of 50 mL centrifuge tubes for transportation and storage prior to colourimetric analysis.

The Astoria2 Analyzer automated colourimetric system is a segmented flow analyzer (Astoria Pacific, 2011) that automates the wet chemistry processes in determining nutrient concentrations of interest. In this study, as plant-available N was of interest, the colourimeter was set up to analyze for NH_4^+ and NO_3^-. The phenate method was used in the determination of NH_4^+ concentrations and the cadmium reduction method was employed for determining NO_3^- concentrations (Pansu and Gautheyrou, 2006). The samples were downsampled to 4 mL cuvettes to be run for analysis and three quality assurance and quality control steps were taken to assess for error: 1 in 10 samples was run in duplicate, 1 in 30 samples was a blank (MilliQ), and 1 in 45 samples was run using blanks to account for instrumentation drift. Overall, all samples were run twice and averaged where valid.

3.3.6.2 Carbon Flux Calculation

A custom Matlab script was created to calculate CO_2 fluxes and GPP from the CO_2 concentration data gathered by the IRGA (Atkinson, 2012). CO_2 concentrations were converted to fluxes by converting ppm values to moles of CO_2 using the ideal gas law and temperature and pressure data collected during field data acquisition. Gas concentrations (μmol/m^3/s) were calculated from the inputted air pressure (hPa), relative humidity (%), temperature (°C), and gas concentrations in parts per million (Equation 1):

$$n = C\left(\frac{\rho}{R\tau}\right)\left(\frac{v}{A}\right) \qquad (1)$$

n: converted gas concentration (μmol m^{-3})
C: original measured gas concentration (ppm)
ρ: air pressure (hPa)
R: ideal gas constant (8.314 J K^{-1}mol^{-1})
τ: temperature (K)
v: combined volume of chamber attached to the collar minus the volume of the sensors (m^3)
A: projected horizontal surface area of the chamber (m^2)

Once converted to moles, an iterative linear regression algorithm went through the inputted data to determine the rate of change during the 5-minute measurement period. The algorithm searches through the data and finds the best subset of points that yields the highest R^2 value (minimum of 12 points). The slopes of these regression lines represent the flux rate (μmol m^{-2}). GPP (total photosynthesis) was calculated using Equation 2:

$$GPP = NEE - ER \qquad (2)$$

NEE (e.g. overall CO_2 exchange) is equal to what the atmosphere gains through respiration (positive values) minus what the terrestrial system sequesters with respect to productivity (negative values) (Chapin et al., 2006). Negative NEE is indicative of C coming into the system, while a positive number represent C being outputted into the atmosphere.

3.3.7 Data Analysis

A variety of spatial and non-spatial statistical analysis techniques were used to analyze the data. The IBM SPSS 22 statistical analysis package was used to conduct descriptive statistical analysis. Two-way repeated measures analysis of variance (ANOVA) was conducted to compare environmental variables, C fluxes, and available soil N in the different moisture regimes. When analysing these variables, studentized residuals were examined for values greater than ±3 and outliers were removed (Laerd Statistics, 2013). All the variables were assessed for normality using the Shapiro-Wilk's test on the studentized residuals and for homogeneity. Mauchly's test of sphericity was indicative of any within-subjects effects that violated the assumption of sphericity; as such, the Greenhouse-Geisser correction (Maxwell and Delaney, 2004) was used for any necessary variables. A second two-way repeated measures ANOVA was conducted to explore spatial differences within a single moisture regime (e.g. dry vs. dry, wet vs. wet). For these analyses, Tukey's post-hoc test was run and individual tracks were compared temporally to determine the areas of greatest variance.

Bivariate and multiple regression was run with available N as the dependent variable to determine relationships between environmental variables with early, late, and total season NO_3^- and NH_4^+. N was used as the independent variable when analyzed against early, late, and total season GPP and ER. The Durbin-Watson statistic determined that there was independence of residuals for all resin regimes. The data were checked for homoscedasticity, multicollinearity, and normality and outliers were removed prior to analysis.

To explore spatial patterns, local indicators of spatial association (LISA) maps were created in GeoDa and analyzed to determine clusters of areas with high and low NO_3^- and NH_4^+ tended to gather within Muskox. Ordinary Kriging in ArcGIS 10.3.1 was conducted on total, early, and late season NO_3^- and NH_4^+ concentrations to interpolate concentrations across the wet sedge meadow and confirm the spatial autocorrelation results. This method was selected as kriging is considered an unbiased interpolation method with the least estimation variance (Siska and Hung, 2001; Yang *et al.*, 2011). Furthermore, as there is hypothesized to be some directional bias or spatial correlation in the data, kriging can be useful in visualizing those biases (Childs, 2004).

3.4 Results

3.4.1 2016 Growing Season Air Temperature and Precipitation

The 2016 growing season exhibited temperature and precipitation patterns, collected at the meteorological stations at CBAWO (Figure 11) consistent with 2014 patterns. When comparing the last three growing seasons, 2016 exhibited significantly higher cumulative rainfall and warmer June temperatures, while 2015 had the highest June temperatures of the three years (Figure 12). Maximum air temperature (AT) of 17.4°C was reached on July 5, 2016, which was preceded by a precipitation high of 2.2 mm the day before. The early season was characterized by little to no precipitation with constant temperature increases, while the later part of the season had more occurrences of precipitation with decreasing AT.

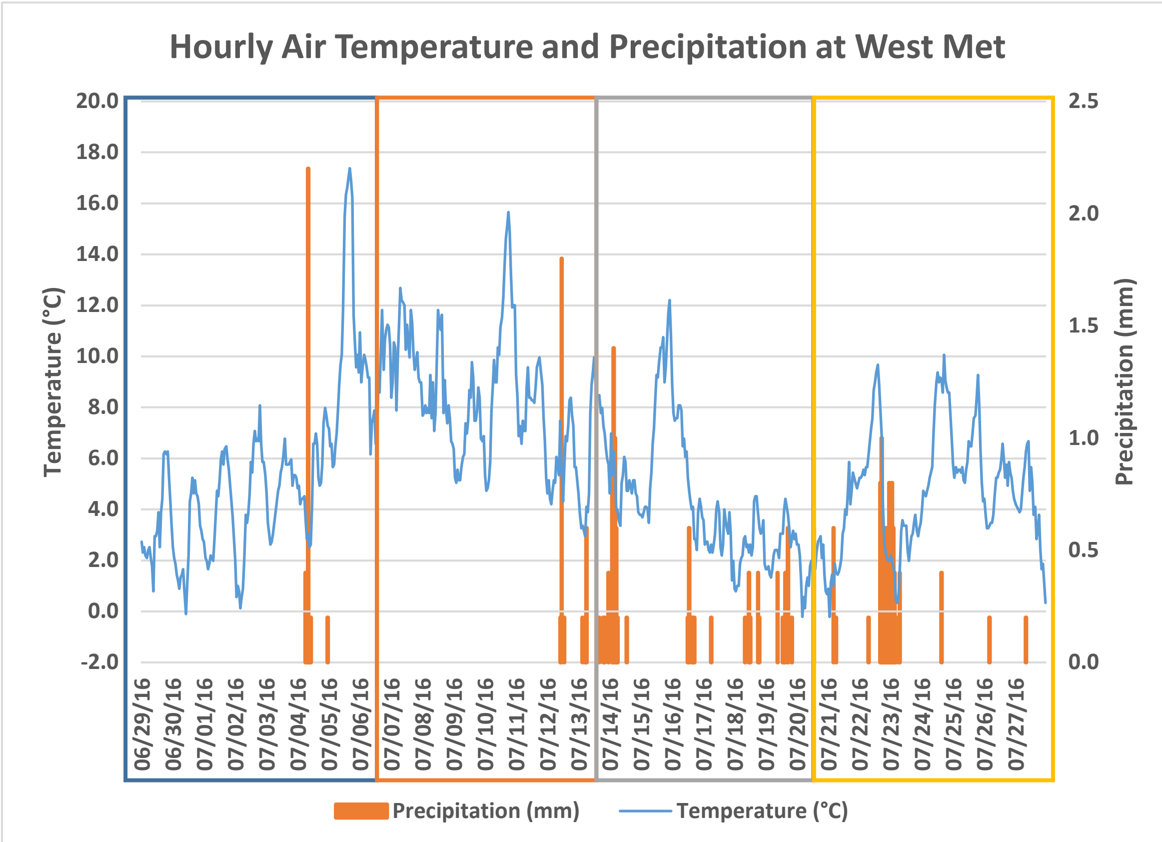

Figure 11: Hourly air temperature and precipitation measurements at the "West Met" meteorological station at CBAWO from June 29 to July 27, 2016. Rectangles represent the partitioning of the study period into weeks for analysis: Week 1 (blue), Week 2 (orange), Week 3 (grey), and Week 4 (yellow).

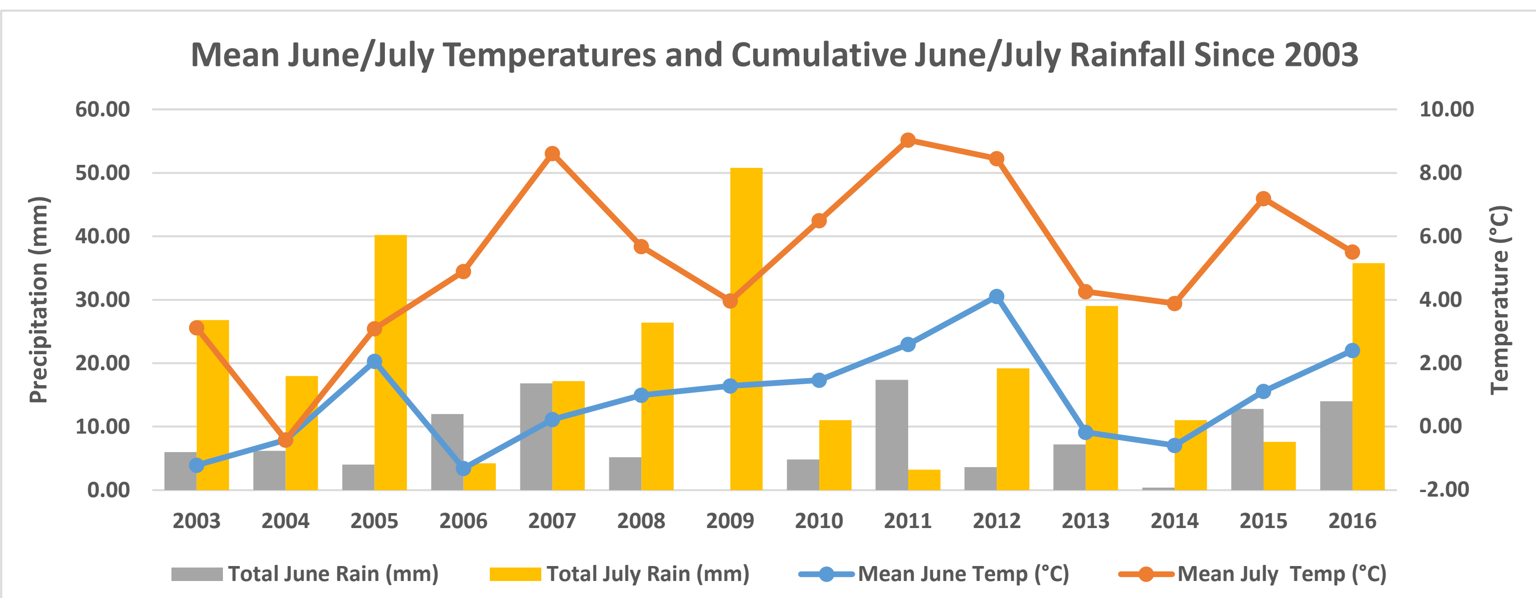

Figure 12: Mean June and July temperatures and cumulative June and July rainfall since monitoring was started at the CBAWO in 2003.

3.4.2 Environmental Variables

Table 1: Mean environmental variables across the moisture tracks over the growing season. Standard deviations are indicated in brackets.

	Week 1	**Week 2**	**Week 3**	**Week 4**
ST Dry (°C)	0.9 (0.8)	2.0 (1.1)	1.3 (0.85)	2.0 (0.87)
ST Wet (°C)	2.4 (1.4)	3.8 (1.3)	2.9 (0.94)	3.6 (0.76)
SM Dry (%)	45.7 (12.2)	55.4 (11.4)	69.5 (12.2)	62.7 (9.24)
SM Wet (%)	80.7 (15.7)	76.8 (13.8)	86.5 (13.4)	88.4 (12.5)
AL Dry (cm)	25.3 (6.03)	28.7 (7.16)	29.8 (8.25)	30.8 (7.87)
AL Wet (cm)	33.9 (6.99)	41.7 (6.55)	43.6 (7.09)	43.9 (6.18)

Table 2: Two-way ANOVA p-values for environmental variables across the growing season in different moisture tracks across the plot. Bolded values indicate significance at p < 0.05.

Interaction	**ST**	**SM**	**AL**
Time	**0.000**	**0.000**	**0.000**
Moisture track	**0.000**	**0.000**	**0.000**
Time x Moisture track	0.286	**0.000**	**0.000**
Time x Moisture track x Spatial location (W vs. E)	**0.000**	**0.001**	**0.005**

Soil temperature was measured ten times during the growing season, and was significantly higher for between-subjects effects in the wet vs. dry tracks (1.5 vs. 3.2^{o}C), $F(1,28) = 19.8$, $p < 0.05$ (Table 2). There was also a statistically significant within-subjects effects across the four-week growing season, $F(1.77,49.4) = 97.5$, $p < 0.05$, $\varepsilon = 0.59$, with the wetter track means increasing from Week 1 to Week 4 (Figure 13). However, there was no statistically significant three-way interaction between ST within the moisture tracks over the growing season, $F(1.765,49.418) = 1.281$, $p = 0.284$. When the tracks were compared within a moisture regime (to test spatial variability), the dry tracks differed significantly for within-subjects effects, $F(3,33) = 106.817$, $p < 0.05$, but there was not statistical difference for between-subjects effect across individual dry tracks across the season, $F(9,33) = 1.51$, $p = 0.186$ (Table 41). In the wet tracks, the measurements were statistically significant across weeks, $F(3,33) = 106.1$, $p < 0.05$, and between individual wet tracks across the growing season, $F(9,33) = 10.1$, $p < 0.05$ (Table 42). The post-hoc results indicated the greatest difference between Wet 1 and Wet 5, which was statistically significant ($p < 0.05$) (Figure 13).

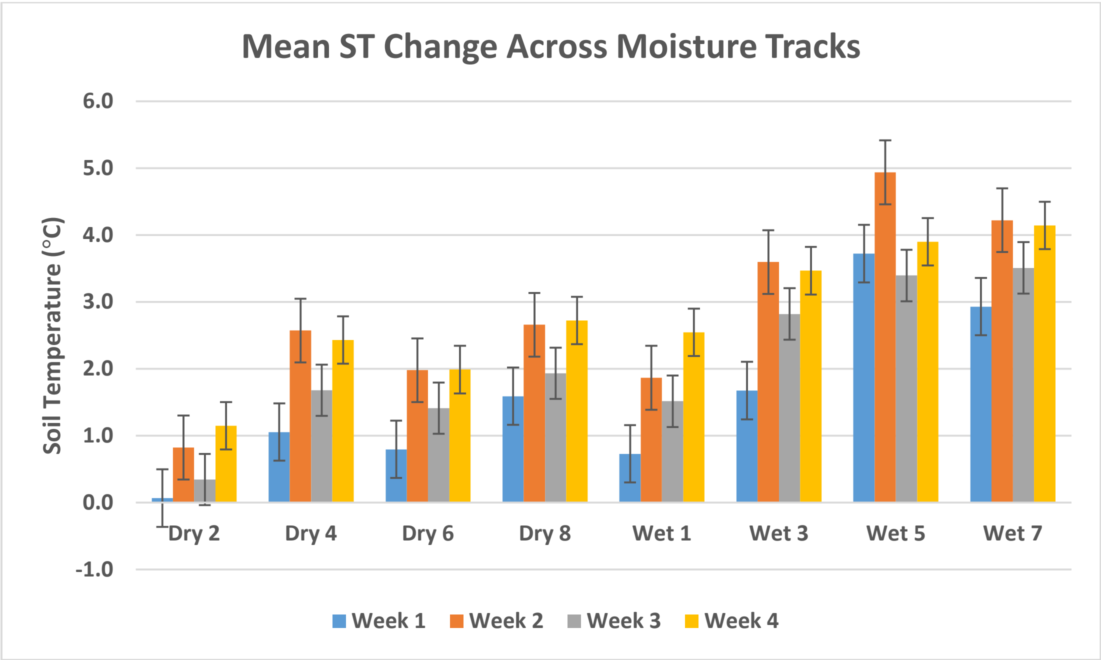

Figure 13: Mean (± 1 SE) ST change across the growing season within the tracks.

SM differed significantly between wet and dry tracks, $F(1,28) = 39.4$, $p < 0.001$ (Table 2). There was a statistically significant within-subjects interaction between SM across weeks over the growing season, $F(2.10,58.7) = 26.1$, $p < 0.05$, $\varepsilon = 0.70$; as with ST, SM also steadily increased from week to week and measurements were greater in the wet tracks than the dry tracks (Figure 14). When the tracks were compared within moisture regimes, the dry tracks were still statistically significant across weeks, $F(1.65,18.2) = 24.4$, $p < 0.05$, but not across the season, $F(4.96,18.2) = 1.33$, $p = 0.297$ (Table 44). In the wet tracks, the measurements were statistically significant across weeks, $F(1.73,19.1) = 10.8$, $p < 0.05$, $\varepsilon = 0.551$, but not between individual wet tracks across the growing season, $F(5.20,19.1) = 2.54$, $p = 0.062$, $\varepsilon = 0.551$ (Table

45). The post-hoc results indicated that wet and dry tracks exhibited the greatest within track differences in the western portion of the plot, while the eastern tracks were more similar to each other.

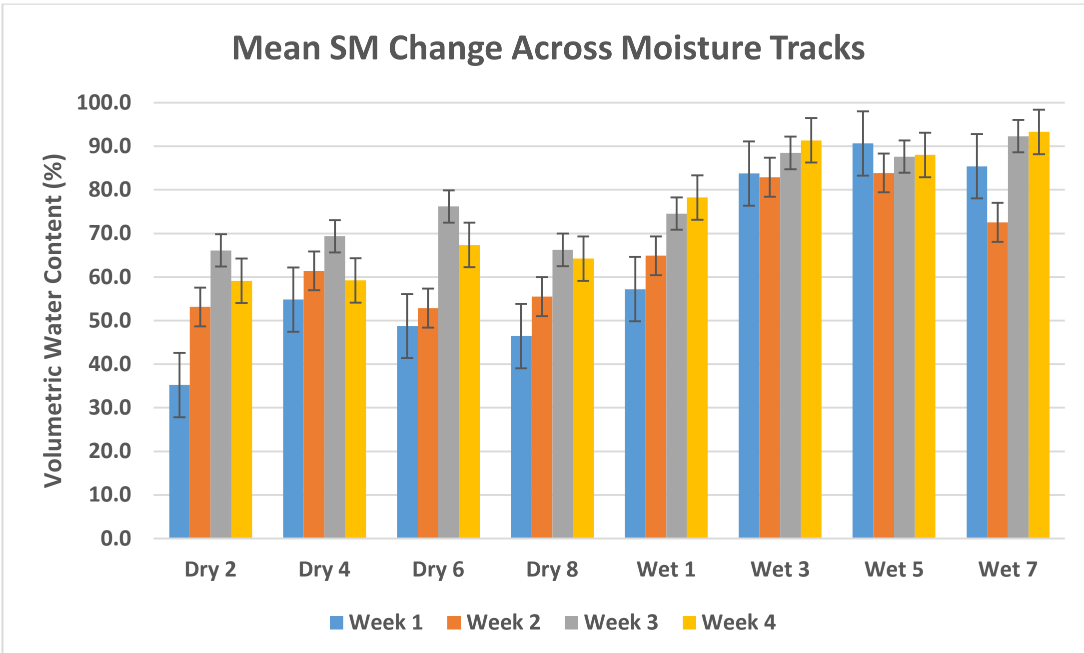

Figure 14: Mean (± 1 SE) SM change across the growing season.

