SPATIAL AND TEMPORAL PATTERNS OF BIOPHYSICAL VARIABLES AND THEIR INFLUENCE ON CO_2 FLUX IN A HIGH ARCTIC WETLAND

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Abstract

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Arctic wetlands have been globally important carbon reservoirs throughout the past but climate change is threatening to shift their status to carbon sources. Increasing Arctic temperatures are depleting perennial snowpacks these wetlands depend upon as their hydrological inputs which is altering their environmental conditions and carbon cycles. The objective of this study is to investigate how the physical conditions of Arctic wetlands will be altered by climate change and what influence these changes will have on CO_2 exchange. High spatial and temporal resolution biophysical data from a high Arctic wetland, collected over the growing season of 2015, was used for this analysis. The results from this study indicate that the wetland is at risk of thawing and drying out under a warmer climate regime. CO_2 emissions were found to increase most significantly with increased air temperatures, while CO_2 uptake increased with increases in solar radiation and soil moisture. Combined, these results suggest that CO_2 production in the soil will increase while CO_2 uptake will decrease in Arctic wetlands as climate change continues.

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:

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The candidate is the primary author of the thesis and manuscript. Author 1 is the candidate's supervisor who contributed to the experimental design development, assisted with the collection of data, and provided guidance on the method of analysis. Author 1 also reviewed and edited the manuscript.

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List of Abbreviations

AL	Active Layer
ANOVA	Analysis of Variance
AT	Air Temperature
CB	Cape Bounty
CBAWO	Cape Bounty Arctic Watershed Observatory
ER	Ecosystem Respiration
GEP	Gross Ecosystem Productivity
GHG	Greenhouse Gas
GPS	Global Positioning System
IPCC	Intergovernmental Panel on Climate Change
MET	Meteorological
MLR	Multiple Linear Regression
NEE	Net Ecosystem Exchange
PAR	Photosynthetic Active Radiation
PVC	Percent Vegetation Cover
SEE	Standard Error of the Estimate
SM	Soil Moisture
SR	Solar Radiation
ST	Soil Temperature

1. Introduction

The effects of climate change have been most drastic in the Arctic (Chapin et al., 1995; Weller et al., 1995; Overpeck et al., 1997; Crowley, 2011) and are occurring earlier than projections predicted (Crowley, 2011). The average Arctic temperatures have increased at nearly double the rate of the average global temperature rise over the last 100 years (Crowley, 2011). A continual Arctic-wide warming trend has been observed since the mid-1960s and the upper layer of permafrost has increased in temperature by 3°C since the 1980s (Crowley, 2011). Along with warming surface temperatures, the 2013 Intergovernmental Panel on Climate Change (IPCC) report predicts that there will be increased summertime precipitation in the form of rainfall in the Arctic (Intergovernmental Panel on Climate Change (IPCC), 2013). These impacts have been found to be altering the composition of vegetation and the hydrological cycle in the Arctic, as well as reducing the snow cover duration and degrading permafrost (McEwing et al., 2015). These alterations then affect the conditions within Arctic ecosystems, including such factors as the percent vegetation cover (PVC), biomass, soil organic matter content, nutrient availability, soil moisture (SM), and active layer (AL) depth (Atkinson and Treitz, 2013). Ecosystems can vary vastly in size, but are generally regarded as areas with similar organisms, vegetation, and soil (British Columbia Ministry of Forests, Lands and Natural Resource Operations, n.d.). The AL is the thawed layer of soil between the soil surface and the permafrost, the term for soil with perennial temperatures below 0°C (Knoblauch et al., 2013). These parameters potentially influence the ecosystem respiration (ER), gross ecosystem production (GEP), and thus the net ecosystem exchange (NEE) of an ecosystem (Atkinson and Treitz, 2013). ER is the rate of release of carbon dioxide (CO_2) from soil and plant respiration, along with any other respiration occurring in the ecosystem. GEP is the rate of CO_2 uptake in an ecosystem by its producers through photosynthesis. NEE is the net CO_2 exchange between the ecosystem and the atmosphere after the ER and GEP have been accounted for (Atkinson, 2012), where in this report a positive NEE indicates a net flux of CO_2 from the ecosystem to the atmosphere and a negative NEE indicates a net uptake of CO_2 from the atmosphere to the ecosystem. Affecting these variables can change an ecosystem that was once a carbon sink, like the Arctic (Olivas, 2010), to a carbon source (Billings et al., 1982; Welker et al., 2004; Ellis and Rochefort, 2006; Atkinson and Treitz, 2013). The emission of methane (CH_4), a greenhouse gas (GHG), has also been found to be positively influenced by temperature, SM, and AL depth (Vourlitis et al., 1993; Knoblauch et al., 2013; McEwing et al., 2015). Moreover, some studies suggest that another GHG, nitrous oxide (N_2O), also undergoes greater production and release from Arctic tundra as air temperatures (ATs) rise and SMs increase (Wagner et al., n.d; Callaghan et al., 2011). The influences of climate change on the carbon exchange in the Arctic are of high importance as they may create a positive feedback system if ER and other GHG emissions exceed carbon uptake, further amplifying the rate of global warming by increasing the GHGs in the atmosphere (Christensen et al., 2000; IPCC, 2013; Knoblauch et al., 2013; McEwing et al., 2015).

High Arctic wetlands play a significant role in the Arctic's carbon cycle due to their cold and saturated soil conditions which are highly suitable for storing large amounts of carbon (Christensen et al, 2000; Ellis and Rochefort, 2006; Sullivan et al., 2008). Climate change, however, has been found to be causing the depletion of perennial or late lying (melt completely during the summer) snowpacks that these wetlands depend on for their soil water throughout the growing season (Callaghan et al., 2011; Knoblauch et al., 2013). This may be altering the environmental conditions of these wetlands, including their SM, soil temperature (ST), and AL depth, which have been shown to influence the flux of GHGs like CO_2 from wetland soils

(Sullivan et al., 2008; Callaghan et al., 2011; Atkinson and Treitz, 2013; McEwing et al., 2015). Thus, climate change is threatening to shift Arctic wetlands from a significant carbon sink to a source of GHGs.

Previous Arctic GHG flux studies have had sampling regimes with high temporal resolution and limited spatial replicates within a study area (Nobrega and Grogan, 2008; Sachs et al., 2010; McEwing et al., 2015), which has not allowed for the spatial patterns and variability of GHG flux within individual ecosystems to be analyzed. This has potentially caused the spatial variability of GHG flux to be missed, possibly causing error when using the data to estimate total GHG emissions from these ecosystems (Olivas, 2010; Sachs et al., 2010; McEwing et al., 2015). In order to develop a greater understanding of the environmental controls on GHG flux, specifically CO_2, their fine scale spatial variability and patterns need to be studied which requires a higher spatial resolution of data (Sullivan et al., 2008; McEwing et al., 2015). This study aims to achieve a high spatial resolution of CO_2 flux data within a high Arctic wet sedge meadow, a type of wetland that is an important carbon sink (Ellis and Rochefort, 2006; Sullivan et al., 2008). The purpose of this study is to investigate how CO_2 flux in wet sedge meadows is related to their abiotic conditions, including SM, ST, and AL depth. It is vital to understand the relationships between Arctic wetlands' abiotic conditions and their carbon cycles in order to predict how these ecosystems and their carbon stocks will be affected by climate change. For instance, the wet sedge in this study, located at the Cape Bounty Arctic Watershed Observatory (CBAWO) on Melville Island, Nunavut, receives meltwater from a perennial snowpack which has been shrinking over the years (Atkinson, 2012). Understanding the spatial variability within this vegetated community will help to predict how this particular ecosystem and its carbon flux will be affected by the disappearing snowpack. The research questions this study addresses are:

What are the spatial and temporal patterns of CO_2 flux in this particular wet sedge meadow over its growing season? What are the spatial patterns of the wet sedge's abiotic conditions SM, ST, and AL depth? What are the potential influences of these abiotic factors, along with weather conditions on CO_2 flux in the wet sedge? Using these observations how might the predicted environmental changes due to global warming in the Arctic affect CO_2 flux in Arctic wet sedge meadows? Will this contribute to a positive or negative feedback system on climate change?

To answer these research questions the following five hypothesis were formed and tested. The results will be presented and discussed in Chapter 3 with a larger discussion on how the results connect to the broader research questions in Chapter 4.

Hypothesis 1: ST and AL depth will increase with AT over the growing season.

Hypothesis 1 is formed off the assumption that the wet sedge's soils will respond to warming ATs in the growing season by increasing in ST which then would increase thawing (Chapin et al., 1995; Beamish et al., 2011; Ramsay et al., 2015). Subsequently, the ST will likely decrease as the ATs cool at the end of the growing season resulting in refreezing of the soil as temperatures near 0°C (Ramsay et al., 2015). Chapin et al. (1995), Beamish et al. (2011), and Ramsay et al. (2015) tested for correlations between ST and AT in their Arctic soil studies and all found a positive correlation. Therefore, the temporal pattern of ST and AL is expected to generally follow that of AT.

H2: SM will remain near saturation and be stable over the growing season from receiving meltwater from a perennial snowpack, and have an E-W trend of decreasing SM.

Ramsay et al. (2015) found in 2014 there was minimal temporal variability in SM in the same wetland as this study, observed from mid-June to the end of July which was attributed to a continuous influx of meltwater from the perennial snowpack. Even as the AL thickened over the 2014 growing season, the constant hydrological input from the snowpack was assumed to be the reason the SM values did not fluctuate (Ramsay et al., 2015). When Ramsay et al. looked at the spatial variability of SM in the wet sedge, some areas underwent a change in SM while others remained steady. This observation strengthens the need for a high resolution of spatial data in order to understand the temporal changes in Arctic ecosystems. On the whole, the wet sedge also appeared to have an E/W trend of decreasing SM present throughout the 2014 sample season, with the strength of the trend varying with time (Ramsay et al., 2015). As these trends were observed in the same wet sedge a year before the data collection for this study took place, it is assumed the temporal and spatial SM trends will be the same.

H3: Areas with highest SM contents will coincide with areas of shallower AL depths.

Since moisture in the soil increases the amount of energy required to warm and in turn thaw the soil (Ramsay et al., 2015), it is expected that areas with drier soils will generally have deeper ALs. Olivas (2010) found that when soil from an Arctic wet sedge underwent both warming and drying thawing of the soil increased. This was also found in Ramsay et al.'s study (2015), in which the areas with the deepest ALs had the lowest SM contents in the wet sedge. It was deemed possible that the reason for this finding was that the AL thickened to a depth that soil saturation was unachievable from the hydrological input of the snowpack (Ramsay et al., 2015).

H4: ER and GEP will follow similar temporal trends over the growing season.

Previous studies focused on Arctic wetlands have found temporal fluctuations in GEP over the growing season to be in phase with fluctuations in ER of a different magnitude.

Overall, GEP and ER have displayed similar temporal trends in the past (Christensen et al., 2000; Boelman et al., 2003; Vourlitis et al., 2003) with greatest variability observed at the beginning and end of the growing season when temperature changes were greatest (Atkinson, 2012). The relatively simultaneous, seasonal variations of ER and GEP result in minimal temporal variation of NEE observed in these studies (Boelman et al., 2003; Vourlitis et al., 2003). This suggests that ER and GEP are influenced by some of the same environmental variables. Vourlitis et al. (2003) suggest these environmental variables are the biophysical traits of an ecosystem that increase GEP, like specific leaf area, which also have "large autotrophic respiratory costs" that increase ER. Moreover, several previous, related studies found some environmental variables to correlate with both ER and GEP (Christensen et al., 2000; Boelman et al., 2003; Fisher et al. 2009; Olivas, 2010), such as Christensen et al.'s (2000) study on two high Arctic wetlands which observed AT and thaw depth, and in some locations water table depth, to correlate positively with both photosynthesis and ER. Boelman et al. (2003) suggest some reasons for similar ER and GEP trends could be that during peak growing season, the majority of ER is from plant respiration as compared to microbial respiration, coinciding with the highest rates of photosynthesis. In addition, greater plant biomass produces more organic matter for microbial respiration, therefore causing ER to increase as GEP increases from greater photosynthesis (Boelman et al., 2003). The findings in these studies are the basis of the formation of Hypothesis 4. However, this is not to assume that GEP and ER will be compensatory of one another, as small differences in their magnitudes can result in large temporal and spatial variation of NEE (Vourlitis et al., 2003) which can have global effects on the carbon system.

H5: CO_2 production (ER) will increase with AT, ST, AL depth, and lower SM.

If these small differences in NEE are created by ER overcompensating GEP, carbon is being lost from the tundra and adding to the GHG's in the atmosphere. In the past the Arctic has been a significant carbon sink from undergoing greater carbon uptake and storage than carbon release, but with the changing climate this is being threatened (Billings et al., 1982; Welker et al., 2004; Ellis and Rochefort, 2006; Atkinson and Treitz, 2013; McEwing et al., 2015). Therefore, it is crucial to understand what environmental variables influence ER and what it could mean for the near future of the Arctic carbon cycle. A previous study at a similar ecosystem in the CBAWO found ER to be positively correlated with both ST and AT (Wagner et al., n.d.). The correlation with AT, however, was much stronger than the correlation with ST (Wagner et al., n.d.). Christensen et al. (2000) also found ER had a stronger correlation with AT than with ST when studying a high Arctic wet sedge and noted this agreed with other high Arctic wetland studies. Beamish et al. (2011) looked at a range of disturbed sites in the CBAWO and found CO_2 flux to be influenced by both ST and SM and even more so by their interaction. Several studies had the same observation as Beamish et al. (2011) in that ST and SM had a combined effect on CO_2 flux in Arctic ecosystems (Billings et al., 1982; Weller et al., 1995; Sullivan et al., 2008; Olivas, 2010). These studies found that warming in combination with soil drying magnified the influence on ER as opposed to just warming or drying alone (Billings et al., 1982; Weller et al., 1995; Sullivan et al., 2008; Olivas, 2010). When saturated, warmer soils could store more carbon than less saturated soils at the same temperature, whereas at cooler temperatures the SM did not have an observable impact on carbon storage (Billings et al., 1982). Multiple studies attribute the reason for greater ER with soil drying to the increased soil aeration causing more aerobic root and microbial respiration to occur (Weller et al., 1995; Welker et al., 2004; Ellis and Rochefort, 2006). Fewer studies discussed the connection between the depth of the AL and CO_2 flux, but an increase in CO_2 ER from a reduced water table may be an indirect effect of increased soil thaw. As the depth to the permafrost increases, more soil water drainage can occur which can lower the water table. Christensen et al. (2000), found a significant positive correlation between thaw depth and ER when looking at two high Arctic wetlands. Ellis and Rochefort (2006) suggest that a deeper AL in combination with a lowered water table could enhance aerobic soil decomposition and thus ER. However, if a wetland has a steady hydrological input that is strong enough to maintain saturation while the AL thickens (Ramsay et al., 2015), the AL may have less or no effect on ER. This may be the reason that Wagner et al.'s study (n.d.) found a correlation between CO_2 flux and AL depth in the mid moisture (MM) site and not the wet sedge site studied. Perhaps the wet sedge's water table was not affected by soil thawing in this case.

Although the majority of studies predicted/observed an increase in ER with decreasing SM, there were some opposing findings at the CBAWO. Wagner et al. (n.d.) did not find a significant correlation between ER and SM when looking at CO_2 flux at a polar desert (PD), mid-moisture (MM), and wet sedge ecosystems, yet did find that the wet sedge site had the highest ER when conditions where warm and sunny in CB. Fisher et al. (2009), who also looked at a PD, MM, and wet sedge ecosystem in the CBAWO, found a positive correlation between CO_2 production and SM. The conflicting reports from these studies emphasizes the need for a greater spatial resolution of data within ecosystems to be used so more confident predictions on how environmental conditions like SM affect ER can be made. Ultimately, Hypothesis 5 was formed using the findings that were most common among these previous, similar studies in that AT, ST, and AL all have positive correlations with ER while SM's correlation with ER is negative.

2. Literature Review

2.1 Environmental Change in the Arctic

Climate change is increasing Arctic temperatures at a greater rate than the rest of the world (Sullivan et al, 2008; Atkinson and Treitz, 2013; Knoblauch et al., 2013). The effects of climate change have already been felt across the globe, but nowhere have these effects been as pronounced as they have been in the Arctic (Billings et al., 1982; Chapin et al., 1995; Weller et al., 1995; Overpeck et al., 1997; Sullivan et al., 2008; Knoblauch et al., 2013). In 1995 Chapin et al. anticipated that climate change would increase Arctic air and soil temperatures, quicken the rate of nutrient release from organic matter decomposition in the soil, and melt the sea ice which would result in greater "summer cloudiness" from increased ocean evaporation. Other environmental changes being caused by rising Arctic temperatures are variable changes to vegetative biomass, thawing permafrost, reduced snow accumulation, and changes to the hydrological regime (Chapin et al., 1995; Harding et al., 2001; Callaghan et al., 2011). The IPCC stated in their 2013 report that Arctic sea ice area and thickness, the global volume of glaciers, and spring snow cover in the northern hemisphere will "very likely" decrease in the 21st century with climate change. A thickening AL and thus thinning permafrost was also reported in the 2013 IPCC report.

Permafrost is the earth material that remains below 0°C year round and has an overlying thawed soil layer in the summer often referred to as the "active layer" for its facilitation of vegetation growth (Knoblauch et al., 2013). Around one quarter of the northern hemisphere's land surface consists of permafrost (Knoblauch et al., 2013), yet the areal extent of the permafrost is shrinking and its southern boundary is increasing in latitude (IPCC, 2013). Moreover, the extent of near-surface permafrost is "virtually certain" by the IPCC (2013) to decrease with increasing surface temperatures as the AL has a high sensitivity to the surface energy balance, requiring little energy addition for greater thaw (Weller et al., 1995). Weller et al. approximated in 1995 that the AL at Toolik Lake in northeast Alaska would double in depth with a 4°C increase of the average annual temperature. Increased thawing of permafrost can have impacts on the Arctic's hydrology, ecology, transportation, construction, and exchange of trace gases like CO_2 and CH_4 (Overpeck et al., 1997). The latter may be very problematic due to the vast amounts of carbon permafrost holds (Wagner et al., 2007; Olivas, 2010; IPCC, 2013) from the Arctic's severe climate limiting organism carbon decomposition in the soil more greatly than its limit on net primary production throughout the past (Wagner et al., 2007). The permafrost's organic matter consists of accumulated plant remains that have remained frozen and unable to be mineralized over the years (Knoblauch et al., 2013). Warmer soils and thawed permafrost will enhance the decay of organic matter which in turn increases CO_2 and CH_4 emissions from the soil (Vourlitis et al., 1993; Christensen et al., 2000; Wagner et al., 2007; Knoblauch et al., 2013). Other environmental factors that are connected to permafrost, like SM, also influence the organic matter decay and ecosystem productivity beyond the AL depth (Wagner et al., 2007; Knoblauch et al., 2013). Permafrost has a direct effect on soil hydrology by impeding drainage and movement of soil water, therefore increasing saturation (Harding et al., 2001; Yang et al., 2001; Olivas, 2010; Knoblauch et al., 2013) along with runoff on the soil surface (Olivas, 2010). Shallow permafrost depths can be favourable to plants as it keeps soil water within reach of their roots (Olivas, 2010). Saturated soils create anaerobic conditions which largely inhibit organic matter mineralization in the soil therefore limiting CO_2 production, yet CH_4 production favours anaerobic soils (Harding et al., 2001; Knoblauch et al., 2013). How soil hydrology, vegetation, and trace gas flux will be impacted by the degradation of permafrost is still uncertain and reliant on other various environmental factors (Harding et al., 2001; Wagner et al., 2007; Olivas, 2010).

The increased temperatures in many Arctic regions have been most profound in the spring when conditions such as snow melt can be influenced by small alterations to the surface energy balance (Weller et al., 1995). This is expected to cause an earlier snowmelt and in turn reduce snow cover duration by around 10-20% in many areas in the Arctic (Callaghan et al., 2011). A shortened duration of snow cover also means a shortened period for snow accumulation (Callaghan et al, 2011). Moreover, although snow accumulation may decrease, the area of snow cover over the land is expected to expand (Callaghan et al., 2011). This would increase the potential for evaporation and sublimation of snow by increasing snow surface exposure in conjunction with higher ATs resulting in more energy being available for these processes (Déry and Yau, 2002; Callaghan et al., 2011). Sublimation is the transformation of ice or snow directly to water vapour and can occur from the ice or snow surface or when being transported as blowing snow (Déry and Yau, 2002; Callaghan et al., 2011). The main factors sublimation is dependent on are AT, wind speed, and relative humidity (Déry and Yau, 2002). An earlier snowmelt with less snow accumulation and greater evaporation and sublimation will affect the Arctic's hydrological regimes, an example being the alteration of long term and seasonal water and ice storage (Callaghan et al., 2011). The hydrological regime could also gain new sources of water from thawing permafrost, although little is known about this potential effect. Moreover, "late-lying and semi-permanent snowbanks will shrink or disappear from the Arctic landscape" (Callaghan et al., 2011). Many wetlands in the Arctic depend on these snowbanks, in this report used interchangeably with "snowpacks", for their soil water throughout the growing season to keep them near saturation. Depletion of wetlands' hydrological inputs will cause these ecosystems to deteriorate with the risk of deteriorating entirely (Callaghan et al., 2011).

2.2 Positive versus Negative Feedback Systems

It is still unknown whether global warming will generate a positive or negative feedback system in the Arctic from its effects on the Arctic's soil carbon and trace gas fluxes. The conditions of the Arctic tundra have been generally cold and anaerobic throughout the past, allowing it to act as a carbon sink from limiting decomposition in its soils (Harding et al, 2001; Knoblauch et al., 2013). Studies have shown the potential for trace gas fluxes to either increase or decrease in Arctic ecosystems as a result of climate change (Christensen, 1999; Harding et al., 2001; Welker et al., 2004; Ellis and Rochefort, 2006; Sullivan et al., 2008; Knoblauch et al., 2013). Higher temperatures in the Arctic may deepen the soil AL and increase microbial degradation, which would release carbon from the soil and permafrost to the atmosphere in the form of CO_2 and CH_4. This is how a positive feedback system to global warming could be created (Oechel et al., 1995; Weller et al., 1995; Boelman et al., 2003; Knoblauch et al., 2013). However, the thawing of the permafrost could also increase water and nutrient movement, enhancing both soil decomposition and mineralization. This could result in greater nutrient availability and primary productivity in the soil, which would require the uptake of carbon from the atmosphere, potentially offsetting the carbon emissions and creating a negative feedback system (Oechel et al., 1995; Welker et al., 2004). Moreover, a warming Arctic climate could also extend the growing season, further increasing biomass production and thus CO_2 uptake (Knoblauch et al., 2013). Yet an increase in vegetation coverage from greater soil fertility would reduce the surface albedo of the previously bare tundra thereby increasing surface energy absorption which is another contributor to the greenhouse effect (Welker et al., 2004). Climate change's effects on the Arctic may also increase the emissions of one trace gas but decrease the emissions of another. For example, if the soil warms and dries in its upper layers, aerobic microbial decomposition would increase from the greater oxygen availability in the soil, which produces CO_2 emissions but can decrease CH_4 production. If the soil warms and becomes saturated on the other hand, CH_4 production would increase and CO_2 production would be inhibited (Harazono et al., 2006; Olivas, 2010). Thus, more research is needed to understand how the carbon budget in the Arctic is correlated to environmental factors.

2.3 The Importance of Arctic Wetlands

Arctic wetlands have been globally important carbon reservoirs since the last ice age (Christensen et al., 2000; Ellis and Rochefort, 2006; Sullivan et al., 2008; Preuss et al., 2013), covering a significant portion of the Earth's surface and thus play a fundamental role in the Earth's climate system by regulating the carbon flux between the land and atmosphere (Ellis and Rochefort, 2006; Sullivan et al., 2008). Roughly 44% of the Earth's wetlands are located at high northern latitudes that make them susceptible to permafrost and permafrost-controlled hydrology (Melton et al., 2013). Wetlands cover 3.4% (48,877 km^2) of Canada's northern Arctic land area (Environment and Climate Change Canada, 2016). However, these wetlands contain a larger, disproportionate amount of the Arctic's terrestrial carbon (Melton et al., 2013) and 14% of the global terrestrial carbon is stored in Arctic tundra ecosystems (Boelman et al., 2003). In 1993, Vourlitis et al. stated that wet Arctic tundra ecosystems were gaining around 30 Tg of carbon per year and contain 1.3×10^4 Tg (24%) of carbon out of the 5.4×10^4 Tg of carbon stored in the Arctic. Of this carbon, 92% is in the form of dead organic matter within the upper permafrost and soil AL (Vourlitis et al., 1993). The cold and saturated soils in Arctic wetlands create a plant production rate greater than a soil decomposition rate which has caused these vast stocks of soil carbon within them. When plant productivity, the production of biomass in an ecosystem, increases, more photosynthesis occurs, requiring the uptake of CO_2 from the atmosphere. Soil decomposition is the breakdown of the dead biomass or organic matter that contains the carbon in the soil and releases CO_2 in the process. Hence, when plant productivity is greater than soil decomposition the ecosystem is a net carbon sink, like these wetlands (Sullivan et al., 2008). However, the saturated conditions in Arctic wetlands are favoured by anaerobic processes that produce CH_4, causing them to be a substantial source of atmospheric CH_4 (Vourlitis et al., 1993; Christensen et al., 2000; Harding et al., 2001; Wagner et al., 2007; Preuss et al., 2013). Methane is GHG with a potency at least 23 times greater than CO_2 (Harazono et al., 2006), further emphasizing Arctic wetlands' importance in the global carbon cycle.

High Arctic wetlands specifically may have greater sensitivity to climate change due to their colder climates limiting the length of their growing seasons compared to more southern wetlands (Sullivan et al., 2008), yet high Arctic wetlands are less studied (Christensen et al., 2000; Sullivan et al., 2008). The warming Arctic ATs may differently impact the uptake and release of carbon in high Arctic wetlands compared to more southern wetlands, and could potentially turn them from significant carbon sinks to carbon sources. This could create a positive feedback system to the greenhouse effect, further accelerating the rate of climate change (Christensen et al., 2000; Ellis and Rochefort, 2006; Sullivan et al., 2008). To illustrate this potential cycle, the emissions of GHGs to the atmosphere from humans burning fossil fuels are enhancing the greenhouse effect, which is altering Arctic environmental conditions that may then increase the GHGs being released from Arctic wetlands. This would then further increase the concentration of GHGs in the atmosphere, amplifying the greenhouse effect. An amplified greenhouse effect would cause Arctic ATs to rise even more, causing the cycle to repeat by further altering Arctic wetland conditions. These feedbacks would have consequences significant at the global scale - not only in the Arctic (IPCC, 2007). However, there are multiple possible outcomes of climate change's effects on Arctic wetlands carbon cycles, as CO_2 and CH_4 may respond differently to changes in environmental conditions (Vourlitis et al., 1993; Harding et al., 2001). For instance, deeper ALs, warmer STs, and lower SMs could reduce CH_4 emissions but increase CO_2 emissions (Vourlitis et al, 1993). The extent of the change in each GHG must be understood to learn the risk of these carbon sinks turning into carbon sources. The findings thus far on changing conditions in Arctic wetlands' effect on their carbon cycles will be further discussed in the upcoming sections.