Between-subject effects of active layer depth was higher in the wet compared to the dry tracks, $F(1,28) = 24.0$, $p < 0.05$ (Table *2*). There was a statistically significant within-subjects effect between AL between weeks throughout the growing season, $F(2.31,64.6) = 74.0$, $p < 0.05$, $\varepsilon = 0.769$. In both the wet and dry tracks, the AL increased from week to week, with the biggest increased in AL happening in the first half of the growing season (Figure 15). A statistically significant interaction was found between AL across the moisture track-week treatment, $F(2.31, 64.6) = 8.36$, $p < 0.05$. When the tracks were investigated individually against each other, the dry tracks were still statistically significant across weeks, $F(3,33) = 17.0$, $p < 0.05$, but there was not statistical difference between individual dry tracks across the season, $F(9,33) = 1.67$, $p = 0.137$ (Table 47). In the wet tracks, the measurements were statistically significant across weeks,

$F(3,33) = 74.1$, $p < 0.05$, but not between individual wet tracks across the growing season, $F(9,33) = 0.736$, $p = 0.673$ (Table 48). The post-hoc results indicated the greatest difference between Wet 1 and Wet 5 ($p < 0.05$) as well as Wet 1 and Wet 7 ($p = 0.067$). As with SM, the post-hoc results indicated that the greatest within-track differences were in the western portion of Muskox for both wet and dry tracks.

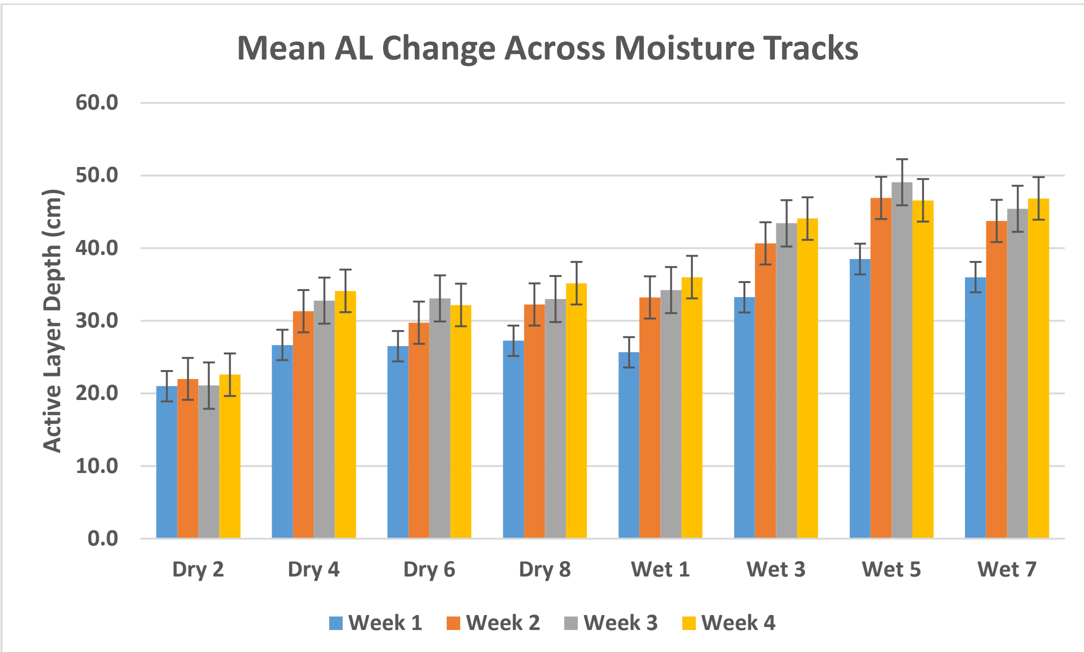

Figure 15: Mean (± 1 SE) AL change across the growing season.

3.4.3 Carbon Flux

Table 3: Mean carbon exchange measurements across the moisture tracks over the growing season. Standard deviations are indicated in brackets.

	Week 1	**Week 2**	**Week 3**	**Week 4**
NEE Dry ($\mu mol/m^2/s$)	1.13 (0.900)	0.590 (0.811)	-0.709 (0.720)	-0.324 (0.802)
NEE Wet ($\mu mol/m^2/s$)	-0.320 (-0.767)	-0.876 (1.01)	-1.83 (0.698)	-1.43 (0.853)
ER Dry ($\mu mol/m^2/s$)	2.06 (0.780)	1.85 (0.803)	1.02 (0.207)	1.12 (0.336)
ER Wet ($\mu mol/m^2/s$)	2.62 (0.807)	2.87 (1.02)	1.09 (0.301)	1.02 (0.407)
GPP Dry ($\mu mol/m^2/s$)	-0.935 (0.941)	-1.26 (1.10)	-1.73 (0.812)	-1.44 (0.899)
GPP Wet ($\mu mol/m^2/s$)	-2.94 (1.07)	-3.75 (1.44)	-2.91 (0.653)	-2.44 (1.09)

Table 4: Two-way ANOVA p-values for carbon flux measurements across the growing season in different moisture tracks across the plot. Bolded values indicate significance at p < 0.05.

Interaction	**NEE**	**ER**	**GPP**
Time	**0.000**	**0.000**	**0.000**
Moisture track	**0.000**	**0.027**	**0.000**
Time x Moisture track	0.452	**0.007**	**0.000**
Time x Moisture track x Spatial location (W vs. E)	**0.077**	**0.000**	**0.000**

NEE differed significantly between tracks, being greatest (most negative) in the wet tracks), $F(1,28) = 29.8$, $p < 0.05$ (Table 3). Dry tracks were C sources in the early season (atmospheric C gain), transitioning into a late season sink, while wet tracks were net C sinks throughout the entire season (terrestrial C uptake). There was also a statistically significant within-subject effect for NEE across the four-week growing season, $F(2.41,67.6) = 46.6$, $p < 0.05$, $\varepsilon = 0.804$, but no statistically significant interaction between-subjects effect of NEE across the moisture tracks over the growing season, $F(2.41, 67.6) = 0.847$, $p = 0.452$. The wet tracks were also a net sink, while dry tracks shifted from being an early season source to late season sink, as shown in Figure 16. When the tracks were investigated individually against each other, the within-subjects effects of dry tracks were still statistically significant across weeks, $F(3,33) = 29.4$, $p < 0.05$, but there was no statistical between-subject effect between individual dry tracks across the season, $F(9,33) = 1.46$, $p = 0.203$ (Table 32). In the wet tracks, results suggest greatest differences in the western end of the plot. In the wet tracks, the within-subject effects were statistically different across weeks, $F(3,33) = 23.9$, $p < 0.05$, but not between individual wet tracks across the growing season, $F(9,33) = 2.02$, $p = 0.068$ (Table 33). As with SM and AL, the greatest differences were in the western portion of Muskox.

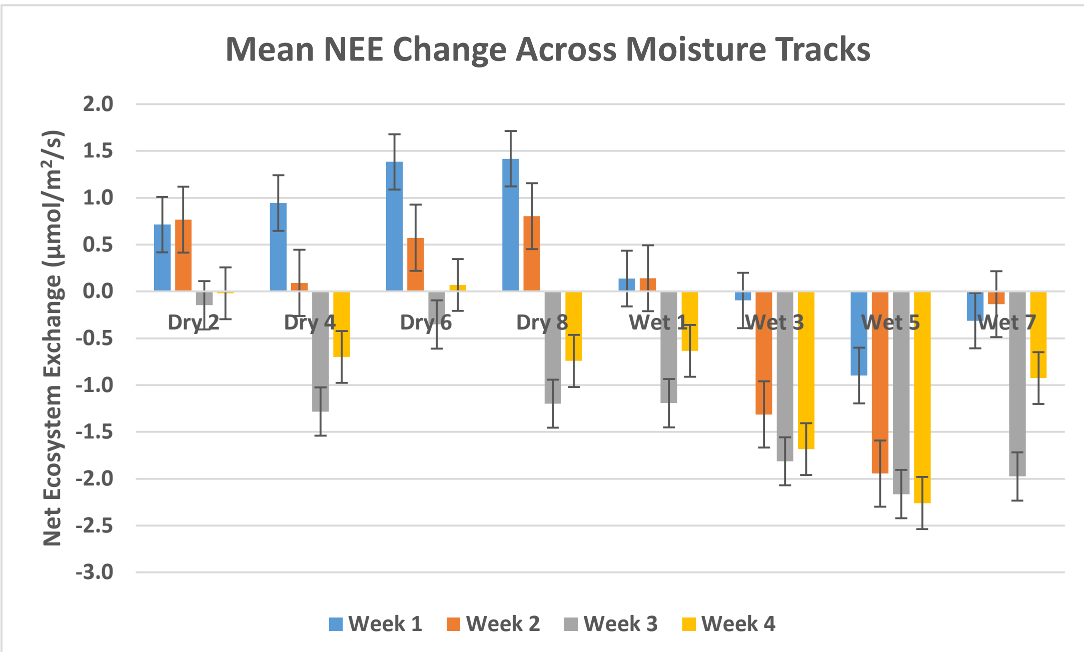

Figure 16: Mean (± 1 SE) NEE change across the growing season.

Ecosystem respiration was significantly higher in the wet tracks, $F(1,28) = 5.46$, $p < 0.05$ (Table 3). There was also a statistically significant within-subjects effect between ER across the four-week growing season, $F(1.42,39.6) = 58.5$, $p < 0.05$, $\varepsilon = 0.472$, and a statistically significant interaction between ER across the moisture tracks over the growing season, $F(1.42,39.6) = 6.70$, $p < 0.05$. When the tracks were investigated individually against each other, the within-subjects effects of dry tracks were still statistically significant across weeks, $F(1.79,19.6) = 47.4$, $p < 0.05$, as well as between individual dry tracks across the season, $F(5.35,19.6) = 3.801$, $p < 0.05$ (Figure 17 and Table 35). Examination of the Tukey's post-hoc test results showed the greatest difference in ER was between Dry 2 and 4 ($p < 0.05$). In the wet tracks, the within-subjects effects were statistically significant across weeks, $F(2.00,22.0) = 78.142$, $p < 0.05$, and between individual wet tracks across the growing season, $F(6.01,22.0) = 8.46$, $p < 0.05$ (Table 36). The post-hoc results indicated the greatest difference between Wet 1 and Wet 5 ($p < 0.05$) as well as Wet 1 and Wet 7 ($p < 0.05$).

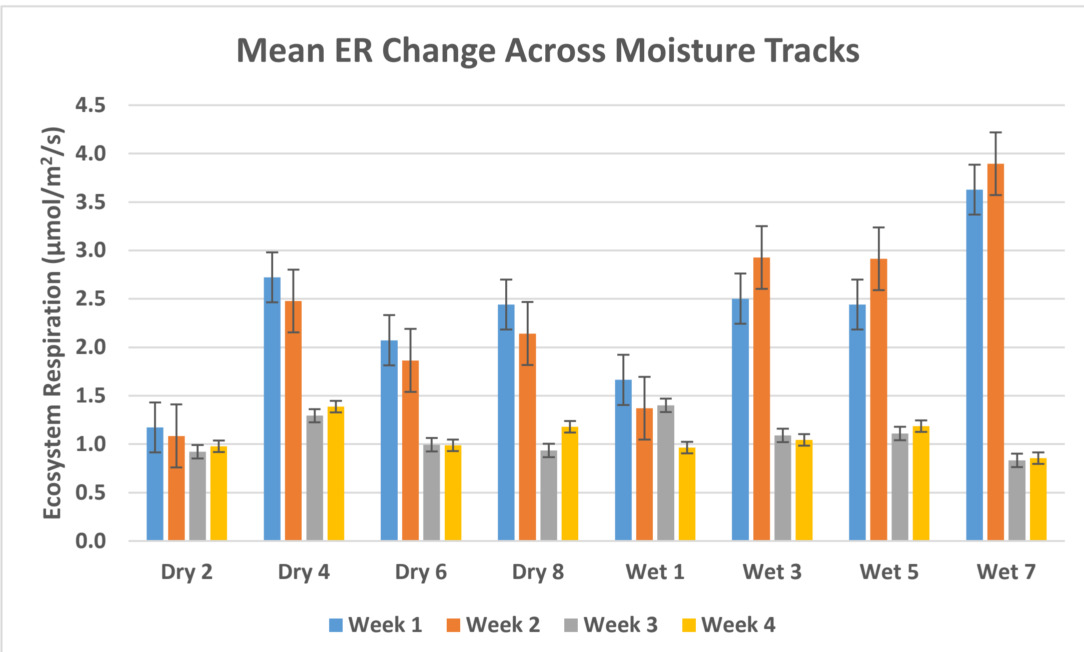

Figure 17: Mean (± 1 SE) ER change across the growing season.

Gross primary production was higher in the wet tracks compared to the dry tracks, $F(1,22) = 391$, $p < 0.05$ (Table 3). There was also a statistically significant within-subjects effect of GPP across the four-week growing season, $F(3,84) = 8.35$, $p < 0.05$. A significant interaction existed between GPP across the moisture tracks over the growing season, $F(1,28) = 24.0$, $p < 0.05$. As with ER, incoming GPP was greater in the wet tracks than the dry tracks, as shown in

Figure 18. When the tracks were investigated individually against each other, the within-subjects effects of dry tracks were still statistically different across weeks, $F(1,12) = 51.8$, $p < 0.05$, but not between individual dry tracks across the season, $F(3,12) = 1.99$ $p = 0.169$ (Figure 18 and Table 38). Examination of the Tukey's post-hoc test results showed the greatest difference in GPP was between Dry 2 and 4, although these differences were not statistically significant. In the wet tracks, the within-subjects effects of wet track measurements were statistically different across weeks, $F(1,12) = 514$, $p < 0.05$, as well as between individual wet tracks across the growing season, $F(3,12) = 11.6$, $p < 0.05$ (Table 39). The post-hoc results indicated the greatest difference between Wet 1 and Wet 5 ($p < 0.05$). Like all other environmental variables, this greatest difference was located in the western portion of the plot.

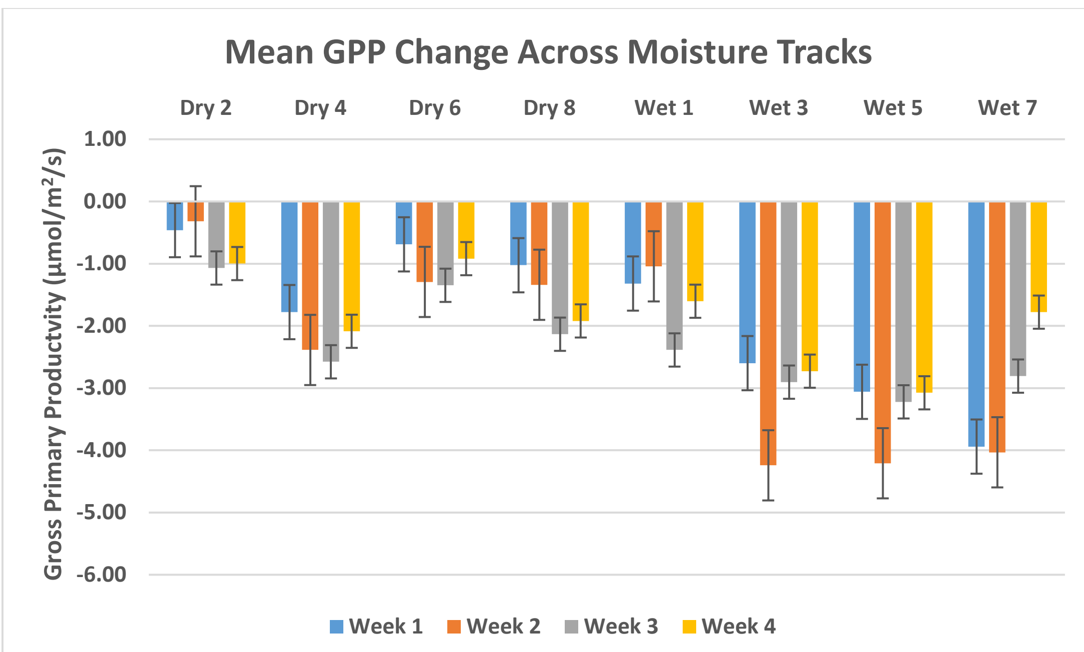

Figure 18: Mean (± 1 SE) GPP change across the growing season.

3.4.4 Quantitative Relationships Between Carbon Flux and Environmental Variables

Pearson's bivariate correlation coefficient was environmental variables and C flux against each other to examine the strength and direction of relationships between the environmental variables at play in the wet sedge meadow. Total season environmental variables showed statistically significant relationships across all measurements (Table 5*Table 5*). Strong positive relationships existed between AL and ST as well as NEE and GPP, while strong negative relationships existed between NEE, GPP, and all environmental variables. For example, the relationship between AL and NEE had a moderately high r^2 of 0.709, which is indicative of the role that a deepening active layer can have on the net C losses.

Table 5: Pearson's bivariate correlation coefficients for carbon flux measurements and environmental variables across the entire growing season. Bolded values indicate significance at $p < 0.05$.

	AL	ST	SM	NEE	ER
ST	**0.963**				
SM	**0.558**	**0.552**			
NEE	**-0.709**	**-0.699**	**-0.700**		
ER	**0.604**	**0.603**	**0.554**	**-0.366**	
GPP	**-0.797**	**-0.789**	**-0.769**	**0.923**	**-0.696**

As with the entire growing season, AL and ST were also strongly related to one another in the early season. Early season GPP had strong significant negative relationships with all environmental variables and carbon flux measurements (Table 6).

Table 6: Pearson's bivariate correlation coefficients for carbon flux measurements and environmental variables across the early season. Bolded values indicate significance at $p < 0.05$.

	AL	ST	SM	NEE	ER
ST	**0.944**				
SM	**0.601**	**0.604**			
NEE	**-0.634**	**-0.640**	**-0.754**		
ER	**0.647**	**0.655**	**0.512**	-0.231	
GPP	**-0.814**	**-0.823**	**-0.819**	**0.825**	**-0.740**

Late season environmental variables and C fluxes were similar to that observed in the early part of the growing season, with AL and ST having the strongest relationship (Table *7*). NEE and GPP also correlated positively.

Table 7: r^2 values for environmental variable regression analysis during the late growing season. Bolded values indicate significance at $p < 0.05$.

	AL	ST	SM	NEE	ER
ST	**0.966**				
SM	**0.464**	**0.453**			
NEE	**-0.668**	**-0.671**	**-0.542**		
ER	-0.061	-0.138	0.064	-0.126	
GPP	**-0.660**	**-0.663**	**-0.496**	**0.928**	-0.276

3.4.5 Available Soil Nitrogen

3.4.5.1 Seasonal Trends

A two-way repeated measures ANOVA was conducted for NO_3^- and NH_4^+ across the growing season, separated into early (June 30 to July 13) and late season (July 13 to 27). When analysing the N concentration values, studentized residuals were examined for values greater than ±3 and any outliers were removed. Early season N values were normally distributed ($p < 0.05$), but late season N values failed the Shapiro-Wilk's test so concentration values for NO_3^- and NH_4^+ (Table *8*) were logarithmic and square root transformed respectively based on their strongly positive and moderately positive skewed values (Laerd Statistics, 2013).

Table 8: Mean and standard error values for NO_3^- and NH_4^+ across moisture tracks, expressed as µg of nutrient adsorbed per 10 cm^2 per two-week period.

Measure	Track	Season	Mean
NO_3^-	**Dry**	**Early**	2.512 ± 0.149
		Late	3.448 ± 0.641
	Wet	**Early**	2.232 ± 0.203
		Late	2.452 ± 0.362
	SZ	**Early**	2.251 ± 0.304
		Late	2.478 ± 0.524
NH_4^+	**Dry**	**Early**	11.728 ± 0.778
		Late	10.238 ± 0.130
	Wet	**Early**	12.487 ± 1.301
		Late	13.683 ± 1.049
	SZ	**Early**	9.795 ± 0.756
		Late	12.761 ± 0.580

There was a statistically significant difference between early and late season NH_4^+ availability, $F(1,27) = 98.462$, $p < 0.05$. However, the interaction between seasonality and moisture track was statistically insignificant, $F(1,27) = 0.163$, $p = 0.689$. Overall, NH_4^+ availability was greater in the late season than in the early season. The sum of early and late season NH_4^+ adsorption as determined through the ion exchange resins was greater than that of total season resin adsorption, suggesting a potential saturation level reached in the resins and a need to further investigate with soil samples.

Nitrate availability also varied seasonally, $F(1,27) = 264.622$, $p < 0.05$. However, the interaction between seasonality and moisture track was statistically insignificant, $F(1,27) = 0.491$, $p = 0.490$. Overall, mean values of NO_3^- in the tracks increased from early to late season (Resin B2 > Resin B1). The sum of early and late season available NO_3^- was greater than that of total season resin adsorption, suggesting a potential saturation of the resins and a need for further investigation. The SZ did not exhibit statistically significant differences in nutrient concentrations from the main wet sedge plot in all resin sampling regimes. No clear patterns were exhibited temporally in the SZ.