2.4. Environmental Controls of the Carbon Cycle

In 1995, Weller et al. predicted that future changes to the Arctic's trace gas fluxes will be attributed to both physical changes to the environment, including hydrology and climate, as well as modifications to biological systems. Here Weller et al. (1995) emphasized the need for consideration of both when studying trace gas flux from the Arctic. Sullivan et al. (2008) found that their study agreed with several other studies performed shortly before theirs on the influence microtopography has on the carbon balance of Arctic wetlands, and how the potential alteration of the carbon balance from climate change is an indication of the "complex interplay among climate forcing, biota, hydrology, and permafrost". Microtopography is the topographic variability of the soil surface at a spatial scale that can range in elevation from as small as one centimeter up to one meter (Moser et al., 2007). The link between climate change and its effects on the microtopography of Arctic wetlands is demonstrated by the degradation of permafrost and its impacts on an Arctic wetland's vegetation and microtopography. Permafrost degradation in a subarctic wetland increased its areal coverage of hollows, which caused greater CO_2 uptake but more significantly raised its CH_4 emissions, cumulatively making the wetland a GHG source (Sullivan et al., 2008). Furthermore, several studies have found the carbon cycling in Arctic wetlands to be influenced by the level of the water table in the soil (Billing et al., 1982; Weller et al., 1995; Welker et al., 2004; Sullivan et al., 2008). Lowering water tables and higher evapotranspiration rates from rising ATs result in larger quantities of drier soils, and drier soils have been found to increase aerobic root and microbial respiration (Weller et al., 1995; Welker et al., 2004; Sullivan et al., 2008). A second mechanism suggested to contribute to a decrease in the net carbon storage of Arctic ecosystems would be higher microbial respiration without a relative increase in photosynthesis at the end of the growing season as the warmer period extends into periods with shorter daylight hours (Welker et al., 2004). In short, ER rates have been suggested to increase with the rising Arctic temperatures but photosynthesis rates may not, ultimately decreasing the net carbon uptake and storage in Arctic wetlands (Welker et al., 2004). However, in 1995 Weller et al. suggested that the drying of the AL from climate change in the Arctic may initially result in higher carbon losses from the soil, but in the long term the net carbon storage could increase from more carbon being stored "above-ground" due to the invasion of new vegetation species like trees and shrubs. The timeframe in which this is perceived to occur is not specified.

The findings from the aforementioned studies make it clear that the indirect effects of rising Arctic ATs need to be studied in order to determine the impacts on the carbon cycle in Arctic ecosystems (Chapin et al., 1995; Weller et al., 1995; Welker et al., 2004; Sullivan et al., 2008). This was the conclusion of many of these studies, including Chapin et al.'s study in 1995 which treated soil cores from an Arctic wetland in a controlled laboratory and found "the effects of [their] temperature treatment and natural climatic warming are complicated by increases in

ST, thaw depth, and nutrient availability, and a decline in irradiance, and should not, therefore, be considered the result of simple changes in air temperature". Furthermore, individual types of tundra and ecosystems need to be studied as varying soil water regimes make it challenging to generalize the high Arctic's response to warming ATs (Welker et al., 2004). Finally, these indirect effects of a warming climate can differently impact CO_2 and CH_4 flux. The findings up to date regarding the environmental influences of CO_2 and CH_4 are focused on separately in the following sections.

2.4.1 Environmental Controls of CO_2

In the high Arctic wet tundra sites Welker et al. (2004) studied in 2001, an overall increase in NEE due to long-term warming was observed, which resulted in an 18% increase of growing season NEE. Between 80-85% of this variance in NEE was found to be explainable by both gravimetric soil water content and thaw depth (Welker et al., 2004). In Christensen et al.'s (2000) high Arctic fen study, ER was found to be positively influenced by AT as well as thaw depth, ST, and depth to the water table. Photosynthesis in the same fen was found to be positively correlated with the same environmental variables (Christensen et al., 2000). Expectedly from these observations, ER and GEP had similar temporal patterns over the growing season, with photosynthesis having greater variation (Christensen et al., 2000). Christensen et al. (2000) also concluded that the correlation of thaw depth and water table depth was likely stronger with ER than with photosynthesis, and in the peak growing season these correlations with photosynthesis were likely confounded by greater plant biomass. Furthermore, Sullivan et al. (2008) studied a high Arctic wetland which they found to have a very sensitive CO_2 flux to temperature changes, suggesting that high Arctic wetlands will be more sensitive to temperature changes than low Arctic wetlands will be since they have experienced a more limited temperature range in the past. Looking at the more specific environmental influences on CO_2 exchange, Welker et al. (2004) found that NEE was largely influenced by SM and permafrost thaw depth in high Arctic dry, mesic, and wet tundra sites. Knoblauch et al. supported this relationship in a statement from their 2013 study that claimed landscapes experiencing "deeper permafrost thawing" are releasing more CO_2. Knoblauch et al. (2013) also found, however, that the production of CO_2 is substantially reduced in anaerobic conditions.

Back in 1982 Billings et al. took frozen turf and soil cores from a wet coastal tundra site in Northern Alaska and measured their CO_2 fluxes in an environmentally controlled experimental system. The vegetation of the site the cores were extracted from was dominated by grasses and sedges (Billings et al., 1982). From this experiment a strong relationship between the depth of the water table and AT on the soil cores' CO_2 exchange with the atmosphere was found. The depth of the water table had a greater influence on carbon storage when temperatures were higher. When the soil core was saturated and the system was set to 8°C there was a considerably higher amount of net carbon storage in the soil compared to when the water level was lowered 5 cm, which caused the soil to have minimal net carbon storage (Billings et al., 1982). Furthermore, the soil's net CO_2 uptake at 4°C was found to nearly double the CO_2 uptake at 8°C (Billings et al., 1982). The cores actually became CO_2 sources with higher ATs and lowered water levels, especially when the controlled system imitated the end of the growing season which had shorter daylight hours and therefore less photosynthesis but continued microbial respiration (Billings et al., 1982). This finding supports Welker et al.'s (2004) hypothesis that warmer temperatures remaining into periods with less daylight could cause ER to overcome GEP and therefore create a carbon source. At lower temperatures, however, the difference in water table level had little effect on the CO_2 flux and the soil cores remained CO_2 sinks (Billings et al., 1982).

2.4.2 Environmental Controls of CH_4

Although CO_2 is the only trace gas being studied in this thesis, the environmental variables that affect all trace gas fluxes are analyzed and therefore predictions can be made for how they will affect CH_4 and N_2O flux using observed correlations from past studies. McEwing et al. (2015) found that CH_4 emissions were greatest at the wettest sites when looking at a mixture of wet sedge and tussock tundra ecosystems. Knoblauch et al. (2013) found sites with anaerobic conditions, which implies wetter sites, are substantial sources of CH_4 to the atmosphere. Vourlitis et al. (1993) found that CH_4 efflux was a function of thaw depth and maximum SM in wet tundra ecosystems. Since thaw depth is both a result of SM and temperature, ST is also a control of CH_4 flux (Vourlitis et al., 1993). The study then indicated that CH_4 efflux increases with the thickening of the soil AL as anaerobic microorganisms have been shown to be distributed throughout the AL. Warmer temperatures at greater soil depths increases the productivity of these microorganisms, causing CH_4 production to increase (Vourlitis et al., 1993). The influence of thawing permafrost and SM on CH_4 production and emissions is further supported in Knoblauch et al.'s 2013 study which found that in the Holocene and late Pleistocene, methanogenic communities positively responded to warmer and wetter time periods. Wagner et al. (2007) emphasized the importance of ST in the regulation of microorganism activity, and found that microbial CH_4 production rises substantially with small ST increases. Microbial CH_4 production is also termed methanogenesis and is the final step in the "anaerobic decomposition of organic matter" (Wagner et al., 2007; Preuss et al., 2013). The reduction in CH_4 production from decreased SM or water table levels is due to microbial CH_4

oxidation, which has been stated as the "key process" lowering wetlands' CH_4 emissions (Preuss et al., 2013). Wagner et al. (2007) also attributes CH_4 emissions to permafrost degradation, which greatly enlarges the CH_4 deposits available for methanogenic activity.

Knoblauch et al.'s study on the long term effects of permafrost degradation on trace gas production (2013) found that it took over a year for the highest CH_4 production rate to be established after long-term incubation began. This was attributed to the potential lower amounts of methanogens initially in the permafrost that increased with deeper permafrost thawing (Knoblauch et al., 2013). The minor production rates of CH_4 that persisted over a year were accompanied by more significant CO_2 production rates, which Knoblauch et al. (2013) recognized as meaning methanogenis is of less importance than CO_2 production from thawing permafrost.

A study performed by Christensen et al. (2000) on trace gas flux variation in high Arctic wetlands contradicts several of the findings of these other studies, reporting no significant correlation between CH_4 emissions and thaw depth or ST. This study found that water table position had the strongest influence on CH_4 exchange in the majority of the study areas where the water table was not near the soil surface. In areas where the soil was permanently saturated or the water table was near the surface, CH_4 production's correlation to water table position was much less significant (Christensen et al., 2000). A different observation from this study, which may not have been tested in the other studies, was the positive correlation between photosynthesis and CH_4 production. Photosynthesis was found to be the strongest controlling factor of CH_4 production in the saturated sites. There was also a significant correlation between NEE and CH_4 emissions since NEE and photosynthesis were strongly related, with about 80% of CH_4's production variance explained by NEE variations (Christensen et al., 2000). Christensen et al. (2000) did note, however, that the environmental factors that influence photosynthesis and NEE, such as thaw depth and temperature, must be considered. The correlation between photosynthesis, NEE and CH_4 exchange may actually be an indirect effect from the variation in these environmental factors (Christensen et al., 2000). These correlations with environmental variables were found in another one of Christensen's study (Friborg et al., 2000) where ST, thaw depth, and water table position were the greatest explainers of CH_4 production's daily variability.

2.4.3 Environmental Controls of N_2O

Relatively little research on N_2O flux from high Arctic ecosystems has been performed as of yet, but Callaghan et al. mentioned in their 2011 study that emissions of N_2O are positively influenced by the extent of waterlogged soils, suggesting that if the soils in the Arctic tundra become more saturated, the release of N_2O will potentially rise. This agrees with the finding of a study on trace gas flux in three types of vegetated communities at the CBAWO on Melville Island, the same area where my research is being performed. This study looked at PD, MM tundra, and wet sedge meadow ecosystems, which have dry, semi-wet, and wet soil conditions in that order. It was found that both N_2O and CH_4 emissions were greatest at the wet sedge meadow, and thus was likely positively influenced by higher SMs (Wagner et al., n.d.). Additionally, N_2O production and release were also observed to increase with warmer ATs (Wagner et al., n.d.).

Buckeridge et al. (2010), in contradiction to the aforementioned studies, found SM and ST were not important controls of N_2O production and consumption in their mesic tundra study area in the low Arctic. N_2O production was found to have a high spatial variability that was positively correlated to inorganic nitrogen (N) availability in the soil (Buckeridge et al., 2010). The areas found with increased N_2O production and greater inorganic N availability were areas where N had been added in the two summers previous to the study (Buckeridge et al., 2010). Other than in areas where N additions had been substantial, N_2O flux was very low throughout the study site (Buckeridge et al., 2010).

2.5 Spatial Analyses

Biophysical variables from SM to ER can be spatially and temporally variable within ecosystems such as wetlands (Petrone et al., 2004; Olivas, 2010; Yang et al., 2011). It has proven important for studies focusing on biophysical variables within an environment to use a high resolution of both spatial and temporal data in order for the variability to be characterised accurately (Olivas, 2010; Sachs et al., 2010; Yang et al., 2011; McEwing et al., 2015). Petrone et al. (2004) has emphasized that the density of data within a grid is more significant than the extent of data coverage when looking to understand the spatial distribution of environmental factors like SM. If the variability of ecosystem parameters are not understood at a range of scales, the derived results of a study may be highly uncertain and misleading (Petrone et al., 2004; Yang et al., 2011). As the spatial and temporal variability of biophysical variables are typically attributed to controlling factors like microtopography and weather, studying these variabilities at the fine scale is vital for understanding the correlations between biophysical variables and other environmental factors (Petrone et al., 2004).

A useful and well-practiced method of assessing spatial variability of biophysical variables within an ecosystem or region is spatial interpolation using geostatistics (Siska and Hung, 2001; Childs, 2004; Lin et al., 2006; Yang et al., 2011). Spatially interpolating data transforms the data from point form into a continuous surface over the study area (Siska and Hung, 2001). Performing spatial interpolation of data using a geostatistical method allows spatial variability to be quantified and characterized and the interpolated values' variances to be estimated (Yang et al., 2011). Geostatistical is one of the two interpolation technique categories (Childs, 2004), the other one being deterministic. Both interpolation techniques are "based on the principle of spatial autocorrelation or spatial dependence, which measures degree of relationship/dependence between near and distant objects" (Childs, 2004). The interrelatedness of values is determined through spatial autocorrelation, which then allows spatial patterns to be determined. Deterministic interpolation uses mathematical formulas and measured points such as the Inverse Distance Weighted (IDW) method. The IDW predicts values at locations not sampled using surrounding data, the weight of which they are used dependant on their distance from the unknown point. Geostatistical interpolation, on the other hand, is a more advanced spatial modelling method that is based on statistics and measures the certainty of its predicted values (Childs, 2004). A commonly used geostatistical interpolation method for studies looking at spatial patterns of environmental parameters within ecosystems or regions is "kriging" (Siska and Hung, 2001; Childs, 2004; Lin et al., 2006; Yang et al., 2011; Ramsay et al., 2015). Kriging is considered an unbiased interpolation method with the least estimation variance (Siska and Hung, 2001; Yang et al., 2011), that is best used when directional bias or a spatially correlated distance is known within the data (Childs, 2004). Once the spatial interpolations of the unmeasured locations have been performed using kriging, a cross validation analysis provides the accuracy of the interpolated model to the real data (Yang et al., 2011). Cross validation does so by individually removing the measured locations from the data and estimating their values using kriging, then comparing the measured values to the kriged values (Yang et al., 2011).

3. Spatial and Temporal Patterns of Biophysical Variables and Their Influence on CO_2 Flux in a High Arctic Wetland

3.1 Abstract

Arctic wetlands have been globally important carbon reservoirs throughout the past but climate change is threatening to shift their status to carbon sources. Increasing Arctic temperatures are depleting perennial snowpacks these wetlands depend upon as their hydrological inputs which is altering their environmental conditions and carbon cycles. The objective of this study is to investigate how the physical conditions of Arctic wetlands will be altered by climate change and what influence these changes will have on CO_2 exchange. High spatial and temporal resolution biophysical data from a high Arctic wetland, collected over the growing season of 2015, was used for this analysis. The results from this study indicate that the wetland is at risk of thawing and drying out under a warmer climate regime. CO_2 emissions were found to increase most significantly with increased air temperatures, while CO_2 uptake increased with increases in solar radiation and soil moisture. Combined, these results suggest that CO_2 production in the soil will increase while CO_2 uptake will decrease in Arctic wetlands as climate change continues.