3.4.5.2 Spatial Patterns

Available N was looked at for local spatial autocorrelation, shown in Table *9*. Local spatial autocorrelations for N were run and the local indicators of spatial association (LISA) maps were analyzed to determine where areas of high and low NO_3^- and NH_4^+ tended to gather within Muskox (Figure 19).

Table 9: Univariate local Moran's I values for NO_3^- and NH_4^+

	Moran's I
Resin A NO_3^-	0.225
Resin A NH_4^+	0.030
Resin B1 NO_3^-	0.019
Resin B1 NH_4^+	0.109
Resin B2 NO_3^-	0.142
Resin B2 NH_4^+	-0.142

High-high (red) values of N ($p < 0.05$) tended to gather in the southwestern portion of the plot in all resins except late season NH_4^+, while low-low (blue) values of N ($p < 0.05$) clustered in the northeastern corner of the plot for all resin regimes of NO_3^- and NH_4^+.

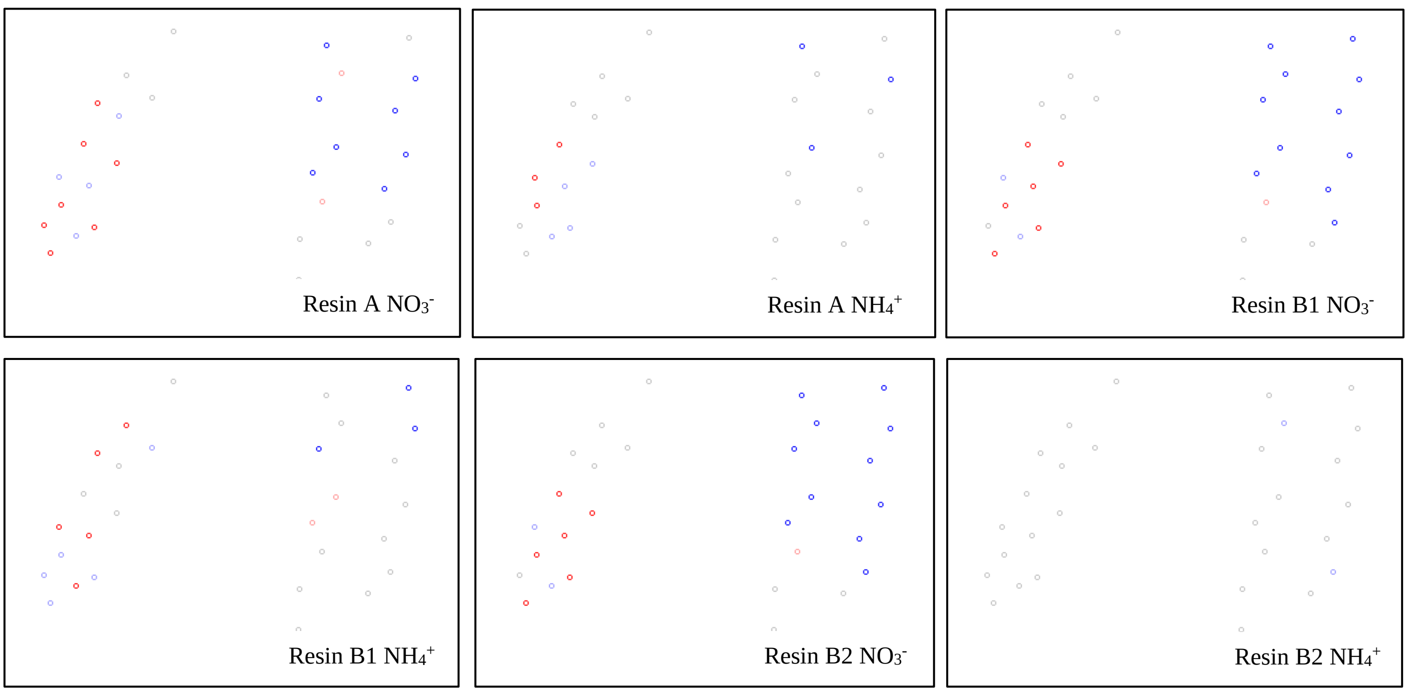

Figure 19: LISA maps of clustered values for NO_3^- and NH_4^+

An examination of interpolation maps created through Kriging analysis in ArcGIS showed similar trends in NO_3^- and NH_4^+ (Figure 20), with higher concentrations of the nutrients in the southwestern corner of the plot and lowest values in the northeastern portion. This pattern followed the gentle sloping of topography in the meadow, where the northeast corner was at the highest elevation, sloping down to the southwest corner at the lowest point.

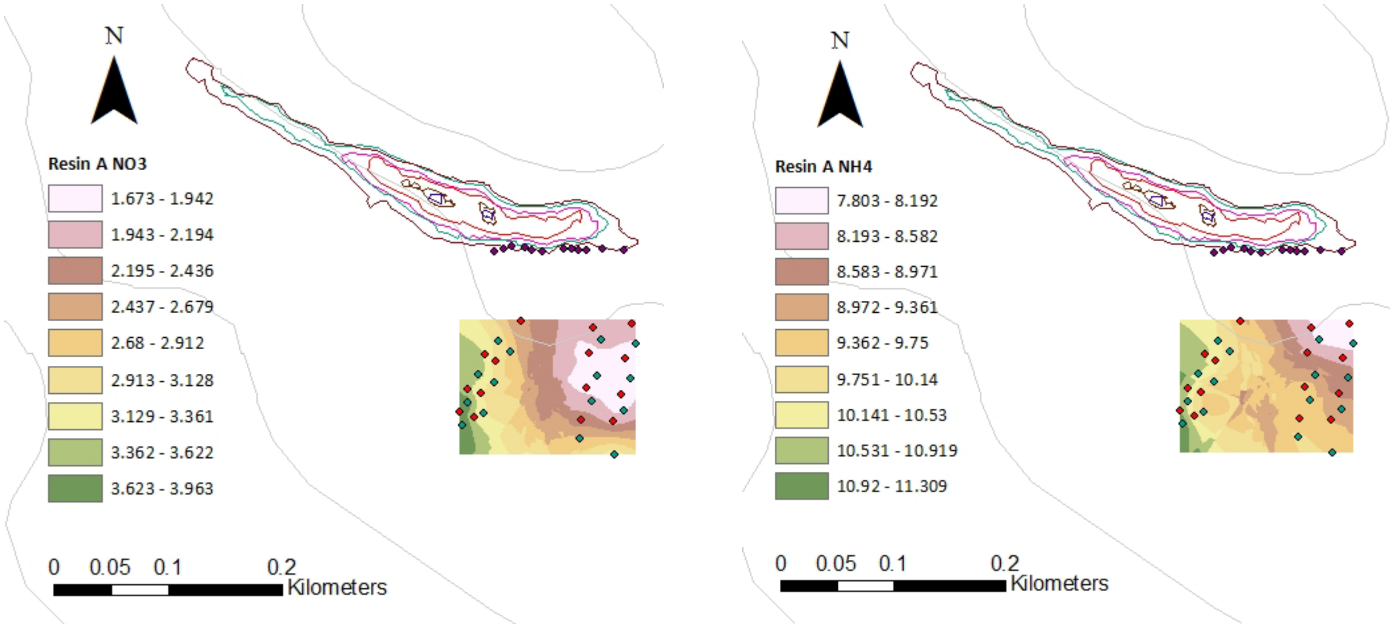

Figure 20: Ordinary kriging maps for total season adsorption of NO_3^- and NH_4+. Red dots represent wet tracks and green dots represent dry tracks.

The early season trend of NH_4^+ was similar to that of total season NH_4^+, with the highest values being in the western portion of the plot (Figure 21). However, early season NH_4^+ is located more north than the end location of total season NH_4^+. No clear patterns are discernable from the early season NO_3^- kriging map, aside from the location of highest values being in the southeastern corner of the plot.

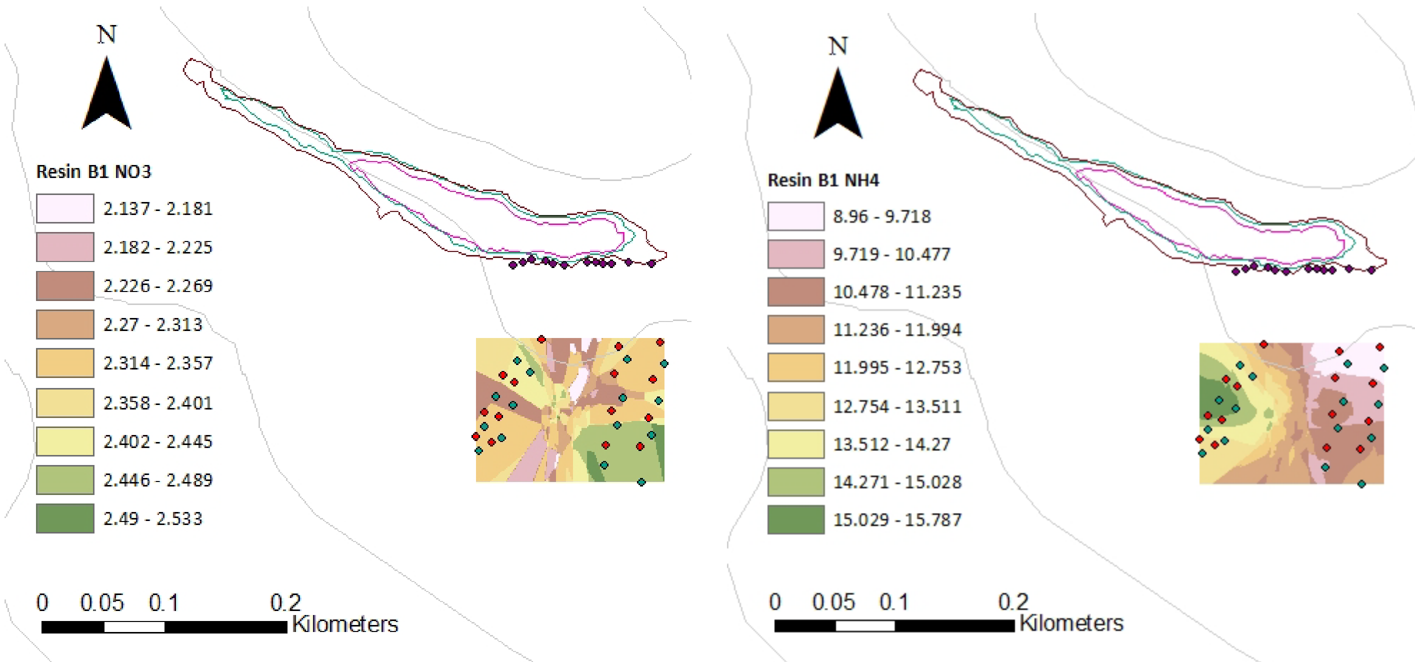

Figure 21: Ordinary kriging maps for early season adsorption of NO_3^- and NH_4^+. Red dots represent wet tracks and green dots represent dry tracks.

When looking at late season N, the NO_3^- and NH_4^+ patterns almost seem like mirror images to those of the early season; late season NH_4^+ matched early season NO_3^- patterns, while late season NO_3^- matched early season NH_4^+ patterns (Figure 22). As compared to the early season, late season NO_3^- had shifted from the southeastern corner to the southwestern corner of the plot. Late season NH_4^+ was highest in the southeastern corner and lower on the western side of the plot.

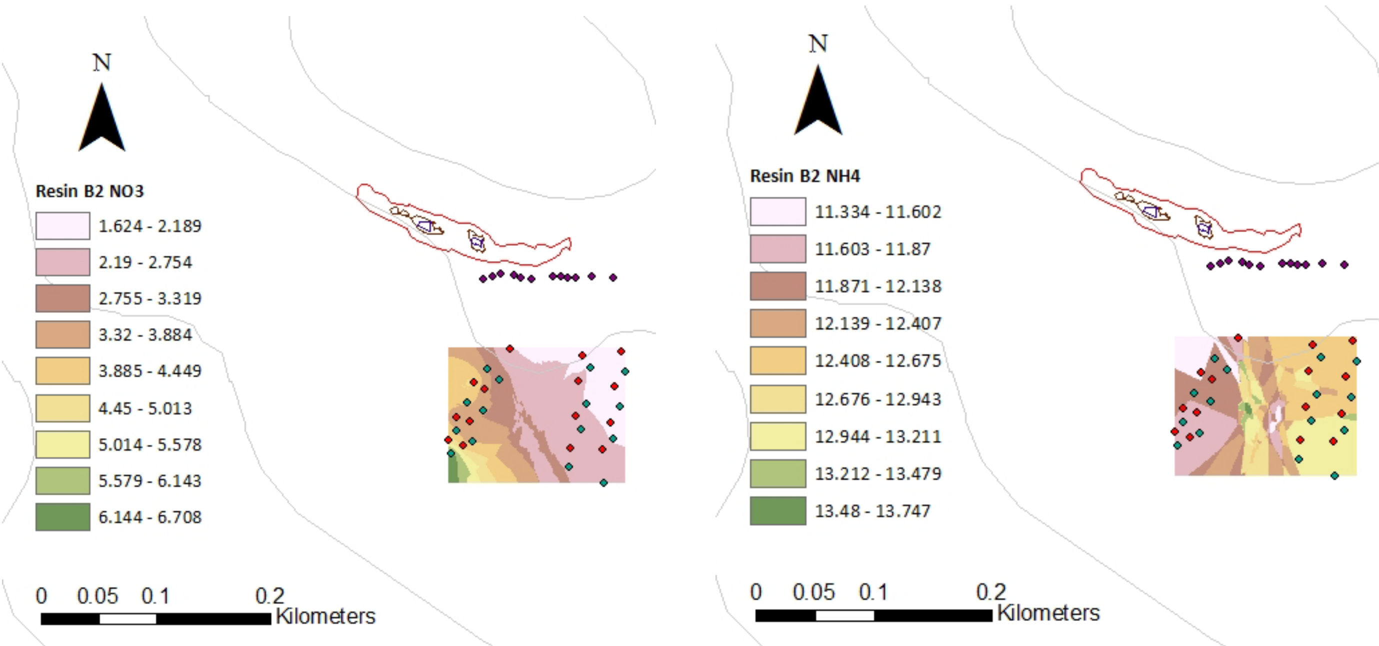

Figure 22: Ordinary kriging maps for late season adsorption of NO_3^- and NH_4^+. Red dots represent wet tracks and green dots represent dry tracks.

3.4.6 Relationships Between Available Nitrogen, Carbon Fluxes, and Environmental Variables

Linear regression analysis showed that across the dry tracks, AL and total season NO_3^- ($R^2 = 0.707$), $F(1,12) = 28.937$, $p < 0.05$, and ST and total season NO_3^- ($R^2 = 0.598$), $F(1,12) = 17.840$, $p < 0.05$ were significantly related (Table 10). Total season NH_4^+ in the dry tracks were significant but moderate in their relationships with AL ($R^2 = 0.470$), $F(1,12) = 10.633$, $p < 0.05$, and ST ($R^2 = 0.456$), $F(1,12) = 10.046$, $p < 0.05$. Carbon flux measurements also showed significant but moderate relationships between total and late season NO_3^- and GPP ($r^2 = 0.323$ and $R^2 = 0.338$), $F(1,14) = 6.64$, $p < 0.05$ and $F(1,14) = 6.20$, $p < 0.05$ respectively, as well as moderate relationships with between total season NH_4^+ and ER ($R^2 = 0.359$) and GPP ($R^2 = 0.348$), $F(1,14) = 7.27$, $p < 0.05$ and $F(1,14) = 6.93$, $p < 0.05$ (Table 11). Early season NO_3^- and early and late season NH_4^+ were not significant or strong in their relationships to biophysical variables and carbon fluxes, suggesting that in a shorter time scale, soil available nitrogen is not a strong predictor of potential ER or GPP.

Table 10: Bivariate regression R^2 coefficients for nitrogen (dependent variable) against environmental variables (independent variable) across dry tracks. Bolded values indicate significant values at $p < 0.05$.

	Resin A NO_3^-	Resin A NH_4^+	Resin B1 NO_3^-	Resin B1 NH_4^+	Resin B2 NO_3^-	Resin B2 NH_4^+
AL	**0.707**	**0.470**	0.000	0.069	**0.326**	0.205
ST	**0.598**	**0.456**	0.009	0.037	**0.342**	0.161
SM	0.026	0.021	0.011	0.150	0.013	0.017

Table 11: Bivariate regression R^2 coefficients for nitrogen (independent variable) against environmental variables (dependent variable) across dry tracks. Bolded values indicate significant values at $p < 0.05$.

	Resin A NO_3^-	Resin A NH_4^+	Resin B1 NO_3^-	Resin B1 NH_4^+	Resin B2 NO_3^-	Resin B2 NH_4^+
ER	0.209	**0.359**	0.002	0.024	0.087	0.100
GPP	**0.323**	**0.348**	0.097	0.095	**0.338**	0.060

In the wet tracks, total season SM had a strong and significant relationship with NO_3^- (R^2 = 0.646), $F(1,13) = 23.765$, $p < 0.05$ (Table 12). Total season NH_4^+ had significant relationships with AL and ST as well. ER and GPP were moderate predictors strong predictors of total season available soil NO_3^-, while early season NH_4^+ predicted ER (Table 13). Early season NO_3^- and late season NH_4^+ were not significant or strong in their relationships to biophysical variables and carbon fluxes.

Table 12: Bivariate regression R^2 coefficients for nitrogen against environmental variables and carbon flux across wet tracks. Bolded values indicate significant values at $p < 0.05$.

	Total Season NO_3^-	Total Season NH_4^+	Early Season NO_3^-	Early Season NH_4^+	Late Season NO_3^-	Late Season NH_4^+
AL	0.227	**0.370**	0.134	0.219	0.127	0.013
ST	**0.289**	**0.420**	0.100	0.230	0.194	0.000
SM	**0.646**	0.054	0.033	0.001	**0.449**	0.094

Table 13: Bivariate regression R^2 coefficients for nitrogen (independent variable) against environmental variables (dependent variable) across wet tracks. Bolded values indicate significant values at $p < 0.05$.

	Total Season NO_3^-	Total Season NH_4^+	Early Season NO_3^-	Early Season NH_4^+	Late Season NO_3^-	Late Season NH_4^+
ER	**0.395**	0.112	0.008	**0.528**	0.037	0.024
GPP	**0.384**	0.023	0.086	0.251	0.010	0.121

Multiple regression models showed to have stronger relationships for environmental variables with total season N than the bivariate models did, indicating that several variables are at play in determining N concentration in a wet sedge meadow. The regression model better predicted N in the wet tracks than the dry tracks, validating the need to separately sample and analyze the plot for moisture tracks that was determined in the original methodology. Two of the multiple regression models statistically significantly predicted total and late season NO_3^- in the wet tracks ($p < 0.05$) (Table *17* and Table 19).

Table 14: Multiple regression statistics for total season NH_4^+ across wet and dry tracks. Bolded values indicate significance at $p < 0.05$.

	DRY TRACKS (R^2= 0.487, p = 0.054)			**WET TRACKS (R^2= 432, p = 0.090)**		
Variable	**B**	**SE_B**	**ß**	**B**	**SE_B**	**ß**
AL	-0.142	0.201	-0.418	0.030	0.305	-0.087
ST	-0.751	1.59	-0.278	-1.51	1.87	-0.712
SM	-0.029	0.059	-0.108	-0.017	0.040	-0.102

Table 15: Multiple regression statistics for early season NH_4^+ across wet and dry tracks. Bolded values indicate significance at $p < 0.05$.

	DRY TRACKS (R^2= 0.223, p = 0.409)			**WET TRACKS (R^2= 0.272, p = 0.302)**		
Variable	**B**	**SE_B**	**ß**	**B**	**SE_B**	**ß**
AL	-0.366	0.388	-0.530	-0.006	0.652	-0.008
ST	1.66	2.643	0.358	-2.06	3.286	-0.549
SM	-0.152	0.107	-0.388	0.079	0.100	0.219

Table 16: Multiple regression statistics for late season NH_4 across wet and dry tracks. Bolded values indicate significance at $p < 0.05$.

	DRY TRACKS (R^2= 0.218, p = 0.419)			**WET TRACKS (R^2= 0.291, p = 0.268)**		
Variable	**B**	**SE_B**	**ß**	**B**	**SE_B**	**ß**
AL	-0.213	0.295	-0.601	0.844	0.483	1.36
ST	0.544	2.80	0.164	-6.29	3.75	-1.30
SM	-0.032	0.086	-0.108	0.134	0.083	0.083

Table 17: Multiple regression statistics for total season NO_3^- across wet and dry tracks. Bolded values indicate significance at $p < 0.05$.

	DRY TRACKS (R^2= 0.533, p < 0.05)			WET TRACKS (R^2= 0.803, p < 0.05)		
Variable	**B**	**SE_B**	**ß**	**B**	**SE_B**	**ß**
AL	0.033	0.110	0.171	-0.039	0.067	-0.299
ST	-1.34	0.874	-0.864	-0.081	0.409	-0.103
SM	-0.28	0.032	-0.182	**-0.046**	0.009	-0.753

Table 18: Multiple regression statistics for early season NO_3^- across wet and dry tracks. Bolded values indicate significance at $p < 0.05$.

	DRY TRACKS (R^2= 0.068, p = 0.847)			WET TRACKS (R^2= 0.157, p = 0.581)		
Variable	**B**	**SE_B**	**ß**	**B**	**SE_B**	**ß**
AL	-0.037	0.052	-0.433	-0.090	0.109	-0.757
ST	0.293	0.357	0.512	0.262	0.551	0.447
SM	-0.007	0.014	-0.149	-0.007	0.017	-0.119

Table 19: Multiple regression statistics for late season NO_3^- across wet and dry tracks. Bolded values indicate significance at $p < 0.05$.

	DRY TRACKS (R^2= 0.397, p = 0.122)			WET TRACKS (R^2= 0.622, p < 0.05)		
Variable	**B**	**SE_B**	**ß**	**B**	**SE_B**	**ß**
AL	0.028	0.213	0.096	0.007	0.122	0.034
ST	-1.96	2.02	-0.720	-0.746	0.944	-0.449
SM	-0.058	0.062	-0.240	**-0.072**	0.021	-0.652

Multiple regression models were also explored to predict C fluxes using both soil available N variables and environmental variables. Three of the models were strongly and significantly predicted for using AL, ST, SM, NO_3^-, and NH_4^+: total season GPP in the wet tracks (R^2 = 0.685) and early season GPP in both dry (R^2 = 0.788) and wet tracks (R^2 = 0.785) (Table *23* and Table 24). None of the models predicting ER were significant at $p < 0.05$.

Table 20: Multiple regression statistics for total season ER across wet and dry tracks. Bolded values indicate significance at $p < 0.05$.

	DRY TRACKS (R^2= 0.506, p = 0.200)			**WET TRACKS (R^2= 0.467, p = 0.259)**		
Variable	**B**	**SE_B**	**ß**	**B**	**SE_B**	**ß**
AL	0.024	0.0246	0.343	-0.050	0.059	-0.798
ST	-0.026	0.393	-0.047	0.362	0.368	0.956
SM	0.017	0.014	0.310	-0.002	0.015	-0.080
NO_3^-	-0.009	0.124	-0.025	-0.264	0.266	-0.552
NH_4^+	-0.069	0.068	-0.336	-0.003	0.058	-0.018

Table 21: Multiple regression statistics for early season ER across wet and dry tracks. Bolded values indicate significance at $p < 0.05$.

	DRY TRACKS (R^2= 0.426, p = 0.331)			**WET TRACKS (R^2= 0.642, p = 0.060)**		
Variable	**B**	**SE_B**	**ß**	**B**	**SE_B**	**ß**
AL	0.068	0.071	0.555	-0.039	0.089	-0.298
ST	0.004	0.478	0.005	0.309	0.448	0.481
SM	0.024	0.020	0.349	0.013	0.014	0.206
NO_3^-	0.025	0.400	0.017	0.128	0.238	0.117
NH_4^+	0.023	0.054	0.129	**-0.113**	0.040	-0.662

Table 22: Multiple regression statistics for late season ER across wet and dry tracks. Bolded values indicate significance at $p < 0.05$.

	DRY TRACKS (R^2= 0.224, p = 0.756)			**WET TRACKS (R^2= 0.515, p = 0.188)**		
Variable	**B**	**SE_B**	**ß**	**B**	**SE_B**	**ß**
AL	0.004	0.030	0.109	0.057	0.039	1.171
ST	0.030	0.293	0.099	-0.662	0.314	-1.740
SM	0.004	0.009	0.146	0.007	0.009	0.276
NO_3^-	-0.019	0.047	-0.170	-0.017	0.087	-0.073
NH_4^+	-0.020	0.034	-0.222	-0.032	0.022	-0.401

Table 23: Multiple regression statistics for total season GPP across wet and dry tracks. Bolded values indicate significance at p < 0.05.

	DRY TRACKS (R^2= 0.623, p = 0.074)			WET TRACKS (R^2= 0.685, p < 0.05)		
Variable	**B**	**SE_B**	**ß**	**B**	**SE_B**	**ß**
AL	-0.016	0.066	-0.138	-0.059	0.095	-0.449
ST	-0.422	0.559	-0.466	-0.346	0.595	-0.436
SM	-0.029	0.019	-0.319	-0.050	0.024	-0.821
NO_3^-	0.013	0.177	0.022	-0.316	0.431	-0.314
NH_4^+	0.042	0.097	0.125	-0.180	0.094	-0.482

Table 24: Multiple regression statistics for early season GPP across wet and dry tracks. Bolded values indicate significance at p < 0.05.

	DRY TRACKS (R^2= 0.788, p < 0.05)			WET TRACKS (R^2= 0.785, p < 0.05)		
Variable	**B**	**SE_B**	**ß**	**B**	**SE_B**	**ß**
AL	-0.011	0.055	-0.071	0.067	0.091	0.390
ST	-0.639	0.371	-0.607	-0.618	0.458	-0.728
SM	-0.026	0.016	-0.289	**-0.041**	0.014	-0.505
NO_3^-	0.685	0.310	0.372	0.072	0.244	0.050
NH_4^+	0.032	0.042	0.142	0.076	0.041	0.336

Table 25: Multiple regression statistics for late season GPP across wet and dry tracks. Bolded values indicate significance at p < 0.05.

	DRY TRACKS (R^2= 0.528, p = 0.171)			WET TRACKS (R^2= 0.220, p = 0.765)		
Variable	**B**	**SE_B**	**ß**	**B**	**SE_B**	**ß**
AL	0.018	0.037	0.349	-0.003	0.051	-0.051
ST	-0.313	0.362	-0.657	-0.069	0.406	-0.178
SM	0.004	0.011	0.092	-0.012	0.012	-0.454
NO_3^-	0.073	0.058	0.416	-0.088	0.112	-0.379
NH_4^+	0.027	0.042	0.186	-0.024	0.028	-0.301

3.5 Discussion

3.5.1 Carbon Flux and Environmental Trends

As expected with the progression of the growing season, ST and SM values increased while AL deepened ($p < 0.05$); this matched results of environmental trends from previous studies by Blaser and Luce in Cape Bounty wet sedge plant communities (Blaser, 2016; Luce, 2016). The local spatial differences of wet and dry tracks for C exchange and environmental variables were all significant; generally, wet tracks had warmer, wetter, and deeper values than dry tracks for ST, SM, and AL. Perhaps the most notable difference between SM in the wet and dry tracks is the consistent increase of SM across the season, while there is a decrease in SM in dry tracks between weeks 3 and 4. This finding is an indication of the start of drying out and return to fall conditions. This difference between the moisture tracks indicative of the need to account for small-scale individuality of ecosystems when sampling in these environments.

Examinations of 2014 and 2015 C fluxes in the wet sedge determined that these wetland communities were a net C sink (Blaser, 2016; Luce, 2016). In examining 2016 C flux data, the wet sedge meadow was an early season source with ER dominant with a net efflux of C, turning into a late season sink as GPP took over with a net C influx. There was spatial variability between the moisture regimes of the wet sedge meadow, with GPP and ER rates higher in wet tracks than dry tracks, which Blaser found in the static chamber measurement sites as well in her 2014 field season (Blaser, 2016). Over the growing season, dry tracks averaged 1.513 $\mu mol/m^2/s$ in ER while mean ER in the wet tracks was 1.899 $\mu mol/m^2/s$. GPP calculated using NEE and ER measurements averaged -1.34 $\mu mol/m^2/s$ and -3.01 $\mu mol/m^2/s$ in the dry and wet tracks respectively. Overall, dry tracks yielded a 0.171 $\mu mol/m^2/s$ seasonal NEE average, while wet tracks had an NEE seasonal average of -1.112 $\mu mol/m^2/s$. These numbers are indicative of the Muskox wet sedge meadow being an overall sink in the 2016 growing season. ER was the driving process for C fluxes in the early season dry tracks, switching over to GPP being the dominant force in the late season, as shown in Figure 23. However, GPP was the dominant factor throughout the entire season in the wet tracks, suggesting the importance of the role that SM has in photosynthetic processes in the High Arctic wetlands.

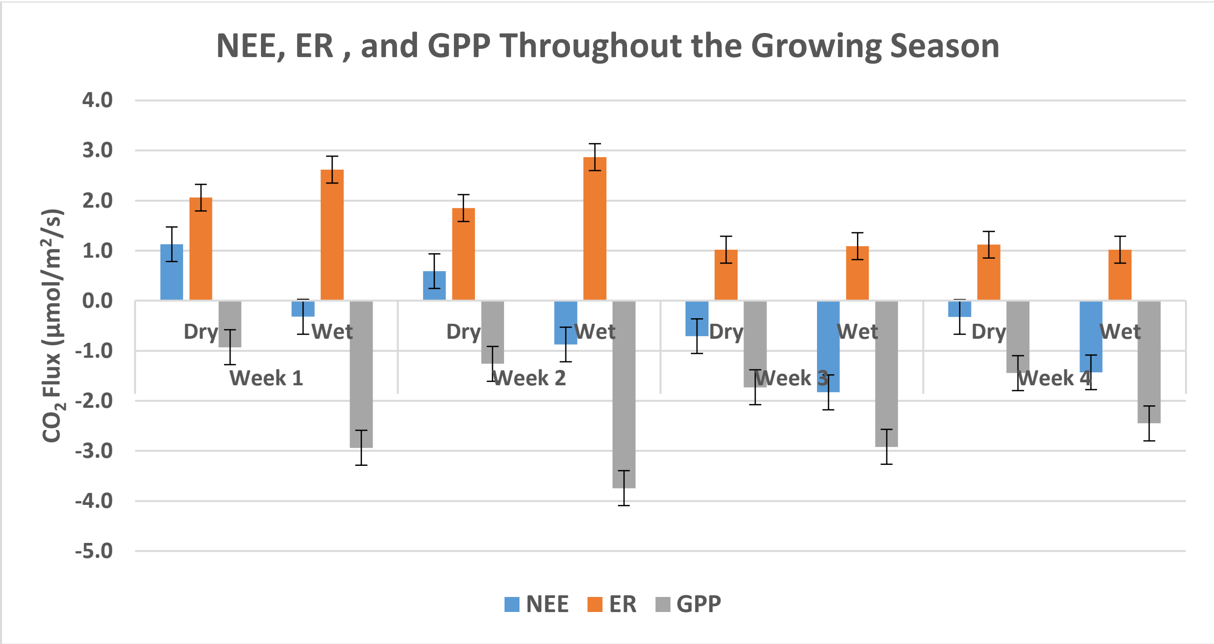

Figure 23: NEE, ER, and GPP change throughout the growing season across moisture tracks. Errors bars indicate ±1 standard error.

Across the entire season, increases in ST strongly corresponded with a deepening active layer. All other variables were also moderately related, except for SM and AL. Early season GPP and NEE had moderate negative relationships with AL, ST, and SM, while increased ST and SM and deeper AL corresponded to higher ER. ST increases across the growing season corresponded a net C release with decreasing NEE. In the early season, ST governed ER, but the transition into the late season saw a shift of ST influencing GPP. Slowing rates of ER in the latter parts of the season corresponded with deepening active layers and higher ST, evidence of increased decomposition with increased temperatures and lowering water table as shown in literature (Schuur *et al.*, 2009; Guicharnaud *et al.*, 2010). As the season progressed all C flux relationships with AL, ST, and SM became negative. Wet and dry tracks exhibited the similar temporal patterns.

3.5.2 Nitrogen Trends

NO_3^- and NH_4^+ were significantly different across wet and dry tracks, again reinforcing the need to explore spatial variability that can exist within a generally homogenous ecosystem. Across most tracks, it was determined that wet tracks generally had higher levels of NH_4^+ than dry tracks, while NO_3^- concentrations were similar across both moisture gradients. Raw concentrations of NH_4^+ were always higher than concentrations of NO_3^-, which is to be expected because of their relative positions and roles in the N cycle and is in accordance with results from prior research (Nadelhoffer *et al.*, 1991; Clein and Schimel, 1995; Gregory, 2011). Within the N cycle, there needs to be a surplus of NH_4^+ before microbes can convert it to NO_3^-. Furthermore, in an anoxic environment like Arctic wetlands, aerobic processes like nitrification are generally limited or absent (Giblin *et al.*, 1991; Nadelhoffer *et al.*, 1991; Clein and Schimel, 1995; Stark, 2007; Beermann, 2016). On average, N adsorption was higher in the later season (July 13 to 27) than the earlier part of the season (June 30 to July 13). This is contrary to findings from 2008 wet sedge nutrient measurements where early season adsorption was higher than the late season (Gregory, 2011); however, the prior study only deployed one PRS measurement in each wet sedge site (for a total of 4), as such the spatial variability is not accounted for. Compared to the polar desert and mesic tundra N PRS probe measurements from 2008 (Gregory, 2011), the values measured in the wet sedge meadow are generally two to three times higher. The later season nutrient release and subsequent adsorption can be explained by a combination of early season snowmelt, increasing ST, and a deepening AL that allowed for water flow, promoting nutrient availability and the release of inorganic N. A lag period follows late in the early season after which organic N is then available for microbes to mineralize into NH_4^+ and then NO_3^-.

The bivariate regression statistics showed that AL and ST have strong positive relationships with NO_3^- and NH_4^+ in the dry tracks. The seasonal NO_3^- and NH_4^+ measurements could not be predicted significantly or strongly by a single variable. SM in the wet tracks was able to predict total and late season NO_3^-, which could be indicative of the role of water in nitrification processes. Multivariate regression analyses showed much stronger relationships between environmental variables and NO_3^- and NH_4^+ concentrations in predicting GPP, which is indicative of the collaborative role that different environmental variables and soil available nitrogen play in promoting photosynthetic activity in wet sedge. While dry track models were not significant, the multivariate regression models favoured wet tracks, strengthening the argument of the importance of water in the processes in wet sedge meadows. In the wet tracks, the multivariate regression model suggests that total season GPP is most affected by ST and NO_3^-. Increases in NO_3^- would also have a greater effect on GPP decrease than NH_4^+ would. Early season GPP is most affected by ST, and the soil available N impacts on GPP are similar.

The results from the regression models point to increases in ST having the greatest effect on mineralization and nitrification as compared to other environmental variables. Furthermore, in the dry tracks, the effect of ST was greater on nitrification than mineralization, while the opposite effect was seen in the wet tracks. This was consistent with results from tundra studies in Toolik Lake, Alaska which found that experimentally elevated temperatures triggered increased N mineralization, while light attenuation resulted in decreased NH_4^+ levels (Shaver and Chapin., 1995). Subsequent experiments with temperature-driven greenhouse incubations found consistent increases in N mineralization (Shaver *et al.*, 1998) at magnitudes of 40-200%. At CBAWO, increases in SM promoted nitrification towards to the latter part of the season, as reflected in the higher late and total season NO_3^-. Nitrification was always secondary to mineralization and absent in some plots; this is a change from previous research where nitrification was often completely absent in wet sedge tundra (Giblin *et al.*, 1991; Stark, 2007).

The southern portion of the meadow generally had higher NO_3^- and NH_4^+ than the north and the west had higher N than the east; this can be attributed to the downslope of the topography promoting water flow, which is a transport method of nutrients down the meadow into lower lying areas (Woo and Young, 2006). This is consistent with research conducted by Stewart *et al.* (2014), where N mineralization rates, and consequently NH_4^+ levels, were higher in lower lying areas. The increase of nutrient concentrations from east to west also follows the east to west retreat of the snowpack as the melt season progressed, which ties back to the importance of this perennial snowpack to the wetland in this environment (Woo and Young, 2014).

Contrary to original hypotheses that the SZ would have significantly higher inorganic N levels due to the direct accessibility to water from snowmelt, the NO_3^- and NH_4^+ levels were not significantly different from the rest of the plot. Previous research in literature would have led us to believe that the N levels would be significantly lower than that of vegetated wetland areas due to premature wetland development and frequent surface erosion (Woo and Young, 2006). However, at Muskox, this could have been countered by a constant and significant water input from the snowpack, bringing in nutrients from upslope under the snowpack, which was the case discovered at Toolik Lake during spring melt by Bilbrough *et al.* (2000).

3.5.3 Implications of Lack of Statistical Significance

While the lack of statistical significance provides some answers towards the research questions posed, we cannot rule out the proven facts of ecological significance that environmental variables have on nutrient distribution. Statistical significance simply implies 90-

95% confidence that the measured variables were not simply due to chance, the lack of the statistical significance in this case does not necessarily mean that interactions do not exist between the environmental variables and soil available N.

The lack of statistical significance may also be pointing to the fact that research questions underestimated the role of water in the wet sedge meadow. The nature of the dependence of the wet sedge meadow on water is such that ion exchange resin membranes may not have been the most robust methodology for measuring nutrient concentrations in this environment. Diffusion is the driving process in the ion exchange resin membrane adsorption (Western Ag, 2012); as such, with the nature of the wetland, the N adsorbed might not represent just nutrient adsorbed from soil, but potentially also nutrients adsorbed through water flow during snowmelt. The general down-slope movement of water is often not included in assessments of terrestrial dynamics in Arctic ecosystems (Shaver *et al.*, 1991; Rastetter *et al.*, 2004), but is an important transport mechanism because dissolved nutrients for soil uptake are often located near the surface due to permafrost (Shaver *et al.*, 1991; Rastetter *et al.*, 2004). Oftentimes, the movement of water downslope carries nutrients that are taken back up and cycled within the system's soils and vegetation through the nutrient-spiraling concept (Newbold *et al.*, 1981; Rastetter *et al.*, 2004). Analysis of soil samples will provide the answer to whether inorganic N in water in the meadow was adsorbed or whether measurements acquired through the ion exchange resin membrane technique was solely from soil adsorption.

Chapter 4: Summary

Table 26 summarizes the measurements of C flux and environmental variables across the 2016 growing season:

Table 26: Summary of environmental variables and carbon flux trends across the growing season. Bolded cells indicate significance at $p < 0.05$.

Variable	Time	Track	Time x Moisture track	Between Tracks
Soil temperature	**Increased**	**Wet > dry**	Insignificant	West ≠ east
Soil moisture	**Increased**	**Wet > dry**	**Significant**	West > east
Active layer depth	**Deepened**	**Wet > dry**	**Significant**	West > east
Ecosystem respiration	**More negative (CO_2 moving from atmosphere into ecosystem)**	**Wet > dry**	**Significant**	**West > east**
Gross primary production	**More negative (CO_2 moving from atmosphere into ecosystem)**	**Wet > dry**	**Significant**	**West > east**
Net ecosystem exchange	**More negative (CO_2 moving from atmosphere into ecosystem)**	**Wet > dry**	Insignificant	**West > east**

Overall, both NH_4^+ and NO_3^- were higher in the latter part of the growing season. Wet tracks generally had higher levels of NH_4^+ than dry tracks, while NO_3^- concentrations were similar across both moisture gradients.

In revisiting the three research questions, the following conclusions can be drawn from this study:

1. *How do active layer depth, soil moisture, and soil temperature affect nitrogen availability of a High Arctic wetland throughout the growing season?*

The 2016 growing season saw increased ST and AL as the season progressed, resulting in higher NH_4^+ and NO_3^- in the latter part of the season. Mineralization was the dominant portion of the N cycle over nitrification, which is consistent with previous Arctic N studies (Giblin *et al.*, 1991; Stark, 2007). Nitrification was present throughout the growing season, as evidenced by the increasing presence of NO_3^- from the early season to late season. This is a change from previous studies where nitrification was generally absent from wet sedge meadows (Giblin *et al.*, 1991; Stark, 2007). SM played a role in nitrification, but only in the latter half of the growing season.

With the sampling methodology that was employed, it was qualitatively demonstrated that water availability plays an important role in controlling the rates of the different environmental processes in this wet sedge meadow. The multivariate regression models had high goodness of fit for all wet tracks, implying that in the presence of higher soil water content, the quantitative relationship between soil N and environmental variables can be better predicted.