3.2 Introduction

Climate change has increased mean Arctic temperatures at nearly twice the rate it has raised the mean global surface temperature (Chapin et al., 1995; Sullivan et al., 2008; Crowley, 2011; Knoblauch et al., 2013). Warming Arctic temperatures have already been causing numerous environmental impacts, including increased permafrost thaw, less snow accumulation, and changes to vegetation and the Arctic's hydrological regime (Chapin et al., 1995; Harding et al., 2001; Callaghan et al., 2011). Precipitation in the Arctic is predicted to increase in the form of rainfall (IPCC, 2013) while snow accumulation is in decline (Callaghan et al., 2011). A major impact of concern is permafrost degradation as permafrost lies beneath one quarter of the northern hemisphere's land surface (Knoblauch et al., 2013), but this coverage is shrinking with climate change (IPCC, 2013). Permafrost degradation is of major importance as permafrost holds significant amounts of carbon (Wagner et al., 2007; Olivas, 2010; IPCC, 2013) thereby connecting it to the exchange of trace gases in Arctic ecosystems (Overpeck et al., 1997) This carbon is at risk of being released from the thawing permafrost due to increased Arctic temperatures (Wagner et al., 2007; Sullivan et al., 2008; Knoblauch et al., 2013) which threatens to create a positive feedback effect to climate change (Weller et al., 1995). In addition to influencing the Arctic's carbon storage, degrading permafrost has also had impacts on northern construction, transportation, ecology, and hydrology (Overpeck et al., 1997).

Permafrost has an important role in the hydrological regime of Arctic ecosystems which is putting these ecosystems at risk as permafrost degrades (Overpeck et al., 1997; Harding et al., 2001; Yang et al., 2001; Olivas, 2010; Knoblauch et al., 2013). The hydrological regime is also being threatened by reductions in snow cover duration (Weller et al., 1995; Callaghan et al., 2011) which may cause the depletion of snowpacks in the Arctic (Callaghan et al., 2011). Important ecosystems in the carbon cycle such as wetlands rely upon snowpacks as their hydrological input (Callaghan et al., 2011; Ramsay et al., 2015). Altering these hydrological inputs will likely cause these ecosystems to deteriorate (Callaghan et al., 2011; Ramsay et al., 2015).

The cold and saturated soils of Arctic wetlands make them extensive reservoirs of carbon, as such they play an essential role in the carbon budget of the Arctic and the globe (Vourlitis et al., 1993; Ellis and Rochefort, 2006; Sullivan et al., 2008). Wetlands in the high Arctic may have a greater sensitivity to climate change from experiencing colder climates and having limited growing seasons compared to more southern wetlands (Sullivan et al., 2008). Thus, high Arctic wetlands are at risk of converting to carbon sources from warmer temperatures and deeper ALs increasing respiration of CO_2 (Christensen et al., 2000; Ellis and Rochefort, 2006; Sullivan et al., 2008). However, wetlands in the high Arctic have had little research performed on them and their carbon fluxes (Christensen et al., 2000; Sullivan et al., 2008).

Studies performed on Arctic wetlands in the past have found that Arctic warming is causing warmer and drier soils due to increased evapotranspiration and lower water tables from deeper permafrost thawing (Billings et al., 1982; Weller et al., 1995; Welker et al., 2004; Sullivan et al., 2008). In turn, drier and warmer soils have been suggested to increase microbial and root respiration, causing greater CO_2 emissions (Weller et al., 1995; Christensen et al., 2000; Welker et al., 2004; Ellis and Rochefort, 2006; Sullivan et al., 2008; Knoblauch et al., 2013). However, an extended growing season could also increase photosynthesis and therefore CO_2 uptake (Knoblauch et al., 2013). Hence, more research is required to predict the future state of these carbon reservoirs.

In the past, studies have generally had low spatial resolution of data while focusing on temporal patterns, representing whole ecosystems with only a few spatial data points (Sachs et al., 2010; McEwing et al., 2015). Using only a few spatial replicates of data at the plot scale risks variability within individual ecosystems to be missed, which can cause inaccurate projections of trace gas fluxes and other biophysical variables' responses to varying conditions in these ecosystems (Olivas, 2010; Sachs et al., 2010; McEwing et al., 2015). Related studies referred to in this paper have used between 3-12 data points to represent carbon flux from various types of Arctic ecosystems (Wagner et al., n.d.; Christensen et al., 2000; Fisher et al., 2009; Olivas, 2010). To better predict how sensitive ecosystems like wetlands in the high Arctic are going to respond to climate change, it is crucial to understand both the spatial and temporal variability of their biophysical traits. With this knowledge, more accurate predictions of responses like CO_2 exchange in these ecosystems can be made.

The purpose of this study is to use a high spatial resolution of biophysical sampling to assess the spatial variability and trends of a high Arctic wetland's conditions, as well as the influence these conditions have on CO_2 flux. The aim of this research is to provide a clearer portrayal of these significant carbon sinks' environmental conditions over a growing season, such as SM and AL depth, and a more accurate estimate of the effect increasing Arctic surface temperatures will have on their carbon exchange. To do so, a high density of data was collected within a high Arctic wet sedge over its growing season, located at the Cape Bounty Arctic Watershed Observatory (CBAWO) on Melville Island, Nunavut. The influence the abiotic factors of the wet sedge and weather have on CO_2 flux was estimated using a combination of temporal, spatial, and statistical analysis. This analysis aims to address the following research questions: What are the spatial and temporal patterns of the biophysical variables in this particular high Arctic wet sedge meadow? Are the spatial and temporal variabilities of these variables statistically significant? What abiotic factors influence CO_2 flux in this wet sedge and what could this mean regarding future effects of climate change on the carbon cycle in Arctic wetlands?

3.3 Method

3.3.1 Study Area

The research for this study was conducted at the Cape Bounty Arctic Watershed Observatory (CBAWO) located on the uninhabited Melville Island which is located in both the

Northwest Territories and Nunavut. Melville Island is considered to be in the high Arctic with a latitude of 74°55′N and a longitude of 109°35′W (Atkinson and Treitz, 2013). The CBAWO is located on the south-central coast of the Nunavut side of Melville Island (Lamoureux et al., 2006). Research has been conducted here since 2003 to provide monitoring of the impacts of climate change on high Arctic environmental systems (Canadian Network of Northern Research Operators (CNNRO), n.d.). Two adjacent watersheds make up the CBAWO. Each watershed drains to its own, separate lake which both drain south to Viscount Melville Sound (Atkinson and Treitz, 2013). These watersheds have glacial and regressive marine sediments of the early Holocene in their surficial geology which is underlain by steeply dipping sedimentary rocks of the Devonian Weatherall and Hecla Bay Formation (Atkinson and Treitz, 2013). Permafrost is continuous throughout the area, with a maximum AL around 1 m in the melt season (Lamoureux et al., 2006). The area's vegetation cover is variable with drainage and is classified as graminoid prostrate dwarf shrub and forb tundra (Atkinson and Treitz, 2013). Cape Bounty has a cold climate and a melt season from June to August that experiences light and infrequent rainfall, low stratus clouds, and fog (Atkinson and Treitz, 2013). During the study period from June 29th to August 8th in 2015, the average temperature recorded at the CBAWO main meteorological (MET) station was 5.4°C, and reached a high of 16.2°C and a low of -1.7°C. The total precipitation during this time period was 114.4 mm with 80.8 mm occurring in July. This is considered a year of high precipitation for CB. From June 29th to August 8th of 2014, the total precipitation recorded at CB's main meteorological station was 55.4 mm, less than half of 2015's precipitation. Moreover, in Atkinson and Treitz's study during July of 2006 and 2008, 2006 had only 4.8 mm and 2008 had 27.4 mm of rain, while the growing season of 2005 only had trace precipitation (Atkinson, 2012). Melville Island does not have a federal meteorological station and there is no long-term climate record of Cape Bounty to compare this data to.

3.3.2 Study Site

This study was conducted within a 200 m by 200 m (4 ha) plot located in a wet sedge meadow (Figure 1). A wet sedge meadow is a common type of wetland found at the CBAWO, defined as a wet grassland with a low species diversity of vegetation that is typically dominated by sedge grasses and moss (The Wetlands Initiative, n.d.; Atkinson and Treitz, 2012) and has a high plant productivity compared to other ecosystems (Atkinson and Treitz, 2012). The soils of wet sedge meadows are permanently or almost permanently saturated (Nobrega and Grogan, 2008). The wet sedge is downslope of a late season snowpack which provides the meadow with meltwater during the growing season (Atkinson and Treitz, 2013). The snowpack used to be perennial but became a late season snowpack with the warming climate, meaning the snowpack melts entirely during the summer season (Atkinson, 2015). A perennial snowpack is a pile of snow that has accumulated and persists over the years (National Snow & Ice Data Center (NSIDC), n.d.). The plot dimensions and coordinates are the same as the ones used in Atkinson and Treitz's (2012, 2013) studies performed on the same wet sedge, which also align with satellite imagery taken of the plot. The plot was equally divided into four directional quadrants, NW, NE, SW, and SE, throughout which the sample sites were equally split amongst to ensure the spatial extent of the sample plot was represented in the sampling. There was a total of 24 points sampled within this plot for environmental and CO_2 measurements. The quantity of sample sites was deemed the highest amount of points which was feasible to sample given the time and resources available, including the number of personnel to help to take the samples and the amount of equipment. The locations of the sample sites were randomly stratified using a function in Microsoft Excel to prevent bias in the sampling. It is commonly recommended to use randomly stratified sample locations when performing spatial analysis (Siska and Hung, 2001). There were more points generated than the number needed for sampling so that the sample sites could be paired to provide spatial replicates of the data to minimize error. The replicates' sites in each pair were chosen to match the conditions of the original sample site and placed approximately 12 m apart. Thus, each of the four quadrants had three pairs of sample sites for CO_2 and environmental measurements. The coordinates of these sites were downloaded onto a GarminGPS map 76 which was used to locate the sites within the wet sedge.

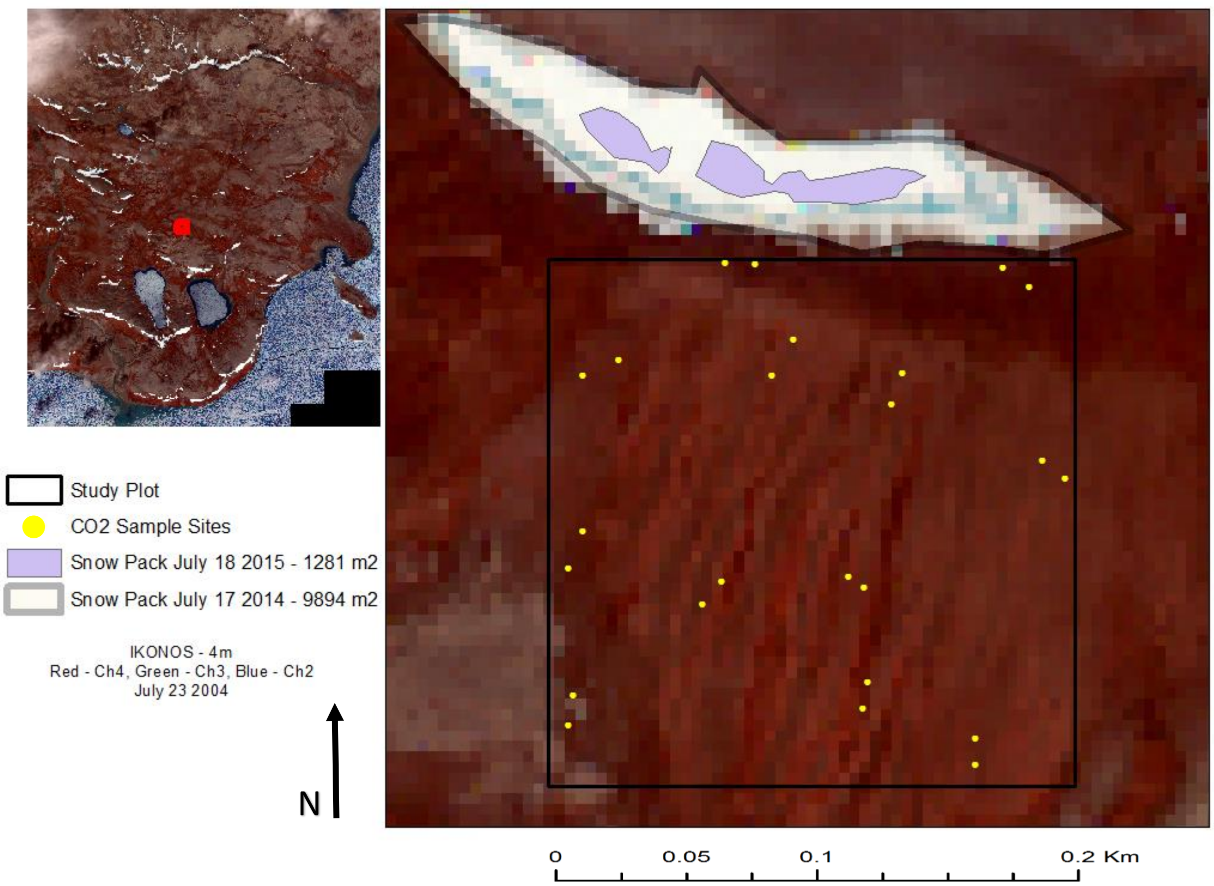

Figure 1: Left: Location of the wet sedge study site at the CBAWO, Melville Island, Nunavut. Right: Study plot outline located south of the late-lying snowpack with sample collection locations in yellow.

Sampling was conducted over a five week period during the summer of 2015, starting on July 4th and finishing on August 9th. This time period was used as it encompassed the majority of the growing season at Cape Bounty and was feasible given the funding and resources available. It also overlaps with Ramsay et al.'s (2015) study at the same wet sedge from June 19th to July 30th 2014, which also performed spatial and temporal modelling of the same biophysical variables with the exception of CO_2 flux. The sample plot was snow free when the CBAWO opened for the season on June 29th, 2015. The CBAWO was not in operation before this time so sampling was not able to take place at the beginning of the melt season in June.

3.3.3 Data Collection

CO_2 flux sampling was performed using a closed, static chamber method to measure the concentration of the gas within the chamber over time (Sachs et al., 2010; Atkinson, 2012). In general, this method uses small, portable, closed system chambers to allow the concentration of these gases to build up within them over a time interval. This allowed the flux rate of CO_2 from the wet sedge to be determined. Using closed, static chambers is a common and cost effective method for measuring gas flux from soil and allows sufficient spatial coverage for small scale studies (Sachs et al., 2010). It has been supported as the most appropriate method for collecting gas flux data at the plot scale as it has a higher likelihood of capturing peak emissions and variability within an ecosystem (Oechel et al., 1995; Weller et al., 1995; Friborg et al., 2000; Sachs et al., 2010; McEwing et al., 2015).

To use the closed chamber method, a PVC collar had to be inserted into the ground at each sample site to which the chambers could be sealed. The collars were inserted roughly 7 cm (about half their height) into the ground in order to provide a seal between the ground and atmosphere to prevent air from entering or leaving the chamber during sampling (Atkinson, 2012). A small circulation fan and pressure equalization vent were fitted to the chambers (Atkinson, 2012).

To measure NEE and ER of CO_2 flux, two transparent chambers were used, each with a Vaisala™ GMP343 (Vaisala, Vantaa, Finland) portable infrared gas analyzer (IRGA) and a Vaisala™ HMP75 relative humidity (RH) and temperature probe (Vaisala, Vantaa, Finland) (Figure 2). The IRGA and RH and temperature probe were attached to a Vaisala™ MI70 handheld data logger that recorded the concentration of CO_2, the RH, and the temperature within the chamber every 5 seconds over a 5 minute interval. NEE was measured first, then the chambers were removed and their interior allowed to return to ambient conditions. ER was then measured by placing the chambers back onto the collar and covering them with an opaque shrowd to block the sunlight and prevent photosynthesis (Figure 3). Air pressure was measured on the CO_2 sample dates using a handheld Kestrel™ weather gauge to later convert the CO_2 concentrations in the chambers in order to calculate the flux of CO_2 using a custom Matlab script. CO_2 measurements were taken during the day and approximately every 4-6 days over the sample season, depending on weather conditions to ensure personnel field safety and safe operation of equipment which were threatened by dense fog and rain. This resulted in a total of eight CO_2 sample dates by the end of the season.

Figure 2: CO_2 Flux Static Chamber Apparatus for NEE Measurements

Figure 3: CO_2 Flux Static Chamber Apparatus for ER Measurements

At the same time that CO_2 flux measurements were taken, the environmental conditions at the sample site were recorded. These included the ST, SM, and AL depth. ST was measured at 5 and 10 cm depths in the soil adjacent to the collars using a digital thermometer model 9878E from Taylor Precision Products Inc. (Ramsay et al., 2015). SM was measured at three points at 5 cm depths around each collar using a Theta probe attached to a HH2 data logger (Delta T

Devices Ltd.) (Ramsay et al., 2015). The average SM of the three measurements for each spot was used for analysis. The AL depth was measured using a stainless steel rod that was inserted into the soil until frozen ground was reached which was discernable from the excessive force required once the ice was hit. ST and SM were measured several times a week to monitor the wet sedge's temporal change. These measurements required less resources and time to measure than gas samples, which allowed them to be sampled on a more frequent basis and were taken a total of 23 times over the sampling period. As AL depth was less variable over time, it was measured one to two times per week. The hourly weather data were also collected from a MET tower located several hundred meters from the study site, which provided hourly AT, wind speed, relative humidity, air pressure, precipitation, and solar radiation (SR). The daily average AT and SR as well as the total daily precipitation over the sampling period were computed from this data.

3.3.4 Data Processing and Analysis

A custom Matlab (Matlab R2015b, MathWorks, Natick, MA, USA) script was used to convert and process the CO_2 concentration readings (ppm) at 5 second intervals over 5 minutes from the Visala GMP343 into a flux rate (μmol CO_2 m^{-2} s^{-1}). To do so, the script first used the simultaneous temperature readings along with the recorded air pressure and the volume of the chamber to convert the CO_2 concentrations into μmol m^{-2} using the Ideal Gas Law (Atkinson, 2012). The flux rate was then found using an iterative multiple regression search algorithm that found the best line of fit to the data, the slope of which was the flux rate (Atkinson, 2012). From this script the flux rate components NEE and ER were obtained from the measured data while GEP was calculated as:

$$GEP = NEE - ER$$

Temporal graphs of all biophysical variables measured were created. Spatial interpolations of the data in the wet sedge were performed using the geostatistical spatial interpolation method “kriging”. Kriging is a geostatistical analysis tool that models spatial patterns in data of a study area by interpolating the data over the area in which it was collected to estimate/predict the values at all locations within the study area. It also provides the uncertainty associated with the values it predicts (Esri, n.d.). The environmental data was averaged into 8 condensed “weeks” from July 1st to August 9th in correlation with the 8 CO_2 flux sample dates. Each “week” consisted of 5 days surrounding the CO_2 sample day with the multiple environmental measurements in each “week” averaged to portray the average conditions of the wet sedge in that “week”. This allowed the variance over time to be more clearly evaluated using statistical and spatial analysis. The weather data were not averaged over the weeks as they had greater temporal variability than the soil measurements. Thus, for each of the 8 “weeks” there were six kriged layers: NEE, ER, GEP, ST, SM, and AL depth. Before the biophysical data sets were kriged, the data were explored using geostatistical analysis including histograms and semivariograms to check for normality, autocorrelation, directional influences, underlying trends, and outliers in the data sets (Siska and Hung, 2001). Multiple kriged layers were created for each variable’s weekly dataset using the original and transformed data where normality could be improved, as well as datasets with removed underlying trends. Once complete, a cross validation was performed between the kriged layers of each data set so the most accurate spatial interpolations of the data were used for this study (Yang et al., 2011; Ramsay et al., 2015). It was found that data transformation or removal of trends did not improve the accuracy of the spatial interpolations and were not used for the final kriged layers.

3.3.5 Statistical Analysis

3.3.5.1 Temporal and Spatial Variability

To test for statistically significant variation of the environmental and biophysical variables over the sample period and within the wet sedge, a Mixed Analysis of Variance (ANOVA) was performed on the data using SPSS Version 22 (SPSS 22, IBM, Armonk, NY, USA). A Mixed ANOVA is suitable for testing data that can be split by a within subjects factor (all subjects undergo the condition, which in this case is time/"week") and a between subjects factor (subjects undergo separate conditions, in this case location/quadrant in the wet sedge) (Laerd Statistics, n.d.-a). The results of this analysis indicated whether there were statistically significant differences between the "weeks" of the sample season and/or between the quadrants of the wet sedge. It also tested whether there was an interaction effect of these two main effects, which stated whether the effect of one factor was amplified by the other factor (Laerd Statistics, n.d.-a). In this study's case this indicated whether the statistical temporal variation of each biophysical variable became more or less significant between quadrants. If the interaction of these effects were not significant, that implied that the temporal variability did not become more or less statistically significant depending on the quadrant the data was from, meaning all quadrants followed the same general temporal trends. For the within-subjects effects and interaction effects, the Greenhouse-Geisser correction was used as sphericity of the within-subjects data was not assumed (Laerd Statistics, n.d.-b).

Once it was determined whether there were statistically significant variations over the weeks and/or between the quadrants, a Tukey Honest Significant Difference (HSD) post-hoc test was used to learn the specific weeks and/or quadrants between which there were significant differences (Beamish et al., 2011; Atkinson, 2012). Before any statistical analyses were performed, all data was tested for normality in SPSS using the Shapiro-wilk test which was deemed most suitable for the size of the data sets (Laerd Statistics, n.d.-c) and transformed when it improved normality.

3.3.5.2 Environmental Influences on CO_2 Flux

Beyond visual inspection of temporal graphs and spatial interpolations of the data, a stepwise multiple linear regression (MLR) was used to test the data for statistically significant influences of environmental variables on CO_2 flux. The influence of ST, SM, AL depth, AT, and SR were tested for NEE, GEP, and ER using the MLR. The MLR analysis regressed the dependent variable (CO_2 flux) on the predictor variables (environmental) to model their relationships (Laerd Statistics, n.d.-d; Christensen et al., 2000; Atkinson, 2012). The results of this analysis provided an estimate of the percent of variance in CO_2 flux that one or more of the environmental variables could account for, denoted by the R^2 value. The coefficient of the outputted models indicated whether the influence of the environmental variable(s) on CO_2 flux were positive or negative (Laerd Statistics, n.d.-d).

The averaged "weekly" data of ST, SM, and AL depth were used in the MLR analysis with their corresponding CO_2 samples. Regarding the weather data, the average AT and SR of the sampling duration on the date of each CO_2 measurement was used since AT and SR were much more variable temporally than the soil conditions, which agreed with the data alignment in similar, previous studies (Beamish et al., 2011; Atkinson, 2012). The sample point "pairs" intended as spatial replicates (explained in Section 3.3.2) were averaged together for each week. This resulted in 12 data points per variable per week being used in the MLR for a total of 96 points per variable. The quadrant averages of each variable per week were used in the MLR afterwards to compare if this decrease in spatial data resolution (4 points per variable per week) altered the MLR results or strengthened them.

3.4 Results

3.4.1 Temporal Variation

3.4.1.1 Temporal Variation of Environmental Variables

The average ST of the quadrants and the entirety of the wet sedge followed the same trend as the average daily AT (Figure 4 and Figure 5), increasing from early to mid-July, fluctuating at warm temperatures for the rest of July then decreasing as the air cooled in early August. The snowpack that fed meltwater to the wet sedge had nearly disappeared by July 21st (Figure 5), after which no snow was left to trace. The wet sedge's SM plateaued around the same time that the snowpack disappeared (Figure 5 and Figure 6). The greatest increase in SM actually appeared to coincide more with the melt of the snowpack, rather than with the rainfall events (Figure 6). From July 11th to July 21st, there was close to zero precipitation yet this is the time period in which the wet sedge experienced the greatest average increase in SM. The separate quadrants seemed to be affected in different ways, with the south side of the wet sedge being the area that was affected by the snow melt in mid-July. The north half of the wet sedge did not appear to vary much in its SM temporally, with the NW quadrant having experienced a somewhat steady increase throughout the sampling period and the NE quadrant remained around 70% (Figure 6). These variances in quadrant moisture conditions suggest there was spatial variation in the wet sedge, which was further explored in upcoming sections.

Lastly, the average depth of the AL in the wet sedge appeared to steadily increase throughout the sample season until early August, after which the final AL measurement suggests that the soil has started to freeze up again (Figure 7). This coincided with when the soil and ATs cooled in early August (Figure 4 and Figure 5).