2. *What relationships exist between carbon flux and the concentration of soil nitrogen in a High Arctic wetland throughout the growing season?*

In the 2016 growing season, the wet sedge meadow was an early season source and late season sink; overall, the system was a net sink. GPP increases throughout the first three weeks of the growing season corresponded with increases in NH_4^+, suggesting that N mineralization promotes and light promotes photosynthetic activity. Higher N adsorption in the latter part of the season corresponded with increased decomposition and C release in the atmosphere through respiration. Billings *et al.* (1984) found that that an increase in soil N significantly increased CO_2 uptake; this relationship was also found in the wet sedge of CBAWO, as regression models suggested NH_4^+ and NO_3^- were drivers of GPP.

3. *What effect does proximity to the perennial snowpacks have on nitrogen availability of a High Arctic wetland as the growing season progresses?*

Proximity to the perennial snowpack had an indirect effect on N availability in the High Arctic wetland. Distance to the snowpack had no direct effect, but the snowpack's function as a water source was evident as the melt season progressed. The north to south and east to west downslopes of the wetland acted as mechanisms for water flow from snowmelt, which was a transport method of inorganic N. As such, higher levels of NH_4^+ and NO_3^- were found in lower-lying areas of the wetland. However, further work is needed to examine the role the nutrient-spiraling concept may have played in N distribution of this downsloping wetland.

The overarching goal of this study was to examine the relationships between processes and physical characteristics that are present in High Arctic vegetation environments. The main findings of this study can be summarized into three main points:

1. *Multiple environmental variables contribute to determining nitrogen concentrations in wet sedge meadows.*

This confirms previous findings that no single variable directly explains nutrient availability, and soil N availability does not show a straightforward response to increases in temperature (Robinson, 2002). Multivariate regression models of environmental variables versus inorganic N performed significantly better than bivariate regression models of individual environmental measures against NO_3^- and NH_4^+. This is indicative of the important of multiple environmental variables in controlling the nutrient dynamics of a High Arctic wetland; similar results have been found in other High Arctic wet sedge studies (Shaver *et al.*, 1998).

2. *ST is a driver of N mineralization; in this study, increased ST coincided with higher* NH_4^+ *concentrations, promoting GPP.*

These findings conform with previous investigations of drivers of Arctic N cycling that N mineralization is highly temperature dependent (Biederbeck and Campbell, 1973; Billings *et al.*, 1982; Nadelhoffer *et al.*, 1991; Shaver *et al.*, 1998; Rustad *et al.*, 2001; Robinson, 2002), as the coupling of light and ST as light is a contributing factor to warmth. Increased NH_4^+ to plants can be incorporated directly into their NH_4^+ assimilation pathways, which will then allow them to harness CO_2 and water to produce glucose, which is what gross primary production encompasses.

3. *The inorganic nitrogen dynamics cannot be fully analyzed separately from the hydrological dynamics in High Arctic wetlands, particularly when there is an elevation gradient present.*

The transport and distribution of inorganic N in this High Arctic wetland is highly dependent on the movement of water, as the wet sedge meadow is located on a downslope. Research has suggested that spatial vegetation patterns are highly dependent on underlying hydrology for the distribution of nutrients necessary for growth (Oberbauer *et al.*, 1989; Rastetter *et al.*, 2004), and as such the nutrient-spiraling models can be applied in these types of terrestrial environments. Using the knowledge gathered from this study and the hillslope-nutrient model developed by Rastetter *et al.* (2004), the movement of N downslope is a slow process, and downslope additions of plant-available N will result in increased photosynthetic rates (Oberbauer *et al.*, 1989).

In summary, the spatial and temporal dynamics of a High Arctic wet sedge meadow exhibit variances within the ecosystem itself and investigations into the processes operating in the wetlands cannot simply be scaled up to the biome level (Rustad *et al.*, 2001). This study found that seasonally, plant-available N was highest in the latter part of the growing season, with the largest concentrations of these inorganic N forms in lower-lying areas. Increases in GPP corresponded to increases in NH_4^+, demonstrating a link between light and photosynthetic activity with mineralization rates. Nitrification, although muted, was present in this environment in the 2016 growing season. Within the plot, significant differences were found between moisture tracks: the patterns were the same between the tracks, but the rates at which these patterns occurred were higher in wet tracks than dry tracks. This finding is indicative of the importance of water availability and moisture in driving the abiotic processes that occur in wet sedge meadows; the next step in this finding would be to determine the magnitude of the role water plays in controlling each of these variables. The underlying hydrology and movement of water was a large factor in determining the spatial pattern of NH_4^+ and NO_3^- in the meadow. The melt of the north-adjacent perennial snowpack as the growing season progressed was the source of water that controlled C flux processes in the meadow. The downslope nature of the Muskox wet sedge meadow allowed for the formation of subsurface preferential flow pathways, transporting and cycling nutrients through the plot (Rastetter *et al.*, 2004).

Historically, Arctic wetlands have been a strong C sink (Mikan *et al.*, 2005), and with projected increases in air temperature affecting soil temperature, increases in soil respiration have the possibility of creating direct positive feedback loops (Post *et al.*, 1982; Elberling *et al.*, 2008; Chae *et al.*, 2015; Christiansen, 2016; Euskirchen *et al.*, 2016). In this study, the 2016 growing season saw the wetland plot shift from being an early season source to a late season sink. Wet tracks were generally sinks throughout the entire season, while the dry tracks saw the shift from source to sink, and again the magnitude of the flux processes in wet tracks were always greater than in the dry tracks. This conforms with research from Welker *et al.* (2004) where the differences between land cover C exchange responses had a strong dependence on hydrologic conditions and that wet sedge productivity is strongly linked to moisture (Reynolds and Tenhunen, 1996). The predicted future increases in air temperature will promote earlier and deeper thaw, allowing for microbial activity to be active and for movement and transfer of nutrients (Biederbeck and Campbell, 1973; Jonasson and Shaver, 1999; Shaver *et al.*, 2000). The spatial and temporal dynamics of these nutrients will dictate future shifts in biotic and abiotic conditions.

4.1 Future Work

With the nature of the dynamic changes that are occurring in the High Arctic regions, continual work should be conducted in these environments as the ecosystems continue to evolve and change. The analysis of soil samples for early season, late season, and total season NO_3^- and NH_4^+ will allow us to definitively determine how well the ion exchange resin membranes performed in this wet sedge environment. It will also help definitively decide whether N adsorbed was from the soil or subterraneous water flow. The knowledge gathered from the 2016 field season at Muskox points to the fact that the hydrological regime of the Muskox wet sedge meadow at Cape Bounty needs to be further sampled to understand the role that water plays in nutrient transport and distribution, particularly after spring melt.

Early spring and late fall measurements would be useful to add for a more robust and comprehensive study. Research through snow manipulation has shown that previous seasons' winter and spring climatic events play a role in summer and year-long growth (Robinson, 2002; Aerts *et al.*, 2005; Edwards *et al.*, 2006). Edwards *et al.* (2006) found peak nutrient availability to be early in the freeze-thaw period when soil temperatures were between -7 and 0°C; as such, solely measuring growing season nutrient availability does not encompass the period when soil-available nutrients may be at their peak. Furthermore, research has found microbial nutrient cycling to be present in Arctic snowpacks (Larose *et al*, 2013), and the release of these snowpack nutrients during melt can affect vegetation cover and productivity in the following growing season. Understanding the role that winter freeze and spring thaw has on Arctic ecosystems can help determine and project future shifts in plant cover and soil composition that are anticipated results of climate change (Aerts *et al.*¸2005).

The distribution and role of N-fixing cyanobacteria needs to be investigated in tandem with belowground inorganic N to get the full spectrum of High Arctic N cycling in wetlands. Quantifying the N fixation of *Nostoc* using stable isotope and chemical analysis would allow for the determination of the contribution of the cyanobacteria in N cycling in an environment like High Arctic wet sedge (Skrzypek *et al.*, 2015). High N_2O concentrations have been linked to higher NH_4^+ levels belowground (Stewart *et al.*, 2014), which could be explored through the analysis of trace gas samples in tandem with nutrient adsorption (trace gas samples were taken of the 2016 growing season in Muskox but not included in this manuscript).

Lastly, improving our understanding of N dynamics within a complex ecosystem like a High Arctic wetland, requires other contributing nutrients with C and P to be examined for their roles in promoting or limiting different processes within the N cycle. P has long been known to be a limiting nutrient in Arctic plant growth (Nadelhoffer *et al.*, 1992; Shaver and Chapin, 1995; Shaver *et al.*, 1998; Shaver *et al.*, 2000; Chapin *et al.*, 2002; Stark, 2007), and in some experiments, has been shown to be the dominant limiting nutrient in Arctic wet sedge (Shaver *et al.*, 1998; Gough and Hobbie, 2003). The balance between N and P in these environments can have effects on the rates and shifts in microbial activity (Shaver *et al.*, 1998), and future nutrient cycling studies need to incorporate both limiting nutrients in examining Arctic wetlands. The importance of the role of C in High Arctic N cycling has also been presented in literature (Stark, 2007). C to N ratios have been shown in literature to be an important proxy of mineralization rates (Janssen, 1996), and the ratio of mineralized C to mineralized N is overall affected by soil temperature (Robinson, 2002). Regardless of the environment and temperature, the important interactions between C and N need to be considered in future studies of N cycling.

Appendices

Appendix A – Sampling locations

Table 27: UTM coordinates (WGS 84, Zone 12N) of all sampling sites in the Muskox wet sedge meadow at the Cape Bounty Arctic Watershed Observatory

Site Name	Track	Easting	Northing
NE-A6	Dry	541878.0	8314208.8
NE-A8	Dry	541908.0	8314213.5
NE-B6	Dry	541877.1	8314199.4
NE-B8	Dry	541907.5	8314196.9
NE-C6	Dry	541875.8	8314186.5
NE-C8	Dry	541906.7	8314180.1
NE-D6	Dry	541874.6	8314168.8
NE-D8	Dry	541903.7	8314165.6
NW-A2	Dry	541793.1	8314217.0
NW-A4	Dry	541812.6	8314208.5
NW-B2	Dry	541787.6	8314198.6
NW-B4	Dry	541798.3	8314189.0
NW-C2	Dry	541779.5	8314183.2
NW-C4	Dry	541791.8	8314175.4
NW-D2	Dry	541770.1	8314169.9
NW-D4	Dry	541783.7	8314161.9
SE-E6	Dry	541873.4	8314157.5
SE-E8	Dry	541900.6	8314149.9
SE-F6	Dry	541869.2	8314146.1
SE-F8	Dry	541897.6	8314137.4
SE-G6	Dry	541865.4	8314131.1
SE-G8	Dry	541893.3	8314124.7
SE-H6	Dry	541859.2	8314113.4
SE-H8	Dry	541889.5	8314099.2
SW-E2	Dry	541765.0	8314157.3
SW-E4	Dry	541778.8	8314146.5
SW-F2	Dry	541760.8	8314144.5
SW-F4	Dry	541774.4	8314135.5
SW-G2	Dry	541759.1	8314136.0
SW-G4	Dry	541772.4	8314127.1
SW-H2	Dry	541756.1	8314124.6
SW-H4	Dry	541770.7	8314118.8
SZ1	SZ	541783.9	8314276.9
SZ10	SZ	541864.5	8314278.7
SZ11	SZ	541879.0	8314280.0

SZ12	SZ	541897.6	8314278.5
SZ2	SZ	541792.6	8314280.1
SZ3	SZ	541798.6	8314281.6
SZ4	SZ	541810.6	8314281.1
SZ5	SZ	541817.0	8314278.7
SZ6	SZ	541826.4	8314277.2
SZ7	SZ	541845.2	8314279.4
SZ8	SZ	541852.1	8314279.4
SZ9	SZ	541857.1	8314278.6
NE-A5	Wet	541870.9	8314210.8
NE-A7	Wet	541905.0	8314213.7
NE-B5	Wet	541868.3	8314197.5
NE-B7	Wet	541902.2	8314198.0
NE-C5	Wet	541867.5	8314188.6
NE-C7	Wet	541899.0	8314183.6
NE-D5	Wet	541868.4	8314170.3
NE-D7	Wet	541896.3	8314168.8
NW-A1	Wet	541787.3	8314219.3
NW-A3	Wet	541807.4	8314216.8
NW-B1	Wet	541781.5	8314201.3
NW-B3	Wet	541796.5	8314196.7
NW-C1	Wet	541775.9	8314186.7
NW-C3	Wet	541784.8	8314181.3
NW-D1	Wet	541767.5	8314173.2
NW-D3	Wet	541778.4	8314167.4
SE-E5	Wet	541865.0	8314158.1
SE-E7	Wet	541894.6	8314151.4
SE-F5	Wet	541864.5	8314144.0
SE-F7	Wet	541890.2	8314142.3
SE-G5	Wet	541859.5	8314130.3
SE-G7	Wet	541888.0	8314128.7
SE-H5	Wet	541853.9	8314114.6
SE-H7	Wet	541878.8	8314103.2
SW-E1	Wet	541759.9	8314156.1
SW-E3	Wet	541772.1	8314152.8
SW-F1	Wet	541755.1	8314145.6
SW-F3	Wet	541769.0	8314138.3
SW-G1	Wet	541753.7	8314136.4
SW-G3	Wet	541766.8	8314131.9
SW-H1	Wet	541749.2	8314124.3
SW-H3	Wet	541764.2	8314121.3

Appendix B – Soil nitrogen data

Table 28: Resin A (June 30 to July 27) NO_3^- (orange) and NH_4^+ (green) adsorbed using ion exchange membranes, expressed as µg of nutrient adsorbed per 10 cm^2 over a four-week period

Saturation Zone	SZ1	SZ2	SZ3	SZ4	SZ5	SZ6	SZ7	SZ8	SZ9	SZ10	SZ11	SZ12
	0.593	1.694	1.566	2.193	2.185	2.602	2.341	1.850	2.989	2.318	4.189	5.979
	4.803	7.857	5.191	6.036	7.069	6.561	4.620	7.034	7.525	6.690	12.176	7.141
Muskox Main Plot			NW-A1	NW-A2	NW-A3	NW-A4		NE-A5	NE-A6	NE-A7	NE-A8	
			7.009	2.664	2.131	2.409		1.936	3.231	2.193	2.315	
			14.441	9.942	8.887	8.350		8.660	5.270	7.014	7.101	
			NW-B1	NW-B2	NW-B3	NW-B4		NE-B5	NE-B6	NE-B7	NE-B8	
			2.880	3.060	1.608	3.091		1.022	3.044	1.920	1.904	
			16.770	9.766	13.344	9.669		11.402	6.214	5.358	7.597	
			NW-C1	NW-C2	NW-C3	NW-C4		NE-C5	NE-C6	NE-C7	NE-C8	
			4.207	2.942	1.881	2.883		1.233	2.638	1.124	2.396	
			11.532	9.679	11.936	2.956		8.475	6.019	8.175	8.690	
			NW-D1	NW-D2	NW-D3	NW-D4		NE-D5	NE-D6	NE-D7	NE-D8	
			2.849	4.797	1.748	3.049		2.451	1.662	1.259	2.646	
			12.709	12.951	5.692	9.369		9.269	9.541	6.737	10.353	
			SW-E1	SW-E2	SW-E3	SW-E4		SE-E5	SE-E6	SE-E7	SE-E8	
			2.201	5.128	1.865	2.084		1.366	1.249	1.218	2.708	
			12.877	15.003	5.062	8.022		11.780	6.844	7.618	9.399	
			SW-F1	SW-F2	SW-F3	SW-F4		SE-F5	SE-F6	SE-F7	SE-F8	
			2.362	6.439	0.911	2.872		1.584	2.810	1.420	1.631	
			9.070	10.197	6.957	7.587		7.645	10.239	6.378	8.685	
			SW-G1	SW-G2	SW-G3	SW-G4		SE-G5	SE-G6	SE-G7	SE-G8	
			3.356	5.370	1.709	1.967		2.102	1.975	1.145	2.380	
			11.203	13.410	7.244	11.569		6.833	11.275	9.116	8.153	
			SW-H1	SW-H2	SW-H3	SW-H4		SE-H5	SE-H6	SE-H7	SE-H8	
			2.849	5.370	1.264	8.601		1.530	2.911	2.295	4.589	
			13.280	16.369	9.256	10.152		8.980	11.696	4.923	10.218	

Table 29: Resin B1 (June 30 to July 13) NO_3^- (orange) and NH_4^+ (green) adsorbed using ion exchange membranes, expressed as µg of nutrient adsorbed per 10 cm^2 over a two-week period

Saturation Zone	**SZ1**	**SZ2**	**SZ3**	**SZ4**	**SZ5**	**SZ6**	**SZ7**	**SZ8**	**SZ9**	**SZ10**	**SZ11**	**SZ12**
	1.936	0.856	1.845	1.384	2.856	1.880	1.704	1.732	2.776	1.656	4.136	4.256
	12.738	12.464	13.362	11.957	11.020	10.349	5.136	7.422	9.912	8.055	7.376	7.750
Muskox Main Plot			**NW-A1**	**NW-A2**	**NW-A3**	**NW-A4**		**NE-A5**	**NE-A6**	**NE-A7**	**NE-A8**	
			5.909	1.192	3.054	2.443		1.352	1.692	3.000	2.376	
			2.824	10.004	8.788	7.135		8.351	6.080	9.361	10.664	
			NW-B1	**NW-B2**	**NW-B3**	**NW-B4**		**NE-B5**	**NE-B6**	**NE-B7**	**NE-B8**	
			3.974	1.544	1.605	2.496		2.384	1.951	2.544	2.600	
			9.190	12.648	13.740	9.171		16.234	7.727	12.698	6.419	
			NW-C1	**NW-C2**	**NW-C3**	**NW-C4**		**NE-C5**	**NE-C6**	**NE-C7**	**NE-C8**	
			3.899	1.504	2.376	2.928		2.096	2.357	2.544	2.176	
			20.012	6.616	13.467	8.876		8.851	11.465	13.179	5.762	
			NW-D1	**NW-D2**	**NW-D3**	**NW-D4**		**NE-D5**	**NE-D6**	**NE-D7**	**NE-D8**	
			3.096	2.688	1.004	1.656		1.728	2.364	1.952	2.360	
			19.297	17.053	14.433	19.449		17.655	12.066	14.638	8.310	
			SW-E1	**SW-E2**	**SW-E3**	**SW-E4**		**SE-E5**	**SE-E6**	**SE-E7**	**SE-E8**	
			2.864	1.792	2.001	1.631		1.400	2.690	2.824	2.456	
			23.547	12.322	14.589	7.994		17.140	16.999	5.400	17.891	
			SW-F1	**SW-F2**	**SW-F3**	**SW-F4**		**SE-F5**	**SE-F6**	**SE-F7**	**SE-F8**	
			2.096	2.424	1.122	2.600		2.488	3.686	2.136	2.640	
			7.471	10.959	10.601	8.437		21.510	8.187	12.270	16.350	
			SW-G1	**SW-G2**	**SW-G3**	**SW-G4**		**SE-G5**	**SE-G6**	**SE-G7**	**SE-G8**	
			1.048	2.248	1.491	0.000		2.112	2.014	2.296	2.352	
			9.269	16.241	15.721	18.618		12.043	13.589	7.583	5.268	
			SW-H1	**SW-H2**	**SW-H3**	**SW-H4**		**SE-H5**	**SE-H6**	**SE-H7**	**SE-H8**	
			1.264	2.560	1.941	5.072		2.017	2.840	2.704	3.184	
			10.672	10.751	10.542	20.954		14.915	5.255	11.362	17.108	

Table 30: Resin B2 (July 13 to July 27) NO_3^- (orange) and NH_4^+ (green) adsorbed using ion exchange membranes, expressed as µg of nutrient adsorbed per 10 cm^2 over a two-week period

Saturation Zone	SZ1	SZ2	SZ3	SZ4	SZ5	SZ6	SZ7	SZ8	SZ9	SZ10	SZ11	SZ12
	1.038	1.577	1.647	1.155	1.660	2.139	1.701	1.631	4.222	1.803	3.848	7.313
	8.878	14.189	12.572	16.140	10.573	14.080	11.044	12.433	13.089	11.582	14.533	14.018
Muskox Main Plot			**NW-A1**	**NW-A2**	**NW-A3**	**NW-A4**		**NE-A5**	**NE-A6**	**NE-A7**	**NE-A8**	
			20.168	2.412	1.545	1.545		1.858	2.857	2.100	1.561	
			18.747	8.414	10.622	8.804		11.237	4.561	13.053	10.172	
			NW-B1	**NW-B2**	**NW-B3**	**NW-B4**		**NE-B5**	**NE-B6**	**NE-B7**	**NE-B8**	
			5.440	2.935	2.295	3.112		1.904	2.412	2.599	1.597	
			10.388	12.886	13.487	8.999		15.379	6.572	9.019	12.087	
			NW-C1	**NW-C2**	**NW-C3**	**NW-C4**		**NE-C5**	**NE-C6**	**NE-C7**	**NE-C8**	
			7.001	3.200	2.237	2.955		2.539	11.465	1.233	1.842	
			12.121	8.695	13.357	10.224		10.928	6.934	15.227	14.371	
			NW-D1	**NW-D2**	**NW-D3**	**NW-D4**		**NE-D5**	**NE-D6**	**NE-D7**	**NE-D8**	
			3.575	4.898	2.076	3.278		2.602	2.217	1.975	1.514	
			10.779	15.391	17.725	9.140		11.951	10.112	17.417	14.293	
			SW-E1	**SW-E2**	**SW-E3**	**SW-E4**		**SE-E5**	**SE-E6**	**SE-E7**	**SE-E8**	
			2.037	3.236	3.007	2.857		1.727	3.013	2.165	2.712	
			15.173	7.711	14.642	10.287		25.783	11.091	9.806	14.423	
			SW-F1	**SW-F2**	**SW-F3**	**SW-F4**		**SE-F5**	**SE-F6**	**SE-F7**	**SE-F8**	
			3.707	4.129	1.920	4.007		1.826	3.403	1.675	2.006	
			10.459	9.600	11.645	4.974		29.921	12.027	12.860	9.495	
			SW-G1	**SW-G2**	**SW-G3**	**SW-G4**		**SE-G5**	**SE-G6**	**SE-G7**	**SE-G8**	
			3.602	4.503	1.264	1.842		2.253	2.490	2.205	2.420	
			10.439	10.919	17.522	8.429		14.981	12.979	10.356	10.529	
			SW-H1	**SW-H2**	**SW-H3**	**SW-H4**		**SE-H5**	**SE-H6**	**SE-H7**	**SE-H8**	
			3.286	11.153	2.576	5.510		1.462	2.685	1.436	3.052	
			11.192	10.170	9.616	11.145		15.813	10.273	11.780	13.775	

Appendix C – Carbon dioxide exchange data

Table 31: Net ecosystem exchange (NEE) throughout the growing season expressed as μmol/m²/s

Date	NW-A1		NW-A3		NE-A5		NE-A7	
July 5	1.089		0.623		-0.303		0.422	
July 10	0.831		-1.252		-1.348		-0.653	
July 17	-1.000		-1.625		-2.120		-1.575	
July 24	-0.898		-2.283		-2.041		-0.955	
		NW-B2		NW-B4		NE-B6		NE-B8
July 5		1.033		0.578		1.332		0.763
July 10		1.333		0.154		0.602		0.539
July 17		-0.516		-0.853		-0.319		-1.117
July 24		-0.518		-0.765		-0.931		-0.811
	NW-C1		NW-C3		NE-C5		NE-C7	
July 5	-0.554		-0.716		-0.819		-0.741	
July 10	-0.476		-0.938		-2.322		-0.254	
July 17	-1.654		-2.176		-2.301		-2.831	
July 24	-0.681		-1.968		-2.161		-0.765	
		NW-D2		NW-D4		NE-D6		NE-D8
July 5		0.814		1.881		0.692		0.774
July 10		0.255		0.702		-1.060		0.287
July 17		-0.412		-1.113		-0.361		-1.468
July 24		-0.278		-0.833		-0.478		-0.817
	SW-E1		SW-E3		SE-E5		SE-E7	
July 5	0.542		1.074		-1.375		-0.283	
July 10	0.378		-0.922		-2.523		0.778	
July 17	-0.470		-1.018		-2.986		-2.274	
July 24	-0.716		-0.970		-3.645		-1.205	
		SW-F2		SW-F4		SE-F6		SE-F8
July 5		0.888		0.373		2.116		0.416
July 10		0.744		-0.583		1.968		0.348
July 17		-0.336		-1.882		0.621		-1.147
July 24		0.198		-0.502		2.162		-0.963
	SW-G1		SW-G3		SE-G5		SE-G7	
July 5	0.425		-1.364		-1.094		-0.645	
July 10	0.522		-2.143		-1.582		-0.414	
July 17	-1.455		-2.436		-1.246		-1.219	
July 24	-0.510		-1.510		-1.189		-0.770	
		SW-H2		SW-H4		SE-H6		SE-H8
July 5		0.121		0.713		1.396		3.714
July 10		0.733		0.207		0.780		2.043
July 17		0.674		-0.270		-1.349		-1.062
July 24		0.520		-0.275		-0.475		-0.376

Table 32: Mean NEE measurements standard deviation across the dry tracks over the growing season

	Dry 2		Dry 4		Dry 6		Dry 8	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Week 1	0.714	0.405	0.944	0.818	1.384	0.582	1.417	1.540
Week 2	0.766	0.441	0.091	0.645	0.573	1.246	0.804	0.833
Week 3	-0.147	0.553	-1.283	0.535	-0.352	0.804	-1.198	0.183
Week 4	-0.019	0.467	-0.700	0.175	0.070	1.411	-0.742	0.254

Table 33: Mean NEE measurements standard deviation across the wet tracks over the growing season

	Wet 1		Wet 3		Wet 5		Wet 7	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Week 1	0.138	0.602	-0.096	1.137	-0.898	0.457	-0.312	0.528
Week 2	0.141	0.539	-1.313	0.573	-1.944	0.567	-0.136	0.631
Week 3	-1.193	0.634	-1.814	0.629	-2.163	0.716	-1.975	0.720
Week 4	-0.636	0.110	-1.683	0.571	-2.259	1.020	-0.924	0.207

Table 34: Ecosystem respiration (ER) throughout the growing season expressed as μmol/m^2/s

Date	NW-A1		NW-A3		NE-A5		NE-A7	
July 5	1.676		3.043		3.140		3.476	
July 10	1.221		3.258		3.736		3.309	
July 17	1.741		1.485		0.738		1.086	
July 24	1.316		1.786		0.752		0.669	
		NW-B2		NW-B4		NE-B6		NE-B8
July 5		1.487		2.417		2.186		3.599
July 10		1.416		2.044		1.971		3.624
July 17		0.987		1.092		1.112		1.169
July 24		1.188		1.110		1.421		1.622
	NW-C1		NW-C3		NE-C5		NE-C7	
July 5	1.387		2.636		1.844		3.164	
July 10	1.126		2.951		3.106		4.326	
July 17	1.355		1.195		1.378		0.517	
July 24	0.910		1.223		1.466		0.562	
		NW-D2		NW-D4		NE-D6		NE-D8
July 5		0.919		3.395		1.547		2.006
July 10		1.065		3.358		1.197		1.849
July 17		0.986		1.561		0.855		0.940
July 24		0.948		1.615		0.368		1.082
	SW-E1		SW-E3		SE-E5		SE-E7	
July 5	1.728		2.458		2.408		3.827	
July 10	1.321		2.532		2.545		4.764	
July 17	1.329		0.886		1.196		0.792	
July 24	0.578		0.411		1.274		0.814	
		SW-F2		SW-F4		SE-F6		SE-F8
July 5		1.387		2.355		2.282		1.657
July 10		1.076		2.030		2.392		1.745
July 17		0.992		1.229		1.060		0.900
July 24		1.019		1.435		1.325		1.050
	SW-G1		SW-G3		SE-G5		SE-G7	
July 5	1.877		1.875		2.371		4.045	
July 10	1.664		2.970		2.275		3.185	
July 17	1.520		0.795		1.128		0.934	
July 24	1.403		0.759		1.258		1.377	
		SW-H2		SW-H4		SE-H6		SE-H8
July 5		0.902		0.998		2.279		2.503
July 10		0.783		0.703		1.901		1.353
July 17		0.723		0.848		0.955		0.733
July 24		0.760		0.728		0.839		0.960

Table 35: Mean ER measurements standard deviation across the dry tracks over the growing season

	Dry 2		Dry 4		Dry 6		Dry 8	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Week 1	1.174	0.307	2.722	0.584	2.073	0.354	2.441	0.846
Week 2	1.085	0.259	2.478	0.763	1.865	0.496	2.143	1.010
Week 3	0.922	0.133	1.294	0.241	0.995	0.114	0.935	0.180
Week 4	0.979	0.177	1.386	0.256	0.988	0.486	1.178	0.300

Table 36: Mean ER measurements standard deviation across the wet tracks over the growing season

	Wet 1		Wet 3		Wet 5		Wet 7	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Week 1	1.664	0.251	2.503	0.485	2.441	0.533	3.628	0.388
Week 2	1.370	0.273	2.928	0.299	2.915	0.647	3.896	0.772
Week 3	1.401	0.104	1.090	0.314	1.110	0.269	0.832	0.242
Week 4	0.964	0.415	1.045	0.596	1.187	0.305	0.855	0.363

Table 37: Gross primary production (GPP) throughout the growing season expressed as µmol/m^2/s

Date	NW-A1		NW-A3		NE-A5		NE-A7	
July 5	-0.586		-2.419		-3.443		-3.053	
July 10	-0.390		-4.510		-5.084		-3.962	
July 17	-2.741		-3.110		-2.859		-2.661	
July 24	-2.213		-4.068		-2.792		-1.623	
		NW-B2		NW-B4		NE-B6		NE-B8
July 5		-0.454		-1.839		-0.854		-2.837
July 10		-0.083		-1.890		-1.369		-3.086
July 17		-1.502		-1.945		-1.431		-2.286
July 24		-1.705		-1.874		-2.352		-2.433
	NW-C1		NW-C3		NE-C5		NE-C7	
July 5	-1.941		-3.352		-2.664		-3.906	
July 10	-1.602		-3.889		-5.428		-4.580	
July 17	-3.009		-3.371		-3.680		-3.348	
July 24	-1.591		-3.191		-3.626		-1.327	
		NW-D2		NW-D4		NE-D6		NE-D8
July 5		-0.106		-1.514		-0.855		-1.232
July 10		-0.810		-2.656		-2.257		-1.562
July 17		-1.397		-2.674		-1.216		-2.408
July 24		-1.226		-2.448		-0.846		-1.899
	SW-E1		SW-E3		SE-E5		SE-E7	
July 5	-1.186		-1.385		-3.783		-4.110	
July 10	-0.943		-3.453		-5.068		-3.986	
July 17	-1.799		-1.905		-4.182		-3.066	
July 24	-1.294		-1.381		-4.919		-2.019	
		SW-F2		SW-F4		SE-F6		SE-F8
July 5		-0.500		-1.982		-0.166		-1.242
July 10		-0.332		-2.613		-0.424		-1.397
July 17		-1.328		-3.112		-0.439		-2.046
July 24		-0.821		-1.937		0.837		-2.013
	SW-G1		SW-G3		SE-G5		SE-G7	
July 5	-1.452		-3.239		-3.465		-4.690	
July 10	-1.142		-5.113		-3.857		-3.599	
July 17	-2.975		-3.231		-2.374		-2.153	
July 24	-1.913		-2.269		-2.447		-2.146	
		SW-H2		SW-H4		SE-H6		SE-H8
July 5		-0.781		-0.285		-0.883		1.211
July 10		-0.049		-0.496		-1.121		0.690
July 17		-0.049		-1.118		-2.304		-1.794
July 24		-0.241		-1.003		-1.314		-1.336

Table 38: Mean GPP measurements standard deviation across the dry tracks over the growing season

	Dry 2		Dry 4		Dry 6		Dry 8	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Week 1	-0.460	0.277	-1.78	0.772	-0.689	0.349	-1.03	1.67
Week 2	-0.318	0.351	-2.39	1.01	-1.29	0.757	-1.34	1.55
Week 3	-1.07	0.684	-2.58	0.874	-1.35	0.767	-2.13	0.272
Week 4	-0.998	0.621	-2.09	0.600	-0.919	1.33	-1.92	0.452

Table 39: Mean GPP measurements standard deviation across the wet tracks over the growing season

	Wet 1		Wet 3		Wet 5		Wet 7	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Week 1	-1.32	0.565	-2.60	0.910	-3.06	0.476	-3.94	0.678
Week 2	-1.04	0.502	-4.24	0.725	-4.21	0.688	-4.03	0.406
Week 3	-2.39	0.567	-2.90	0.675	-3.22	0.811	-2.81	0.519
Week 4	-1.60	0.397	-2.73	1.16	-3.08	1.10	-1.78	0.375

Appendix D – Soil moisture, soil temperature, and active layer depth data

Table 40: Soil temperature data collected throughout the growing season, expressed in Celsius

Sample Location	Date									
	June 29-30	04-Jul	05-Jul	10-Jul	15-Jul	17-Jul	20-Jul	24-Jul	25-Jul	26-Jul
NW-A1	-1.5	0.6	1.4	3.0	1.9	1.4	1.6	1.8	3.1	2.5
NW-C1	0.0	1.3	2.3	3.6	1.4	1.8	1.9	2.2	3.6	2.8
SW-E1	-0.2	0.4	1.1	1.8	1.0	1.3	1.5	1.8	3.3	2.6
SW-G1	0.2	0.5	1.1	2.0	1.4	1.4	1.2	1.3	3.2	2.1
SW-H2	-0.3	-0.5	-0.2	0.6	0.2	0.0	-0.1	0.4	1.0	0.3
SW-F2	-0.2	0.2	0.9	1.8	0.4	0.5	0.9	1.4	2.4	1.8
NW-D2	-0.4	-0.1	0.7	1.5	0.5	0.6	0.1	0.5	1.6	0.5
NW-B2	-0.3	-0.1	1.2	0.9	0.6	0.5	0.4	0.8	1.9	1.3
NW-A3	0.0	1.1	3.2	4.0	2.4	2.7	2.2	2.9	4.0	3.2
NW-C3	0.1	0.4	1.6	3.3	1.8	2.1	1.9	2.1	3.5	2.7
SW-E3	0.7	2.2	4.4	5.5	3.5	3.6	3.4	3.4	4.6	4.0
SW-G3	0.8	1.8	3.8	4.8	3.5	3.4	3.3	3.1	4.2	4.0
SW-H4	-0.2	0.6	1.9	2.0	1.2	0.8	1.0	1.6	2.2	1.6
SW-F4	0.5	2.3	3.6	4.8	3.0	2.9	2.6	3.1	4.1	3.5
NW-D4	0.3	0.2	1.0	2.8	1.7	1.5	1.3	1.8	2.9	2.1
NW-B4	-0.2	0.6	1.3	2.0	1.2	1.0	0.8	1.2	1.6	1.4
NE-A5	2.0	6.2	8.4	8.3	4.8	4.9	4.1	4.5	5.4	5.2
NE-C5	1.6	3.7	5.5	5.9	4.1	3.4	3.3	3.2	4.3	3.9
SE-E5	0.9	3.4	4.5	4.6	3.3	2.8	3.0	3.0	3.8	3.5
SE-G5	1.0	3.7	3.7	4.9	3.5	3.0	2.7	2.9	3.7	3.4
SE-H6	-0.2	0.8	0.8	2.3	1.7	1.6	1.4	1.4	1.8	2.1
SE-F6	-0.2	1.3	0.8	2.1	1.7	1.1	1.2	1.6	2.3	2.1
NE-D6	0.2	1.7	2.3	2.9	2.2	2.0	1.6	2.2	2.7	2.4
NE-B6	0.1	0.9	1.0	1.8	1.2	1.1	1.4	1.4	2.0	1.9
SE-G7	1.4	2.9	4.2	4.4	4.0	3.7	2.9	3.5	3.8	4.3
SE-E7	1.1	2.7	3.6	3.6	3.9	3.2	3.2	3.6	4.1	4.8
NE-C7	1.2	2.9	4.5	4.6	3.7	4.3	3.9	3.9	4.4	4.6
NE-A7	1.6	4.0	5.0	5.7	3.8	4.0	3.0	3.4	4.3	5.0
SE-H8	0.1	0.3	1.1	1.3	1.2	1.2	0.8	1.8	1.9	1.9
SE-F8	1.2	2.3	3.2	4.0	3.1	2.9	2.3	3.2	3.6	3.7
NE-D8	0.6	1.5	1.8	2.8	1.3	1.6	1.3	2.2	2.7	2.5
NE-B8	1.2	2.7	3.2	4.0	3.5	2.9	2.4	2.5	3.3	3.4

Table 41: Mean ST measurements standard deviation across the dry tracks over the growing season

	Dry 2		Dry 4		Dry 6		Dry 8	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Week 1	0.069	0.288	1.056	0.915	0.797	0.404	1.592	0.865
Week 2	0.825	0.296	2.572	1.188	1.979	0.447	2.658	1.209
Week 3	0.346	0.299	1.681	0.974	1.413	0.279	1.933	0.820
Week 4	1.150	0.552	2.430	1.098	1.989	0.297	2.722	0.704

Table 42: Mean ST measurements standard deviation across the wet tracks over the growing season

	Wet 1		Wet 3		Wet 5		Wet 7	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Week 1	0.730	0.408	1.675	0.782	3.722	1.263	2.931	0.448
Week 2	1.867	0.569	3.596	0.892	4.938	1.183	4.221	0.424
Week 3	1.517	0.277	2.821	0.728	3.396	0.779	3.508	0.414
Week 4	2.544	0.340	3.467	0.543	3.900	0.797	4.142	0.203

Table 43: Soil moisture data collected throughout the growing season, expressed as a percentage

Sample Location	Date									
	June 29-30	04-Jul	05-Jul	10-Jul	15-Jul	17-Jul	20-Jul	24-Jul	25-Jul	26-Jul
NW-A1	34.5	25.7	23.4	19.0	51.6	58.4	39.4	38.7	32.0	46.5
NW-C1	68.7	51.9	52.3	45.4	79.6	62.3	56.5	59.9	56.4	66.3
SW-E1	43.5	79.6	79.2	63.7	91.7	94.9	89.5	100.0	94.6	89.2
SW-G1	39.9	45.9	53.8	45.3	63.5	71.1	73.0	81.4	72.2	84.4
SW-H2	30.6	45.5	34.3	38.8	82.0	76.4	71.9	64.9	47.5	73.6
SW-F2	28.6	43.5	35.9	45.0	72.7	72.5	55.1	70.5	66.3	54.1
NW-D2	35.3	33.3	32.9	46.9	49.7	54.1	48.3	46.3	36.1	55.2
NW-B2	32.5	28.8	41.4	29.3	60.7	70.4	80.1	65.8	51.5	77.7
NW-A3	79.1	86.7	89.7	90.7	89.1	88.0	88.9	97.2	90.8	88.6
NW-C3	71.6	61.9	78.4	49.4	96.6	92.9	94.5	99.1	96.7	98.2
SW-E3	87.5	84.1	82.3	74.3	74.0	72.3	80.7	77.5	85.2	82.4
SW-G3	100.0	90.2	93.5	94.3	94.8	93.3	97.3	88.1	101.0	91.8
SW-H4	53.4	47.2	42.6	38.7	51.0	59.5	58.1	55.6	54.9	56.4
SW-F4	47.6	50.6	46.0	44.1	59.0	49.4	54.7	50.1	47.8	53.3
NW-D4	48.1	47.0	49.6	38.8	72.3	79.4	85.2	39.4	51.6	68.4
NW-B4	66.4	65.9	72.4	67.7	86.4	73.4	74.0	77.5	73.6	71.4
NE-A5	86.7	62.9	69.5	50.6	70.9	64.1	69.9	61.1	66.9	59.2
NE-C5	101.1	95.9	98.8	94.2	100.8	100.6	104.0	96.5	100.2	100.7
SE-E5	99.3	101.2	101.9	96.6	99.7	99.5	99.9	98.7	98.7	100.5
SE-G5	88.3	92.2	89.8	83.3	75.1	86.2	76.6	91.4	82.4	99.7
SE-H6	63.5	73.1	77.0	61.9	79.9	71.6	82.5	78.2	78.6	78.0
SE-F6	39.0	26.0	25.3	23.9	41.3	67.8	76.8	73.3	46.2	68.1
NE-D6	53.9	57.7	48.1	42.1	60.0	63.7	64.5	64.8	60.8	60.1
NE-B6	55.5	40.1	25.7	32.5	81.3	91.2	91.4	76.5	45.8	77.9
SE-G7	95.6	69.2	84.2	54.9	67.8	91.1	98.8	93.1	96.9	97.5
SE-E7	100.1	73.6	82.6	61.1	82.1	95.0	98.5	98.3	97.0	340.4
NE-C7	99.1	97.5	99.5	73.3	92.1	100.3	100.7	99.7	94.7	98.8
NE-A7	90.9	64.3	68.1	66.1	83.0	76.7	77.6	83.5	80.8	87.5
SE-H8	41.5	35.3	44.1	43.0	67.1	67.4	66.6	71.7	62.6	76.1
SE-F8	42.7	43.1	46.5	37.7	52.3	51.5	53.2	54.7	54.9	62.4
NE-D8	42.5	44.0	48.0	40.1	62.9	51.1	70.6	61.2	39.2	65.4
NE-B8	47.9	56.4	65.5	71.5	69.6	76.9	92.5	89.4	53.7	79.4