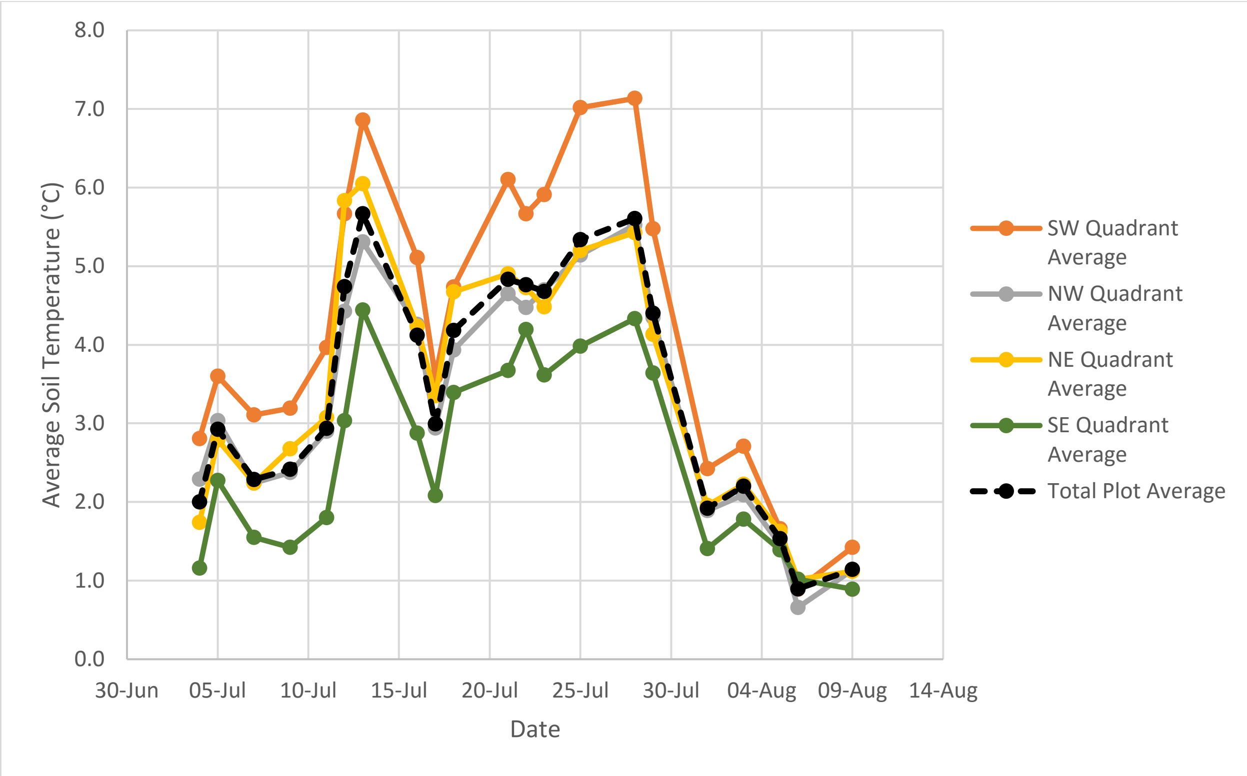

Figure 4: Average Soil Temperature per Quadrant and Total Plot Average over Time

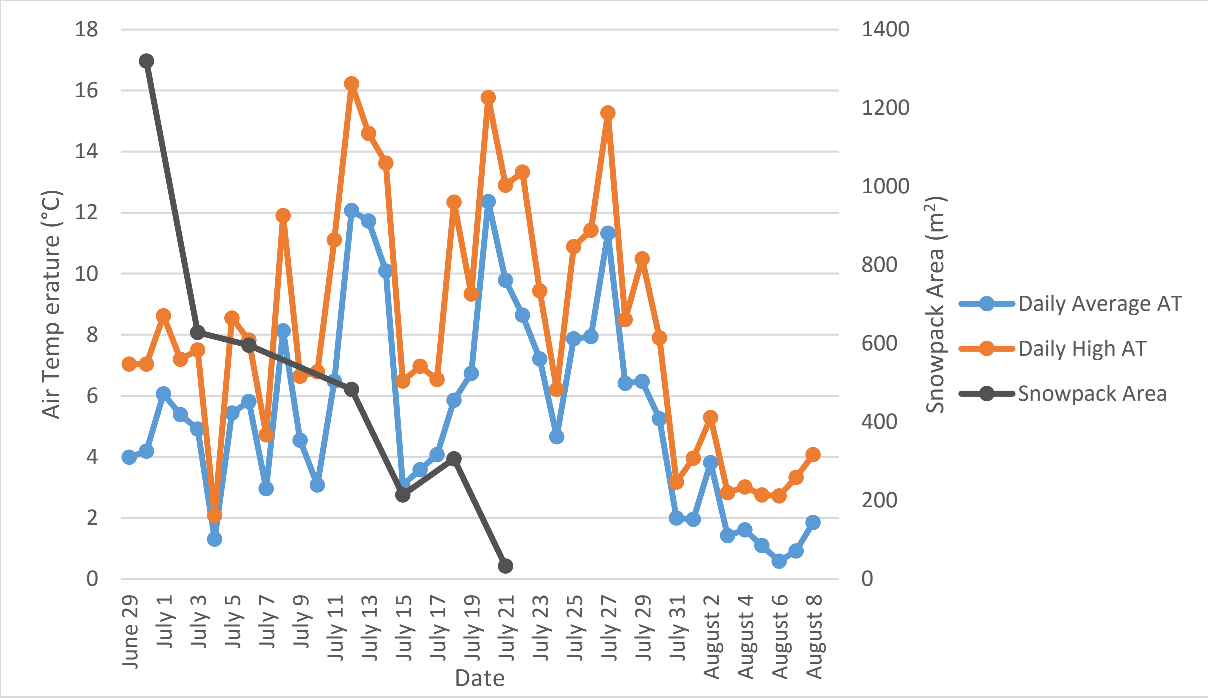

Figure 5: Daily Average Air Temperature and Snowpack Area over Time

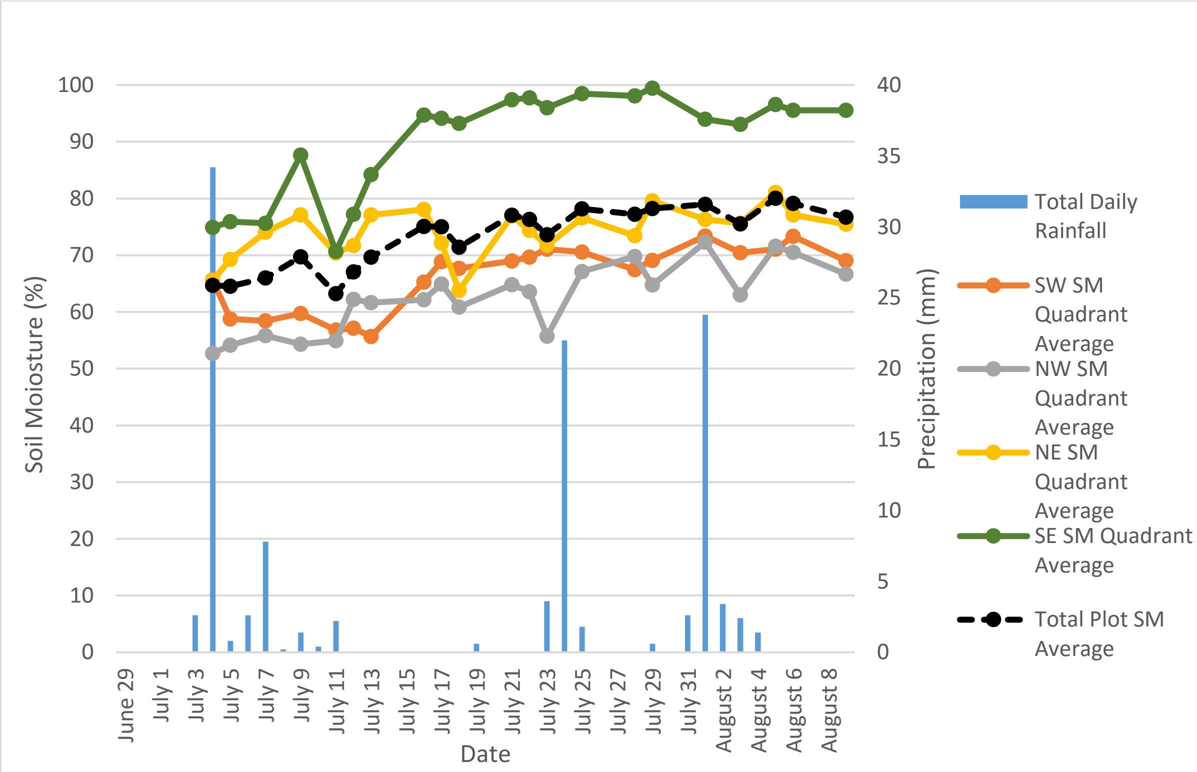

Figure 6: Daily Precipitation and Average Soil Moisture over Time

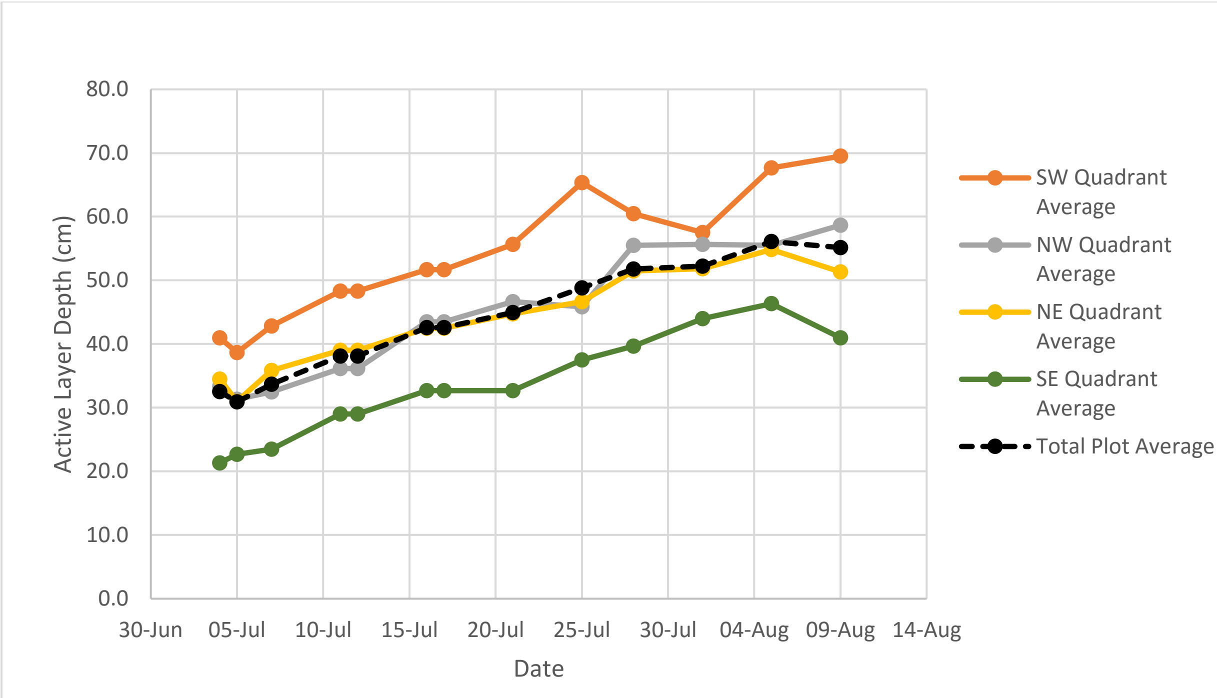

Figure 7: Active Layer Depth over Time

The results from the mixed ANOVA indicated which physical variables had actual statistical significance in their variation over the sampling period (Table 1). Every physical variable tested had statistically significant temporal variation ($p < 0.05$), meaning no one condition of the wet sedge remained stable over the growing season.

Table 1: Mixed ANOVA Results of Within Subjects Effects (Time) on Physical Variables

Variable	**F-Value**	**P-Value**
ST (5 cm)	178.991	.000
ST (10 cm)	122.300	.000
SM	9.306	.001
AL Depth	84.967	.000

To decipher between which weeks there were statistically significant variation, a Tukey HSD post-hoc test was performed. The results from this test (Appendix A) indicated that the wet sedge conditions during the first two sample "weeks" remained relatively unchanged for ST (5 and 10 cm), SM, and AL depth. From week 2 onward, ST at both 5 and 10 cm depths appeared to be significantly different between nearly every week. Active layer depth significantly varied between weeks 2-6, but weeks 6-8 did not see statistical differences, which aligned with Figure 7 where the thickening of the AL appeared to slow down and stop in early and mid-August. In regards to SM, week 3 was the only week that varied significantly from the other weeks, except for week 2 and week 6 which were statistically different from one another. Week 3 varied significantly from every week except weeks 1 and 2. The week 3 SM value was averaged from measurements taken on July 11th, 12th, and 13th, which coincided with a large AT and ST spike (Figure 4 and Figure 5). From Figure 6 it was clear that the significant difference in week 3 came from a drop in SM in nearly all quadrants of the wet sedge on these dates.

3.4.1.2 Temporal Variation of CO_2 Flux

From Figure 8 it was apparent that the NEE of the wet sedge fluctuated over the sampling season, but appeared to have remained, on average, a CO_2 sink from the first sample date of July 4th to the final CO_2 measurement on August 6th. The first two CO_2 readings, however, hinted that the wet sedge had just switched from a CO_2 source to a CO_2 sink. Other than the NW quadrant, the NEE average of each quadrant remained a CO_2 sink after July 7th.

ER and GEP appeared to follow the same trend (Figure 9 and Figure 10), both undergoing a large increase from early to mid-July, staying fairly high for the remainder of July, and dropping again in early August. As indicated by the NEE results (Figure 8), the GEP increase was larger in magnitude than ER, which resulted in the wet sedge being a CO_2 sink. Also observable from these graphs was how the east half of the wet sedge experienced both higher ER and GEP than the west half, except in the first two weeks.