Table 44: Mean SM measurements standard deviation across the dry tracks over the growing season

	Dry 2		Dry 4		Dry 6		Dry 8	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Week 1	35.207	1.418	54.826	11.611	48.750	17.714	46.467	7.044
Week 2	53.129	7.643	61.411	13.720	52.858	15.876	55.529	10.848
Week 3	66.113	11.189	69.350	15.587	76.192	11.421	66.217	13.705
Week 4	59.114	8.936	59.233	12.996	67.356	7.583	64.214	9.334

Table 45: Mean SM measurements standard deviation across the wet tracks over the growing season

	Wet 1		Wet 3		Wet 5		Wet 7	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Week 1	57.204	10.473	83.761	9.856	90.642	12.606	85.400	10.054
Week 2	64.872	11.844	82.908	10.942	83.879	17.771	72.550	8.825
Week 3	74.556	16.541	88.483	8.518	87.617	16.574	92.325	10.390
Week 4	78.263	16.915	91.367	6.915	88.008	17.487	93.289	6.312

Table 46: Active layer depth collected throughout the growing season, expressed in centimetres

Sample Location	Date			
	06-Jul	11-Jul	18-Jul	25-Jul
NW-A1	30.0	36.0	41.7	40.7
NW-B1	29.0	27.0	25.7	26.0
NW-C1	25.0	37.7	37.3	40.0
NW-D1	20.0	32.0	33.0	37.7
SW-E1	22.0	30.0	33.7	36.0
SW-F1	26.0	32.3	36.7	41.0
SW-G1	30.0	32.0	31.7	32.0
SW-H1	32.0	38.3	40.7	41.7
SW-H2	15.0	16.0	18.0	18.3
SW-G2	28.0	26.0	29.0	32.3
SW-F2	31.0	27.7	29.3	28.3
SW-E2	20.0	25.0	26.3	26.3
NW-D2	16.0	23.0	17.0	19.3
NW-C2	20.0	19.3	20.0	22.7
NW-B2	22.0	21.3	20.0	24.3
NW-A2	20.0	24.3	26.0	28.0
NW-A3	29.0	40.3	40.3	42.3
NW-B3	27.0	33.0	33.7	37.7
NW-C3	27.0	33.3	35.7	38.3
NW-D3	38.0	45.3	45.7	50.0
SW-E3	41.0	45.3	49.3	49.0
SW-F3	43.0	44.0	49.0	48.0
SW-G3	36.0	43.7	48.3	46.7
SW-H3	36.0	37.0	43.3	47.7
SW-H4	22.0	24.0	25.7	26.0
SW-G4	30.0	30.3	30.0	30.0
SW-F4	33.0	38.7	41.0	43.3
SW-E4	36.0	39.3	44.0	43.0
NW-D4	25.0	35.0	35.0	32.0
NW-C4	25.0	30.7	27.3	30.0
NW-B4	22.0	20.3	22.3	27.0
NW-A4	32.0	35.7	40.3	38.0
NE-A5	48.0	54.3	57.7	57.3
NE-B5	40.0	48.3	51.7	50.3
NE-C5	38.0	47.0	49.3	45.0
NE-D5	38.0	43.0	47.0	46.0
SE-E5	35.0	46.3	48.0	45.0
SE-F5	33.0	40.3	44.0	44.0
SE-G5	33.0	40.0	41.3	39.0

SE-H5	30.0	35.0	38.0	35.7
SE-H6	29.0	28.7	33.7	30.3
SE-G6	29.0	33.7	40.0	40.0
SE-F6	28.0	28.7	30.0	31.0
SE-E6	18.0	19.7	27.3	28.3
NE-D6	25.0	32.7	38.3	36.3
NE-C6	30.0	33.0	39.7	37.3
NE-B6	24.0	29.0	30.3	31.0
NE-A6	33.0	40.3	45.7	42.7
NE-A7	42.0	48.3	47.0	48.0
NE-B7	47.0	48.7	49.7	53.0
NE-C7	32.0	43.0	46.7	47.0
NE-D7	38.0	46.7	45.7	48.7
SE-E7	31.0	40.0	41.0	44.7
SE-F7	40.0	40.0	42.0	42.0
SE-G7	39.0	43.7	47.0	47.7
SE-H7	43.0	49.3	53.3	56.3
SE-H8	17.0	21.7	21.7	22.3
SE-G8	30.0	37.3	39.7	45.7
SE-F8	31.0	38.3	37.7	37.7
SE-E8	21.0	29.3	29.7	26.3
NE-D8	27.0	30.3	31.7	36.7
NE-C8	18.0	30.3	32.3	33.3
NE-B8	34.0	38.7	41.0	44.0
NE-A8	31.0	41.0	44.7	44.3
SZ12	28.0	44.0	55.0	61.7
SZ11	33.0	39.0	64.7	58.0
SZ10	44.0	56.7	63.3	63.7
SZ9	42.0	56.0	68.0	70.7
SZ8	40.0	53.3	61.0	62.7
SZ7	36.0	52.0	57.3	57.3
SZ6	36.0	53.0	59.0	60.3
SZ5	33.0	53.3	60.7	62.3
SZ4	22.0	50.3	59.0	58.3
SZ3	28.0	55.3	63.3	59.0
SZ2	41.0	56.7	63.0	64.3
SZ1	41.0	53.7	64.7	64.7

Table 47: Mean AL measurements standard deviation across the dry tracks over the growing season

	Dry 2		Dry 4		Dry 6		Dry 8	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Week 1	21.000	7.348	26.667	5.686	26.500	2.380	27.250	7.411
Week 2	22.000	4.815	31.333	9.701	29.750	1.951	32.250	8.039
Week 3	21.083	5.640	32.778	9.530	33.083	3.872	33.000	8.485
Week 4	22.583	4.646	34.111	8.369	32.167	2.795	35.167	9.151

Table 48: Mean AL measurements standard deviation across the wet tracks over the growing season

	Wet 1		Wet 3		Wet 5		Wet 7	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Week 1	25.667	4.041	33.250	6.449	38.500	6.658	36.000	5.354
Week 2	33.222	3.977	40.667	5.312	46.917	5.865	43.750	3.447
Week 3	34.222	2.874	43.417	6.551	49.083	6.708	45.417	2.949
Week 4	36.000	4.000	44.083	4.725	46.583	7.705	46.833	1.503

References

Arctic Climate Impact Assessment [ACIA]. (2005). Arctic Tundra and Polar Desert Ecosystems, in *Arctic Climate Impact Assessment – Scientific Report* (Chapter 7). Cambridge, UK: Cambridge University Press

Aerts, R., Cornelissen, J.H.C., and Dorrepaal, E. (2005). Plant performance in a warmer world: General responses of plants from cold, northern biomes and the importance of winter and spring events. *Plant Ecology, 182*(1): 65-77.

Aren, S.J.T., Sullivan, P.F., and Welker, J.M. (2008). Nonlinear responses to nitrogen and strong interaction with nitrogen and phosphorus additions drastically alter the structure and function of a High Arctic ecosystem. *Journal of Geophysical Research, 113*, G03S09.

Astoria Pacific. (2011). What is micro seg flow? *Astoria Pacific*. Retrieved May 12, 2017 from http://www.astoria-pacific.com/industrial/technology-industrial/what-is-micro-seg-flow/.

Atkinson, D.M. (2012). Modelling biophysical variables and carbon dioxide exchange in Arctic tundra landscapes using high spatial resolution remote sensing data. Doctoral dissertation. Retrieved from Queen’s Theses & Dissertations. (http://hdl.handle.net/1974/7709).

Atkinson, D.M. and Treitz, P. (2012). Arctic ecological classifications derived from vegetation community and satellite spectral data. *Remote Sensing, 4*: 3948-3971.

Atkinson, D.M. and Treitz, P. (2013). Modeling biophysical variables across an Arctic latitudinal gradient using high spatial resolution remote sensing data. *Arctic, Antarctic, and Alpine Research, 45*(2): 161-178.

Atkinson, D.M. (2016). Personal communication. Department of Geography and Environmental Studies, Ryerson University. Toronto, Canada.

Avis, C.A., Weaver, A.J., and Meissner, K.J. (2011). Reduction in areal extent of high-latitude wetlands in response to permafrost thaw. *Nature Geoscience, 4*: 444–448. doi: 10.1038/ngeo1160.

Beamish, A., Neil, A., Wagner, I., and Scott, N.A. (2014). Short-term impacts of active layer detachments on carbon exchange in a High Arctic ecosystem, Cape Bounty, Nunavut, Canada. *Polar Biology, 37*: 1459-1468.

Beermann, F. (2016). Nutrient availability and limitation within soils of polygonal tundra in the Sakha Republic, Russian Federation. Doctoral dissertation. Retrieved from Max Planck Society Public Repository (http://pubman.mpdl.mpg.de/pubman/item/escidoc:2296827/component/escidoc:2296826/Dissertation_Beermann.pdf)

Bell, T.H., Callender, K.L., Whyte, L.G., and Greer, C.W. (2013). Microbial competition in polar soils: A review of an understudied but potentially important control on productivity. *Biology (Basel), 2*(2): 533-554.

Biederbeck, V.O. and Campbell, C.A. (1973). Soil microbial activity as influenced by temperature trends and fluctuations. *Canadian Journal of Soil Science, 53*: 363-376.

Bilbrough, C., Welker, J., and Bowman, W.D. (2000). Early spring nitrogen uptake by snow-covered plants: a comparison of arctic and alpine plant function under the snowpack. *Arctic, Antarctic and Alpine Research, 32*: 404-411.

Billings, W.D., Luken, J.O., Mortensen, D.A., and Peterson, K.M. (1982). Arctic tundra: a source or sink for atmospheric carbon dioxide in a changing environment? *Oecologia, 53*(1): 7-11.

Billings, W.D., Peterson, K.M., Luken, J.O., and Mortensen, D.A. (1984). Interaction of increasing atmospheric carbon dioxide and soil nitrogen on the carbon balance of tundra microcosms. *Oecologia, 65*(1): 26-29.

Binkley, P. and Matson, P. (1983). Ion exchange resin bag method for assessing available forest soil nitrogen. *Soil Science Society of America Journal, 47*: 1050-1052.

Bintanja, R. and Andry, O. (2017). Towards a rainfall-driven Arctic. *Nature Climate Change, 7*: 263-268.

Blaser, A. (2016). Spatial and temporal patterns of carbon dioxide exchange for a wet sedge plant community, Melville Island, NU. Master's thesis. Retrieved from Queen's Theses & Dissertations. (http://hdl.handle.net/1974/13987).

Bunnell, F.L., Tait, D.E.N., Flanagan, P.W., and Van Cleve, K. (1977). Microbial respiration and substrate weight loss – I: A general model of the influences of abiotic variables. *Soil Biology and Biochemistry, 9*: 33-40.

Callaghan, T.V., Johansson, M., Brown, R.D., Groisman, P.Y., Labba, N., Radionov, V., Barry, R.G., Bulygina, O.N., Essery, R.L.H., Frolov, D.M., Golubev, V.N., Grenfell, T.C., Petrushina, M.N., Razuvaev, V.N., Robinson, D.A., Romanov, P., Shindell D., Shmakin, A.B., Sokratov, S.A., Warren, S., and Yang, D.Q. (2011). The changing face of Arctic snow cover: A synthesis of observed and projected changes. *Ambio, 40*: 17-31.

Callaghan, T.V., Johansson, M., Brown, R.D., Groisman, P.Y., Labba, N., Radionov, V., Bradley, R.S., Blangy, S., Bulygina, O.N., Christensen, T.R., Colman, J.E., Essery, R.L.H., Forbes, B.C., Forchhammer, M.C., Golubev, V.N., Honrath, R.E., Juday, G.P., Meshcherskaya, A.V., Phoenix, G.K., Pomeroy, J., Rautio, A., Robinson, D.A., Schmidt, N.M., Serreze, M.C., Shevchenko, V.P., Shiklomanov, A.I., Shmakin, A.B., Sköld, P., Sturm, M., Woo, M.K., and Wood, E.F. (2011). Multiple effects of changes in Arctic snow cover. *Ambio, 40*(1): 32-45.

Canadian Network of Northern Research Operators [CNNRO]. (2015). *Cape Bounty Arctic Watershed Observatory*. Retrieved June 2, 2016 from http://cnnro.ca/cape-bounty-arctic-watershed-observatory/.

Chae, Y., Kang, S.M., Jeong, S.J., Kim, B., and Frierson, D.M.W. (2015). Arctic greening can cause earlier seasonality of Arctic amplification. *Geophysical Research Letters, 42*. doi:10.1002/2014GL061841.

Chapin, D.M. and Bledsoe, C.S. (1992) Nitrogen fixation in Arctic plant communities. In Chapin, F.S. III, Jefferies, R.L., Reynolds, J.F., Shaver, G.R., Svoboda, J., and Chu, E. (Eds). *Arctic ecosystems in a changing climate* (301-319). New York: Elsevier Science.

Chapin, F.S. III, Shaver, G.R., Giblin, A.E., Nadelhoffer, K.J., and Laundre, J.A. (1995). Responses of Arctic tundra to experimental and observed changes in climate. *Ecology, 76*(3): 694-711. doi: 10.2307/1939337.

Chapin, F.S. III, Matson, P.A., and Mooney, H.A. (2002). *Principles of terrestrial ecosystem ecology*. New York: Springer.

Chen, Z., Ding, W., Xu, Y., Müller, C., Yu, H., and Fan, J. (2016). Increased N_2O emissions during soil drying after waterlogging and spring thaw in a record wet year. *Soil Biology and Biogeochemistry, 101*: 152-164.

Christiansen, C.T. (2016). Seasonal controls on litter and soil carbon and nutrient cycling in Arctic tundra ecosystems and potential impacts of climate change. Doctoral dissertation. Retrieved from Queen's Theses & Dissertations. (http://hdl.handle.net/1974/13988).

Childs, C. (2004). *Interpolating surfaces in ArcGIS Spatial Analyst*. Retrieved April 17, 2017 from https://www.esri.com/news/arcuser/0704/files/interpolating.pdf

Clein, J.S. and Schimel, J.P. (1995). Microbial activity of tundra and taiga soils at sub-zero temperatures. *Soil Biology and Biochemistry, 27*(9): 1231-1234.

Commane, R., Lindaas, J., Benmerqui, J., Luus, K.A., Chang, R.Y.W., Daube, B.C., Euskirchen, E.S., Henderson, J.M., Karion, A., Miller, J.B., Miller, S.M., Parazoo, N.C., Randerson, J.T., Sweeney, C., Tans, P., Thoning, K., Veraverbeke, S., Miller, C.E., and Wofsy, S.C. (2017). Carbon dioxide sources from Alaska driven by increasing early winter respiration from Arctic tundra. *Proceedings of the National Academy of Sciences of the United States of America*. doi: 10.1073/pnas.1618567114.

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Ojima, D.S., Kulmala, A.E., and Phongpan, S. (2000). General model for N_2O and N_2 gas emissions from soils due to denitrification. *Global Biogeochemical Cycles, 14*(4): 1045-1060.

Edwards, K.A., McCulloch, J., Kershaw, P.G., and Jefferies, R.L. (2006). Soil microbial and nutrient dynamics in a wet arctic sedge meadow in late winter and early spring. *Soil Biology and Biochemistry*, *38*(9): 2843-2851. doi: 10.1016/j.soilbio.2006.04.042.

Elberling, B., Christiansen, H.H., and Hansen, B.U. (2010). High nitrous oxide production from thawing permafrost. *Nature Geoscience*, *3*: 332-325. doi:10.1038/ngeo803.

Elberling, B., Nordstrøm, C., Grøndahl, L., Søgaard, H., Friborg, T., Christensen, T.R., Ström, L., Marchand, F., and Nijs, I. (2008). High-Arctic soil CO_2 and CH_4 production controlled by temperature, water, freezing, and snow. In Meltofte, H., Christensen, T.R., Elberling, B., Forchhamer, M.C., and Rasch, M. (Eds.). *Advances in ecological research: High-Arctic ecosystem dynamics in a changing climate* (Vol. 40, 441-472). Oxford: Elsevier.

Environment and Climate Change Canada. (2016). *Canadian Environmental Sustainability Indicators: Extent of Canada's Wetlands*. Retrieved April 30, 2017 from http://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=en&n=69E2D25B-1.

Euskirchen, E.S., Bret-Harte, M.S., Shaver, G.R., Edgar, C.W., and Romanovsky, V.E. (2016). Long-term release of carbon dioxide from Arctic tundra ecosystems in Alaska. *Ecosystems*: 1-15. doi: 10.1007/s10021-016-0085-9.

Fortier, D., Allard, M., and Shur, Y. (2007). Observations of rapid drainage system development by thermal erosion of ice wedges on Bylot Island, Canadian Arctic Archipelago. *Permafrost and Periglacial Processes*, *18*: 229-243.

Gebauer, R.L.E., Reynolds, J.F., and Tenhunen, J.D. (1995). Growth and allocation of the Arctic sedges *Eriophorum angustifolium* and *E. vaginatum*: effects of variable soil oxygen and nutrient availability. *Oecologia*, *104*: 330-339.

Giblin, A.E., Nadelhoffer, K.J. Shaver, G.R., Laundre, J.A., and McKerrow, A.J. (1991). Biogeochemical diversity along a riverside toposequence in Arctic Alaska. *Ecological Monographs*, *61*(4): 415-435.

Gorham, E. (1991). Northern peatlands: role in the carbon cycle and probably response to climatic warming. *Ecological Applications*, *1*(2): 182-195.

Gough, L. and Hobbie, S.E. (2003). Responses of moist non-acidic Arctic tundra to altered environment: productivity, biomass, and species richness. *OIKOS*, *103*(1): 204-216.

Gregory, F.M. (2011). Biophysical remote sensing and terrestrial CO_2 exchange at Cape Bounty, Melville Island. Master's thesis. Retrieved from Queen's Theses & Dissertations. (http://hdl.handle.net/1974/6953).

Griffith, D.A. (2014). Nitrogen fixation by the cyanobacterium *Nostoc punctiforme* in response to variation in nitrogen availability, temperature, and atmospheric CO_2 concentrations. Electronic Thesis and Dissertation Repository. Paper 2309.

Grogan, P. and Chapin, F.S. III. (2000). Initial effects of experimental warming on above- and belowground component of net ecosystem CO_2 exchange in arctic tundra. *Oecologia, 125*: 512-520. doi: 10.1007/s004420000490

Grogan, P. and Jonasson, S. (2005). Temperature and substrate controls on intra-annual variation in ecosystem respiration in two subarctic vegetation types. *Global Change Biology, 11*: 465-475. doi: 10.1111/j.1365-2486.2005.00912.x.

Grosse, G., Romanovsky, V.E., Jorgenson, T., Anthony, K.W., Brown, J., and Overduin, P.P. (2011). Vulnerability and feedbacks of permafrost to climate change. *Eos, 92*(9): 73–80.

Guicharnaud, R., Arnalds, O., and Paton, G.I. (2010). Short term changes of microbial processes in Icelandic soils to increasing temperatures. *Biogeosciences, 7*: 671-682.

Gunther, A.J. (1989). Nitrogen fixation by lichens in a subarctic Alaskan watershed. *The Bryologist, 92*: 202-208.

Henry, G.H.R. (1998). Environmental influences on the structure of sedge meadows in the Canadian High Arctic. *Plant Ecology, 134*: 119-129.

Henry, G.H.R., Svoboda, J., and Freedman, B. (1990). Standing crop and net production of ungrazed sedge meadows of a polar desert oasis. *Canadian Journal of Botany, 68*: 2660-2667.

Hill, G.B. and Henry, G.H.R. (2011). Responses of High Arctic wet sedge tundra to climate warming since 1980. *Global Change Biology, 17*: 276-287.

Hobbie, S.E. and Chapin, F.S. III. (1996). Regulation of tundra litter carbon and nitrogen dynamics. *Biogeochemistry, 35*(2): 327-338.

Hodgson, D.A., Vincent, J.S., and Fyles, J.G. (1984). *Quaternary Geology of Central Melville Island, Northwest Territories.* Ottawa: Geological Survey of Canada, Paper 83-16.

Hodson, A.J., Mumford, P.N., Kohler, J., and Wynn, P.M. (2005). The high Arctic glacial ecosystem: new insights from nutrient budgets. *Biogeochemistry, 72*: 233-256.

Intergovernmental Panel on Climate Change [IPCC]. (2013). *The Physical Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

Isaksen, K., Benestad, R.E., Harris, C., and Sollid, J.L. (2007). Recent extreme near-surface permafrost temperatures on Svalbard in relation to future climate scenarios. *Geophysical Research Letters*, *34*. doi: 10.1029/2007GL031002.

Janssen, B.H. (1996). Nitrogen mineralization in relation to C:N ratio and decomposability of organic materials. *Plant and Soil, 181*: 39-45.

Jasrotia, P. and McSwiney, C. (2009). *Ion Exchange Resin Strips to Estimate Nitrogen Availability*. Retrieved June 9, 2016 from http://lter.kbs.msu.edu/protocols/105.

Johnson, L.C., Shaver, G.R., Cades, D.H., Rastetter, E., Nadelhoffer, K., Giblin, A.E., Laundre, J., and Stanley, A. (2000). Plant carbon-nutrient interactions control CO_2 exchange in Alaskan wet sedge tundra ecosystems. *Ecology, 81*(2): 453-469.

Jonasson, S. and Shaver, G.R. (1999). Within-stand nutrient cycling in Arctic and boreal wetlands. *Ecology, 80*(7): 2139-2150.

Jones, A., Stolbovoy, V., Tarnocai, C., Broll, G., Spargaren, O., and Montanarella, L. (Eds.). (2010). *Soil atlas of the northern circumpolar region*. Luxembourg: European Commission.

Jorgenson, M.T., Shur, Y.L., and Pullman, E.R. (2006). Abrupt increase in permafrost degradation in Arctic Alaska. *Geophysical Research Letters, 33*. doi: 10.1029/2005GL024960.

Kahn, B. (2016). The world passes 400 ppm threshold. Permanently. *Climate Central*. Retrieved March 20, 2017 from http://www.climatecentral.org/news/world-passes-400-ppm-threshold-permanently-20738.

Laerd Statistics. (2013). Mixed ANOVA using SPSS Statistics. Retrieved from https://statistics.laerd.com/spss-tutorials/mixed-anova-using-spss-statistics.php

Lafleur, P.M., Humphreys, E.R., St. Louis, V.L., Myklebust, M.C., Papakyriakou, T., Poissant, L., Barker, J., Pilote, M., and Swystun, K.A. (2012). Variation in peak growing season net ecosystem production across the Canadian Arctic. *Environmental Science and Technology*, *46*: 7971–7977.

Lafrenière, M.J., Laurin, E., and Lamoureux, S.F. (2013). The impact of snow accumulation on the active layer thermal regime in High Arctic soils. *Vadose Zone Journal, 12*: 1-13. doi: 10.2136/vzj2012.0058.

Lagerström, A., Nilsson, M.C., Zackrisson, O., and Wardle, D.A. (2007). Ecosystem input of nitrogen through biological fixation in feather mosses during ecosystem retrogression. *Functional Ecology, 21*: 1027-1033

Lajtha, K. (1988). The use of ion-exchange resin bags for measuring nutrient availability in an arid ecosystem. *Plant and Soil, 105*(1): 105-111.

Lamoureux, S.F. and Lafrenière, M.J. (2009). Fluvial impact of extensive active layer detachments, Cape Bounty, Melville Island, Canada. *Arctic, Antarctic, and Alpine Research, 41*(1): 59-68.

Larose, C., Dommergue, A., and Vogel, T.M. (2013). Microbial nitrogen cycling in Arctic snopacks. *Environmental Research Letters, 8*: 1-9.

Lavoie, M., Mack, M.C., and Schuur, E.A.G. (2011). Effects of elevation nitrogen and temperature on carbon and nitrogen dynamics in Alaskan Arctic and boreal soils. *Journal of Geophysical Research, 116*, G03013.

Lennihan, R., Chapin, D.M., and Dickson, L.G. (1994). Nitrogen fixation and photosynthesis in High Arctic forms of *Nostoc commune*. *Canadian Journal of Botany, 72*: 940-945.

Leppänen, S.M., Rissanen, A.J., and Tiirola, M. (2015). Nitrogen fixation in Sphagnum mosses is affected by moss species and water table level. *Plant Soil, 389*: 185-196. doi: 10.1007/s11104-014-2356-6.

Luce, S.J. (2016). Spatial and temporal patterns of biophysical variables and their influence on CO_2 flux in a High Arctic wetland. Master's thesis. Retrieved from Ryerson University Digital Repository.

Mack, M.C., Schuur, E.A.G., Shaver, G.R., and Chapin, F.S. III. (2004). Ecosystem carbon storage in Arctic tundra reduced by long-term nutrient fertilization. *Nature, 431*: 440-443. doi:10.1038/nature02887.

Maxwell, S.E. and Delaney, H.D. (2004). *Designing experiments and analyzing data: A model comparison perspective (2nd ed)*. New York, NY: Psychology Press.

McGuire, A.D., Christensen, T.R., Hayes, D., Heroult, A., Euskirchen, E., Kimball, J.S., Koven, C., Lafleur, P.M., Miller, P.A., Oechel, W., Peylin, P., Williams, M., and Yi, Y. (2012). An assessment of the carbon balance of Arctic tundra: comparisons among observations, process models, and atmospheric inversions. *Biogeosciences, 9*(8): 3185-3204.

Mellinger, M.V. and McNaughton, S.J. (1975). Structure and function of successional vascular plant communities in Central New York. *Ecological Monographs, 45*: 161-182.

Mikan, C.J., Schimel, J.P., and Doyle, A.P. (2002). Temperature controls of microbial respiration in Arctic tundra soils above and below freezing. *Soil Biology and Biochemistry, 34*: 1785-1795.

Milligan, P. (2010). PRS-Probe: Not Just a Soil Test. *Grainews*. Retrieved May 20, 2016 from http://www.grainews.ca/2010/03/08/prsprobe-not-just-a-soil-test/.

Nadelhoffer, K.J., Giblin, A.E., Shaver, G.R., and Laundre, J.A. (1991). Effects of temperature and substrate quality on element mineralization in 6 Arctic soils. *Ecology, 72*: 242-253.

Nadelhoffer, K.J., Giblin, A.E., Shaver, G.R., and Linkins, A.E. (1992). Microbial processes and plant nutrient availability in arctic soils. In Chapin, F.S. III, Jefferies, R.L., Reynold, J.F., Shaver, G.R., and Svoboda, J. (Eds.). *Arctic ecosystems in a changing climate, an ecophysiological perspective*. San Diego: Academic Press. pp. 281-300

Natali, S.M., Schuur, E.A.G., Trucco, C., Hicks Pries, C.E., Crummer, K.G., and Baron Lopez, A.F. (2011). Effects of experimental warming of air, soil, and permafrost on carbon balance in Alaskan tundra. *Global Change Biology, 17*: 1394-1407. doi: 10.1111/j.1365-2486.2010.02303.x.

National Atmospheric Deposition Program [NADP]. (2002). *National Atmospheric Deposition Program 2001 Summary, NADP Report*. Champaign, IL: Illinois State Water Survey.

National Aeronautics and Space Administration [NASA]. (2017). NOAA/NASA Annual Global Analysis for 2016 – 2016 was third successive record-warm year [Powerpoint slides]. Retrieved from https://www.giss.nasa.gov/research/news/20170118/NOAA-NASA_Global_Analysis-2016-FINAL.pdf.

National Oceanic and Atmospheric Administration [NOAA]. (2015). National Ocean Service. Retrieved September 20, 2016 from http://oceanservice.noaa.gov/facts/remotesensing.html.

National Wetlands Working Group. (1988). *Wetlands of Canada, Volume 24*. Montreal: Environment Canada and Polysciences Publications Inc., Ecological Land Classification Series.

Newbold, J.D., Elwood, J.W., O'Neill, R.V., and Van Winkle, W. (1981). Measuring nutrient spiraling in streams. *Canadian Journal of Fisheries and Aquatic Science, 38*: 860-863.

Nobrega, S. and Grogan, P. (2008) Landscape and ecosystem-level controls on net carbon dioxide exchange along a natural moisture gradient in Canadian Low Arctic tundra. *Ecosystems, 11*: 377-396. doi: 10.1007/s10021-008-9128-1.

Oberbauer, S.F., Hastings, S.J., Beyers, J.L., and Oechel, W.C. (1989). Comparative effects of downslope water and nutrient movement on plant nutrition, photosynthesis, and growth in Alaskan tundra. *Holarctic Ecology, 12*: 324-334.

Oechel, W.C., Hastings, S.J., Vourlitis, G., Jenkins, M., Riechers, G., and Grulke, N. (1993). Recent change of arctic tundra ecosystems from a net carbon dioxide sink to a source. *Nature, 361*: 520-523.

Pansu, M. and Gautheyrou, J. (2006). *Handbook of Soil Analysis: Mineralogical, Organic and Inorganic Methods*. Springer: Berlin/Heidelberg, Germany.

Post, W.M., Emmanuel, W.R., Zinke, P.J. Strangenburger, A.G. (1982). Soil carbon pools and world life zones. *Nature, 298*: 156-159.

Qian, P. and Schoenau, J.J. (2005). Use of ion-exchange membrane to assess nitrogen-supply power of soils. *Journal of Plant Nutrition, 28*: 2193-2200.

Ramsay, G. (2015). Spatial and temporal modelling of biophysical variables within a High Arctic wetland. Master's thesis. Retrieved from Ryerson University Digital Repository.

Rastetter, E.B., Kwiatkowski, B.L., Le Dizès, S., and Hobbie, J.E. (2004). The role of down-slope water and nutrient fluxes in the response of Arctic hill slopes to climate change. *Biogeochemistry, 69*: 37-62.

Reynolds, J.F. and Tenhunen, J.D. (1996). *Landscape function and disturbance in Arctic tundra*. Berlin: Springer.

Robinson, C.H. and Wookey, P.A. (1997). Microbial ecology, decomposition, and nutrient cycling. In Woodin, S.J. and Marquiss, M. (Eds.). *Ecology of Arctic Environments* (41-67). Oxford: Blackwell.

Robinson, C.H. (2002). Controls on decomposition and soil nitrogen availability at high latitudes. *Plant and Soil, 242*(1): 65-81.

Rustad, L.E., Campbell, J.L., Marion, G.M., Norby, R.J., Mitchell, M.J., Hartley, A.E., Cornelissen, J.H.C., Gurevitch, J. (2000). A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. *Oecologia, 126*: 543-562. doi: 10.1007/s004420000544.

Schmidt, I.K., Michelsen, A., and Jonasson, S. (1997). Effect on plant production after addition of labile carbon to Arctic/alpine soils. *Oecologia, 112*: 305-313.

Schmidt, I.K., Jonasson, S., and Michelsen, A. (1999). Mineralization and microbial immobilization of N and P in Arctic soils in relation to season, temperature, and nutrient amendment. *Applied Soil Ecology, 11*: 147-160.

Schmidt, I.K., Jonasson, S., Shaver, G.R., Michelsen, A., and Nordin, A. (2002). Mineralization and distribution of nutrients in plants and microbes in four Arctic ecosystems: responses to warming. *Plant and Soil, 242*(1): 93-106.

Schmidt, S.K. and Lipson, D.A. (2004). Microbial growth under the snow: Implications for nutrient and allelochemical availability in temperature soils. *Plant and Soil, 259*: 1-7.

Schuur, E.A.G., Vogel, J., Crummer, K., Lee, H., Sickman, J., and Osterkamp, T. (2009) The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. *Nature*, *459*: 556-559.

Shaver, G.R., Billings, W.D., Chapin, F.S. III, Giblin, A.E., Nadelhoffer, K.J., Oechel, W.C., and Rastetter, E.B. (1992). Global change and the carbon balance of Arctic ecosystems. *Bioscience, 42*: 433-441

Shaver, G.R., Canadell, J., Chapin, F.S. III, Gurevitch, J., Harte, J., Henry, G.H.R., Ineson, P., Jonasson, S., Mellilo, J., Pitelka, L., and Rustad, L.E. (2000). Global warming and terrestrial ecosystems: A conceptual framework for analysis. *BioScience, 50*(10): 871-882.

Shaver, G.R., and Chapin, F.S. III. (1991). Production: biomass relationships and element cycling in contrasting Arctic vegetation types. *Ecological Monographs, 61*(1): 1-31.

Shaver, G.R., and Chapin, F.S. III. (1995). Long-term responses to factorial, NPK fertilizer treatment by Alaskan wet and moist tundra sedge species. *Ecography, 18*(3): 259-275.

Siska, P.P. and Hung, I-K. (2001). Assessment of Kriging Accuracy in the GIS Environment. Faculty Presentations. Paper 7. In 21st Annual ESRI International Conference, San Diego, CA.

Skrzypek, G., Wojtuń, B., Richter, D., Jakubas, D., Wojczulanis-Jakubas, K., and Samecka-Cymerman, A. (2015). Diversity of nitrogen sources in various tundra vegetation types in the High Arctic. *PLoS One, 10*(9).

Stark, S. (2007). Nutrient cycling in the tundra. In Marschner, P. and Rengel, Z. (Eds.), *Soil biology: Nutrient cycling in terrestrial ecosystems* (Vol. 10, 309-331). Berlin: Springer.

Stewart, K.J., Brummel, M.E., Coxson, D.S., and Siciliano, S.D. (2012). How is nitrogen fixation in the High Arctic linked to greenhouse gas emissions? *Plant and Soil, 362*(1): 215-229. doi: 10.1007/s11104-012-1282-8.

Stewart, K.J., Grogan, P., Coxson, D.S., and Siciliano, S.D. (2014). Topography as a key factor driving atmospheric nitrogen exchanges in Arctic terrestrial ecosystems. *Soil Biology and Biochemistry, 70*: 96-112. doi: 10.1016/j.soilbio.2013.12.005.

Stocker, T.F., Qin, D., Plattner, G.-K., Alexander, L.V., Allen, S.K., Bindoff, N.L., Bréon, F.-M., Church, J.A., Cubasch, U., Emori, S., Forster, P., Friedlingstein, P., Gillett, N., Gregory, J.M., Hartmann, D.L., Jansen, E., Kirtman, B., Knutti, R., Krishna Kumar, K., Lemke, P., Marotzke, J., Masson-Delmotte, V., Meehl, G.A., Mokhov, I.I., Piao, S., Ramaswamy, V., Randall, D., Rhein, M., Rojas, M., Sabine, C., Shindell, D., Talley, L.D., Vaughan, D.G., and Xie, S.-P. (2013). 2013: Technical Summary. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report* *of the Intergovernmental Panel on Climate Change*. Cambridge, U.K. and New York, NY: Cambridge University Press.

Sullivan, P.F., Arens, S.J.T., Chimner, R.A., and Welker, J.M. (2008). Temperature and microtopography interact to control carbon cycling in a High Arctic fen. *Ecosystems, 11*: 61-76.

Tarnocai, C., Canadell, J.G., Schuur, E.A.G., Kuhry, P., Mazhitova, G., and Zimov, S. (2009). Soil organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochemical Cycles, 23*. doi:10.1029/2008GB003327.

Thompson, D.K. and Woo, M.K. (2009). Seasonal hydrochemistry of a High Arctic wetland complex. *Hydrological Processes, 23*: 1397-1407. doi: 10.1002/hyp.7271.

Tilman, D. (1982). *Resource competition and community structure*. Princeton University Press, Princeton, New Jersey: Princeton University Press.

United States Environmental Protection Agency [US EPA]. (2017). *Understanding global warming potentials*. Retrieved April 30, 2017 from https://www.epa.gov/ghgemissions/understanding-global-warming-potentials.

Van Cleve, K. and Alexander, V. (1981). Nitrogen cycling in tundra and boreal systems. In Clark, F.E. and Rosswall, T. (Eds.), *Terrestrial nitrogen cycles* (Vol. 33, 375-404). Stockholm: Ecological Bulletins.

Verhoeven, J.T.A., Maltby, E., and Schmitz, M.B. (1990). Nitrogen and phosphorus mineralization in fens and bogs. *Journal of Ecology, 78*: 713-726.

Voigt, C., Lamprecht, R.E., Marushchak, M.E., Lind, S.E., Novakovskiy, A., Aurela, M., Martikainen, P.J., and Biasi, C. (2016). Warming of subarctic tundra increases emissions of all three important greenhouse gases – carbon dioxide, methane, and nitrous oxide. *Global Change Biology, 22*(12). doi: 10.1111/gcb.13563.

Walker, D.A., Raynolds, M.K., Daniels, F.J.A., Einarsson, E., Elvebakk, A., Gould, W.A., Katenin, A.E., Kholod, S.S., Markon, C.J., Melnikov, E.S., Moskalenko, N.G., Talbot, S.S., Yurtsev, B.A., Bliss, L.C., Edlund, S.A., Zoltai, S.C., Wilhelm, M., Bay, C., Gudjónsson, G., Moskalenko, N.G., Ananjeva, G.V., Drozdov, D.S., Konchenko, L.A., Korostelev, Y.V., Melnikov, E.S., Ponomareva, O.E., Matveyeva, N.V., Safranova, I.N., Shelkunova, R., Polezhaev, A.N., Johansen, B.E., Maier, H.A., Murray, D.F., Fleming, M.D., Trahan, N.G., Charron, T.M., Lauritzen, S.M., and Vairin, B.A. (2005). The circumpolar Arctic vegetation map. *Journal of Vegetation Science, 16*: 267–282.

Welker, J.M., Fahnestock, J.T., Henry, G.H.R., O'Dea, K.W., and Chimners. R.A. (2004). CO_2 exchange in three Canadian High Arctic ecosystems: Response to long-term experimental warming. *Global Change Biology, 10*(12): 1981-1995.

Weller, G., Chapin, F.S., Everett, K.R., Hobbie, J.E., Kane, D., Oechel, W.C., Ping, C.L., Reeburgh, W.S., Walker, D., and Walsh, J. (1995). The Arctic flux study: a regional view of trace gas release. *Journal of Biogeography, 22*: 365-374.

Western Ag. (2012). *PRS Technology*. Retrieved June 8, 2016 from https://www.westernag.ca/innovations/technology/basics.

Woo, M.K. (2011). Northern wetlands. In: Woo, M.K. (Ed). *Permafrost Hydrology*. Berlin: Springer-Verlag Berlin Heidelberg.

Woo, M.K. and Young, K.L. (2006). High Arctic wetlands: their occurrence, hydrological characteristics and sustainability. *Journal of Hydrology*, *320*(3-4): 432-450. doi: 10.1016/j.jhydrol.2005.07.025.

Woo, M.K. and Young, K.L. (2012). Wetlands of the Canadian Arctic. In: Bengtsson, L., Herschy, R.W., and Fairbridge, R.W. (Eds.). *Encyclopedia of Lakes and Reservoirs*. Dordrecht, Netherlands: Springer Netherlands.

Woo, M.K. and Young, K.L. (2014). Disappearance of semi-permanent snow in the High Arctic and its consequences. *Journal of Glaciology*, *60*(219): 192-200. doi: 10.3189/2014JoG13J150.

Woo, M.K., Young, K.L., and Brown, L. (2013). High Arctic patchy wetlands: *Hydrologic* variability and their sustainability. *Physical Geography*, *27*(4): 297-307.

Woodin, S.J. (1997). Effects of acid deposition on arctic vegetation. In: Wooding, S.J. and Marquiss, M. (Eds.). *Ecology of Arctic Environments*. Oxford: Blackwell Science.

Yang, Z., Ouyang, H., Zhang, X., Xu, X., Zhou, X., and Yang, W. (2011). Spatial variability of soil moisture at typical alpine meadow and steppe sites in the Qinghai-Tibetan Plateau permafrost region. *Environmental Earth Sciences*, *63*:477-488.

Young, K.L. (2006). Assessment of snow storage and ground ice melt in High Arctic environments. *Hydrological Processes, 20*: 2643-2645. doi: 10.1002/hyp.6348.

Zoltai, S.C. and Martikainen, P.J. (1996). The role of forested peatlands in the global carbon cycle. *NATO ASI Ser I, 40*: 47-58.