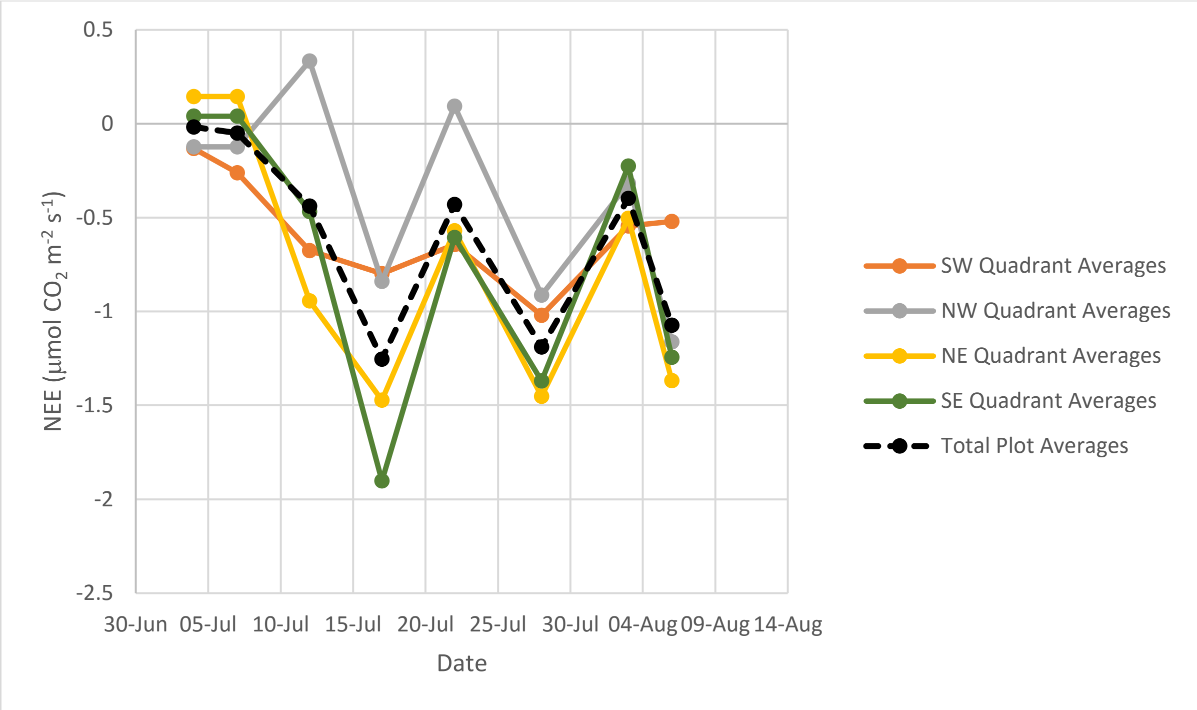

Figure 8: Net Ecosystem Exchange over Time

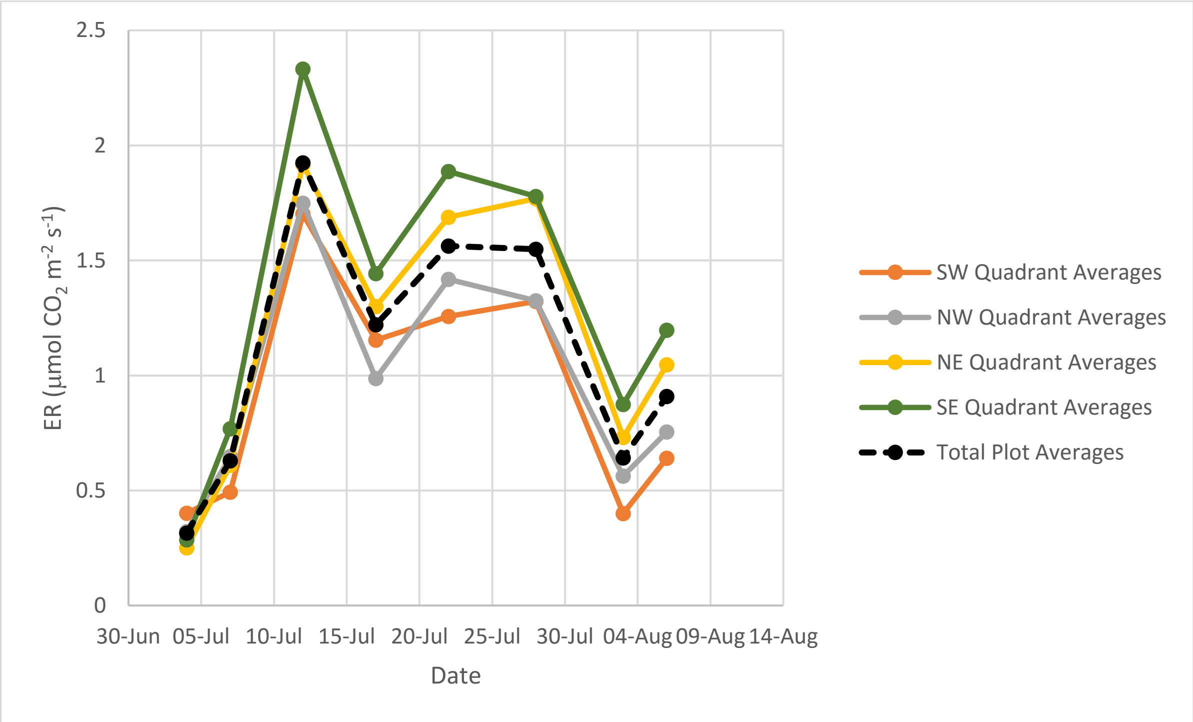

Figure 9: Ecosystem Respiration over Time

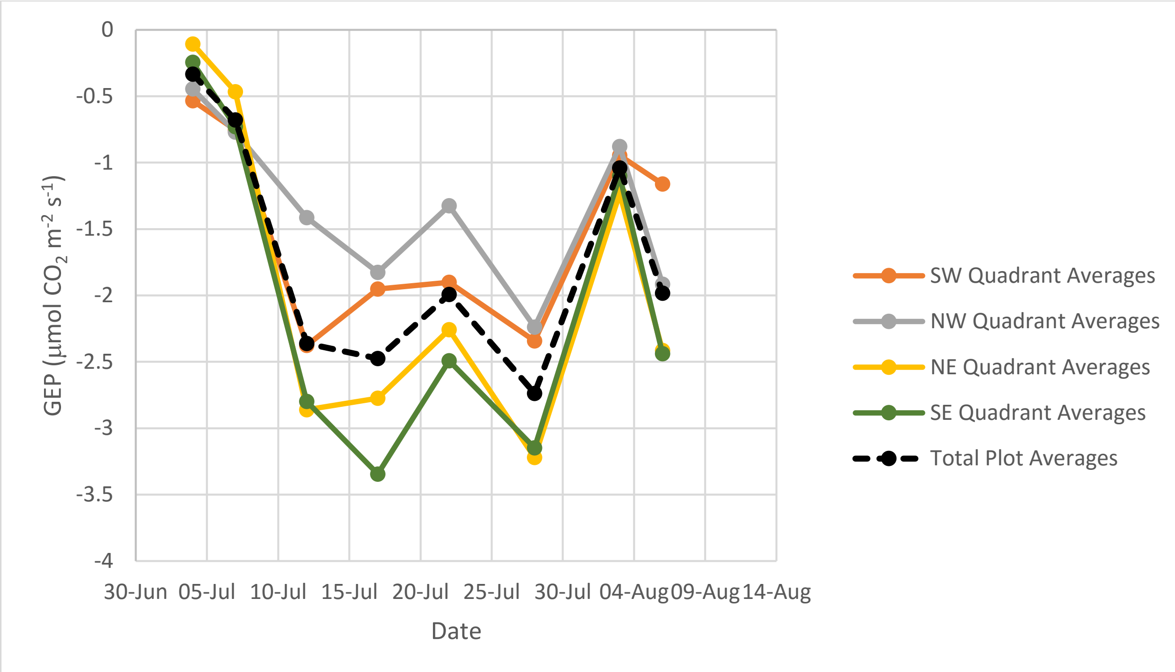

Figure 10: Gross Ecosystem Productivity over Time

The mixed ANOVA results (Table 2) indicated that there were statistically significant variations for each CO_2 flux type over the sampling period. A Tukey HSD post-hoc test was performed again on the CO_2 data (Appendix A). Similar to the physical variables' data, NEE, ER, and GEP each remained at approximately the same level for the first two weeks, then started to vary significantly in week 3. The post-hoc results also showed a relatively stable middle few weeks for all CO_2 flux, observable in the above figures, followed by a significant change in the later weeks of the sampling period.

Table 2: Mixed ANOVA Results of Within Subject Effects (Time) on CO_2 Flux

Variable	**F-Value**	**P-Value**
NEE	10.090	.000
ER	70.756	.000
GEP	35.327	.000

3.4.2 Spatial Variation

3.4.2.1 Spatial Variation of Environmental Variables

The mixed ANOVA tested the effects of both time (weeks) and space (quadrants) on the biophysical variables within the wet sedge. Of the physical variables, the results indicated that there was only statistically significant spatial variation (p =0.048) for SM (Table 3). A Tukey HSD post-hoc test was performed which specified the significant variation in SM was between the SE and NW quadrants.

Table 3: Mixed ANOVA Test Results of Between-Subject Effects (Quadrant) on Physical Variables

Variable	**F-Value**	**P-Value**
ST (5 cm)	1.189	.339
ST (10 cm)	1.445	.259
SM	3.145	.048
AL Depth	2.106	.132

Although no other physical variables had statistically significant spatial variation within the wet sedge, there were clear spatial trends when the means of each quadrant were compared, as well as in the kriged maps of the data that should not be ignored. The means of the biophysical variables displayed in Table 4 show that there was a clear east/west (E/W) trend in SM throughout the wet sedge. Soil moisture was consistently greater on the E half of the wet sedge throughout the sampling period, and remained greatest in the SE quadrant. Active layer depth was smallest in the SE quadrant and greatest in the SW quadrant. For the majority of the sampling period, the W half had deeper ALs than the E half, although the N quadrants' depths remained relatively close to one another. From comparing the quadrant means alone there did not appear to be a trend in ST within the wet sedge. Spatial variability in ST, however, was apparent in the spatial interpolations of the wet sedge.

Table 4: Quadrant and Total Plot Means of Biophysical Variables. The cells highlighted in brown represent the west quadrants; the cells highlighted in green represent the east quadrants.

		NEE		ER		GEP		ST (5 cm) (K)		ST (10 cm) (K)		SM (%)		AL Depth (cm)	
Week	Quadrant	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation
Week 1	SW	-0.132	0.254	0.402	0.304	-0.534	0.523	276.9	1.5	275.8	1.4	63	18	40	13
	NW	-0.123	0.219	0.322	0.367	-0.445	0.394	276.4	1.8	275.3	1.5	53	23	33	14
	NE	0.145	0.271	0.251	0.352	-0.106	0.182	276.0	1.6	274.9	1.6	68	26	33	12
	SE	0.040	0.320	0.286	0.414	-0.246	0.286	275.2	1.9	274.5	1.5	76	24	22	13
	Total	-0.017	0.277	0.315	0.342	-0.333	0.384	276.1	1.7	275.1	1.5	65	23	32	14
Week 2	SW	-0.261	0.328	0.492	0.169	-0.753	0.425	276.6	1.1	276.0	1.2	59	16	43	16
	NW	-0.123	0.219	0.647	0.238	-0.770	0.357	275.7	1.8	275.2	1.7	55	21	33	17
	NE	0.145	0.271	0.611	0.298	-0.465	0.477	275.9	1.2	275.3	1.2	76	20	36	8
	SE	0.040	0.320	0.769	0.332	-0.729	0.330	275.0	1.6	274.3	1.6	82	16	24	12
	Total	-0.050	0.312	0.630	0.268	-0.679	0.395	275.8	1.5	275.2	1.5	68	21	34	15
Week 3	SW	-0.675	0.393	1.702	0.514	-2.377	0.776	279.3	1.7	278.0	1.6	57	16	48	15
	NW	0.334	1.698	1.750	0.453	-1.415	1.315	278.0	2.6	276.7	2.5	60	22	36	16
	NE	-0.943	1.167	1.917	0.480	-2.860	0.801	279.0	1.9	277.3	1.7	73	20	39	10
	SE	-0.468	1.322	2.331	0.381	-2.799	1.321	277.0	1.9	275.5	1.8	77	8	29	13
	Total	-0.438	1.254	1.925	0.498	-2.363	1.172	278.3	2.1	276.9	2.0	67	18	38	15
Week 4	SW	-0.799	0.582	1.153	0.294	-1.952	0.620	278.2	1.3	277.1	1.2	67	21	52	15
	NW	-0.163	1.903	1.167	0.636	-1.330	1.408	277.5	1.9	276.3	1.9	63	22	44	18
	NE	-1.473	0.659	1.301	0.277	-2.773	0.787	277.9	1.4	276.6	1.5	71	21	43	13
	SE	-1.902	0.648	1.443	0.350	-3.345	0.973	276.6	2.0	275.3	1.7	94	6	33	11
	Total	-1.084	1.226	1.266	0.405	-2.350	1.213	277.5	1.7	276.3	1.6	74	21	43	15
Week 5	SW	-0.643	0.740	1.257	0.270	-1.901	0.780	279.8	1.5	278.8	1.5	70	22	61	15
	NW	0.094	1.709	1.419	0.382	-1.324	1.572	278.4	2.2	277.4	2.4	63	18	47	17
	NE	-0.569	1.754	1.688	0.558	-2.257	2.036	278.5	1.3	277.5	1.4	75	24	46	13
	SE	-0.605	1.382	1.887	0.429	-2.492	1.572	277.7	2.0	276.3	1.9	98	3	35	13
	Total	-0.431	1.391	1.563	0.465	-1.994	1.520	278.6	1.8	277.5	2.0	76	22	47	16
Week 6	SW	-1.020	0.628	1.322	0.353	-2.342	0.827	279.8	1.1	279.1	1.2	68	20	61	16
	NW	-0.913	0.849	1.325	0.287	-2.238	0.899	278.5	2.0	277.7	2.3	67	19	56	18
	NE	-1.452	0.815	1.768	0.407	-3.220	0.993	278.3	1.4	277.5	1.6	77	23	52	15
	SE	-1.369	1.205	1.779	0.706	-3.148	1.247	277.7	1.9	276.6	1.9	99	2	40	10
	Total	-1.189	0.870	1.548	0.492	-2.737	1.043	278.6	1.7	277.7	1.9	78	21	52	16
Week 7	SW	-0.545	0.190	0.400	0.251	-0.945	0.424	275.8	0.5	275.6	0.6	72	18	58	18
	NW	-0.318	0.487	0.562	0.131	-0.880	0.398	275.3	1.1	275.0	1.2	68	13	56	20
	NE	-0.503	0.399	0.731	0.155	-1.234	0.300	275.4	0.5	275.1	0.5	76	22	52	16
	SE	-0.225	0.573	0.874	0.314	-1.100	0.433	275.0	1.0	274.5	1.0	94	6	44	6
	Total	-0.398	0.428	0.642	0.278	-1.040	0.392	275.4	0.8	275.1	0.9	77	18	52	16
Week 8	SW	-0.521	1.111	0.640	0.260	-1.161	1.156	274.6	0.4	274.3	0.3	71	20	69	18
	NW	-1.162	0.766	0.754	0.230	-1.915	0.870	274.4	0.9	274.1	0.8	70	20	57	20
	NE	-1.368	0.791	1.047	0.273	-2.415	0.838	274.6	0.5	274.2	0.5	78	22	53	14
	SE	-1.243	0.511	1.196	0.478	-2.440	0.759	274.5	0.9	274.0	0.7	96	6	44	8
	Total	-1.073	0.837	0.909	0.379	-1.983	1.007	274.5	0.7	274.2	0.6	79	20	56	17

Looking at the spatial interpolations of the “weekly” data over the entirety of the wet sedge allowed for further spatial and temporal analysis at a higher spatial resolution. First, in Figure 11 ST appeared to have high variability within the wet sedge, with multiple warm and cold measurements located close to one another. This was likely why there were no statistically significant differences between quadrants for ST. It also seems that the warmest STs were present around the W and N boundaries of the plot area, with the cooler areas located more central and to the SE. When compared to the SM maps in Figure 12, SM was generally greater in areas of lower ST (towards the SE) and lower around the W and N borders where ST is high. For temporal trends, Figure 11 and Figure 12 showed that ST and SM had the greatest high-magnitude-area-coverage in weeks 5 and 6.

The spatial patterns visible in the kriged AL depth surface (Figure 13) were similar to what could be predicted from the SM and ST spatial patterns. Figure 13 showed how the AL depth was greatest along the W and N borders, where ST was highest and SM was lower. Similarly, the AL depth was lower in the central and SE area of the wet sedge where the soil was colder and wetter. The spatial patterns in the ST (Figure 11) and AL (Figure 13) looked to be quite similar, with warm and cold locations in the same areas. Soil moisture, on the other hand, generally had a smoother, more gradual pattern within the wet sedge, except in week 8, where warm and cold spots appeared. It was also noticeable that the AL depth did not respond as quickly to the drop in AT (Figure 5) at the end of the sampling season like ST did.

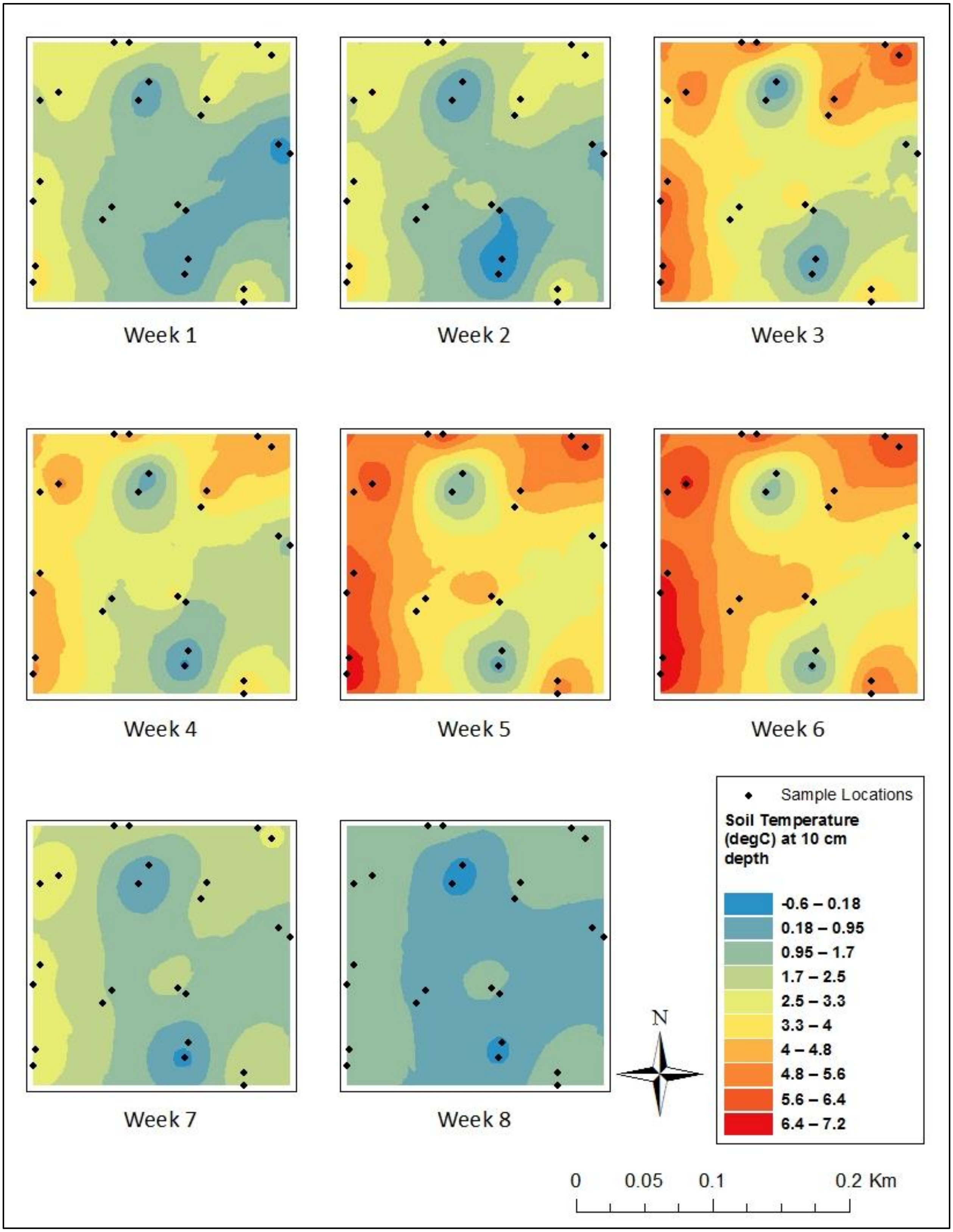

Figure 11: Soil Temperature Kriging Results

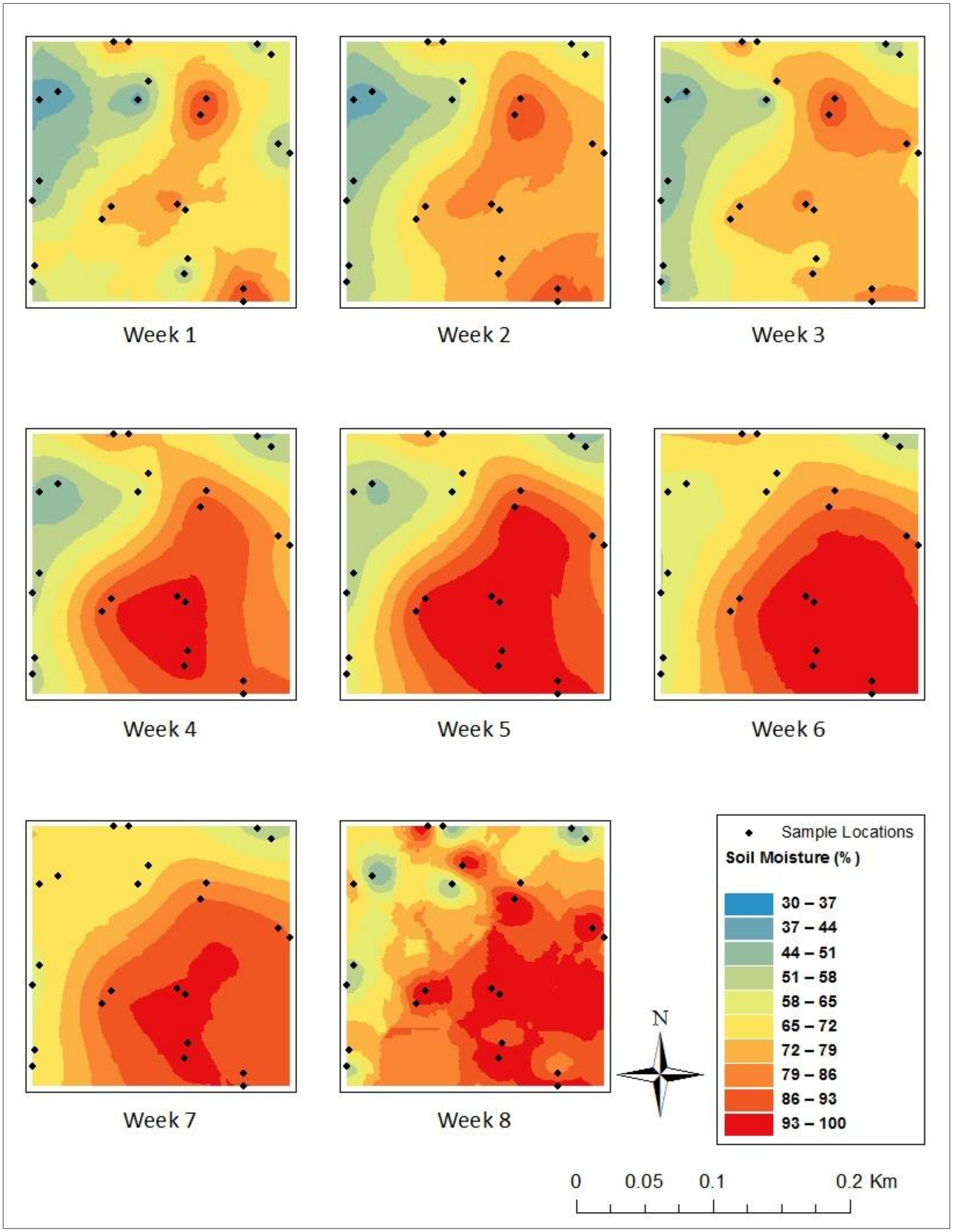

Figure 12: Soil Moisture Kriging Results

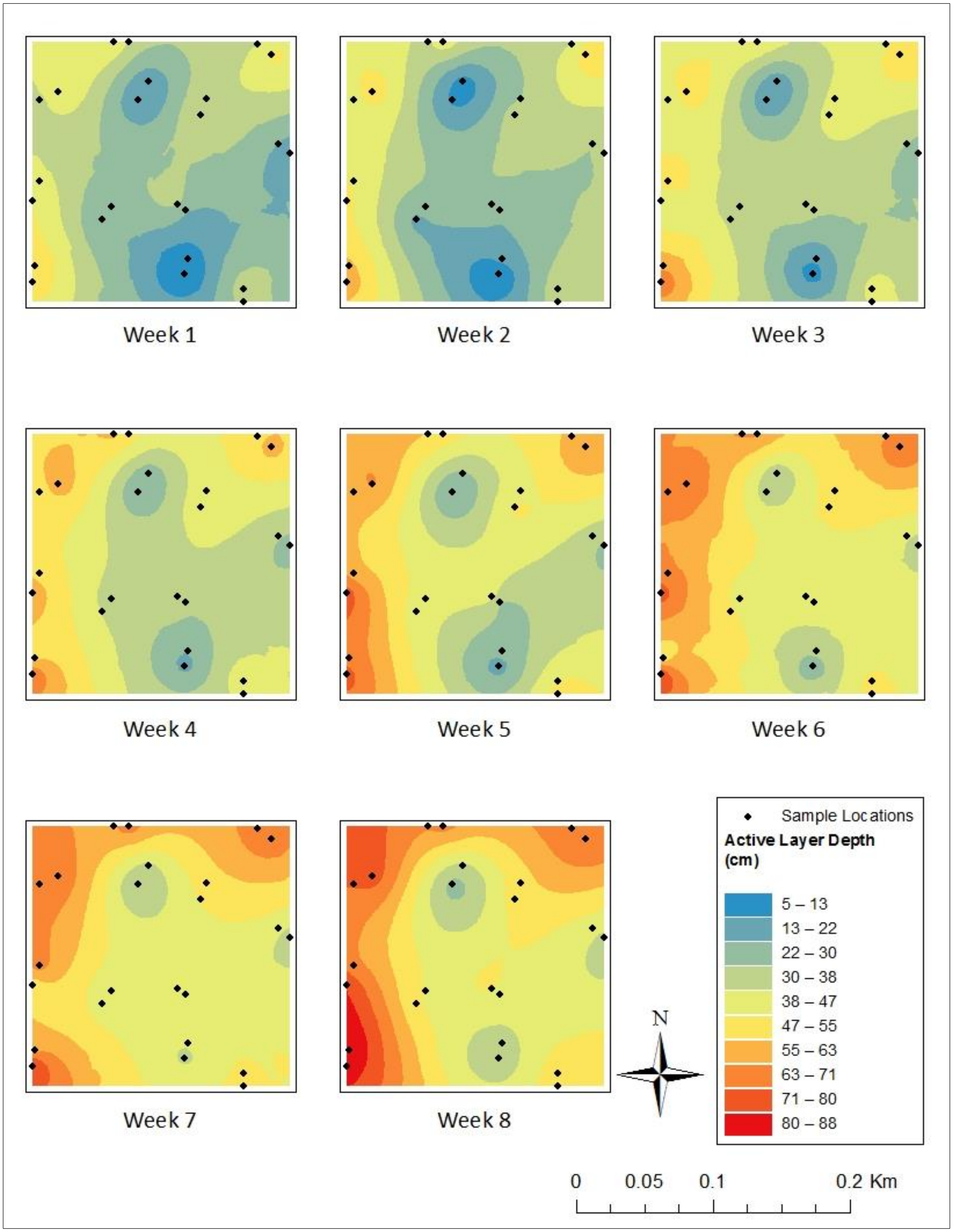

Figure 13: Active Layer Depth Kriging Results

3.4.2.2 Spatial Variation of CO_2 flux

For NEE, ER, and GEP the Mixed ANOVA test showed that only ER had statistically significant variation between the quadrants of the wet sedge with a *p* value of 0.023 (Table 5). The Tukey post-hoc test revealed that this variation of ER was between the SE and SW quadrants.

Table 5: Mixed ANOVA Test Results of Between-Subject Effects (Quadrant) on CO_2 Flux

Variable	F-Value	P-Value
NEE	.682	.573
ER	3.950	.023
GEP	1.857	.169

The mixed ANOVA also tested whether there was a statistically significant interaction ($p<0.05$) between the two factors, time and space, on the biophysical variables. The interaction results of the ANOVA (Table 6) showed that the interaction of these effects were not statistically significant, therefore implying that the effect of time or space was not amplified by one another (Laerd Statistics, n.d.-a). Thus, the statistical differences between the quadrants were not statistically significantly affected by time, suggesting all quadrants had statistically similar temporal trends for all biophysical variables.

Table 6: Mixed ANOVA Test Results of the Interaction of Within-Subject and Between-Subject Effects (Week*Quadrant) on Biophysical Variables

Variable	F-Value	P-Value
NEE	1.557	.156
ER	.921	.532
GEP	1.973	.055
ST (5 cm)	2.357	.055
ST (10 cm)	2.401	.053
SM	1.121	.368
AL Depth	1.366	.199

Referring back to Table 4 and the kriging results below, non "statistically" significant but still existent trends could be observed for NEE, ER, and GEP. By comparing the quadrant means in Table 4, for all "weeks" following week 2, the E half of the wet sedge underwent greater ER and GEP then the W half. The opposite was true for weeks 1 and 2.

The same trend identified in Table 4 could again be recognized in the surface interpolations of the ER and GEP data, displayed in Figure 15 and Figure 16. For both ER and GEP there was a clear E/W trend, with red and orange representing areas with greater magnitudes of each. This correlated back to the SM surfaces, which also displayed an E/W trend of decreasing SM (Figure 12). NEE, on the other hand, appeared to have less obvious spatial trends over the wet sedge, with sporadic high and low spots in weeks 4 and 5 and little spatial variability in the beginning and final weeks (Figure 14). ER and GEP appeared to have a similar temporal pattern in this regard, with less variability in the beginning and final weeks, and greatest variability visible from weeks 3-6.

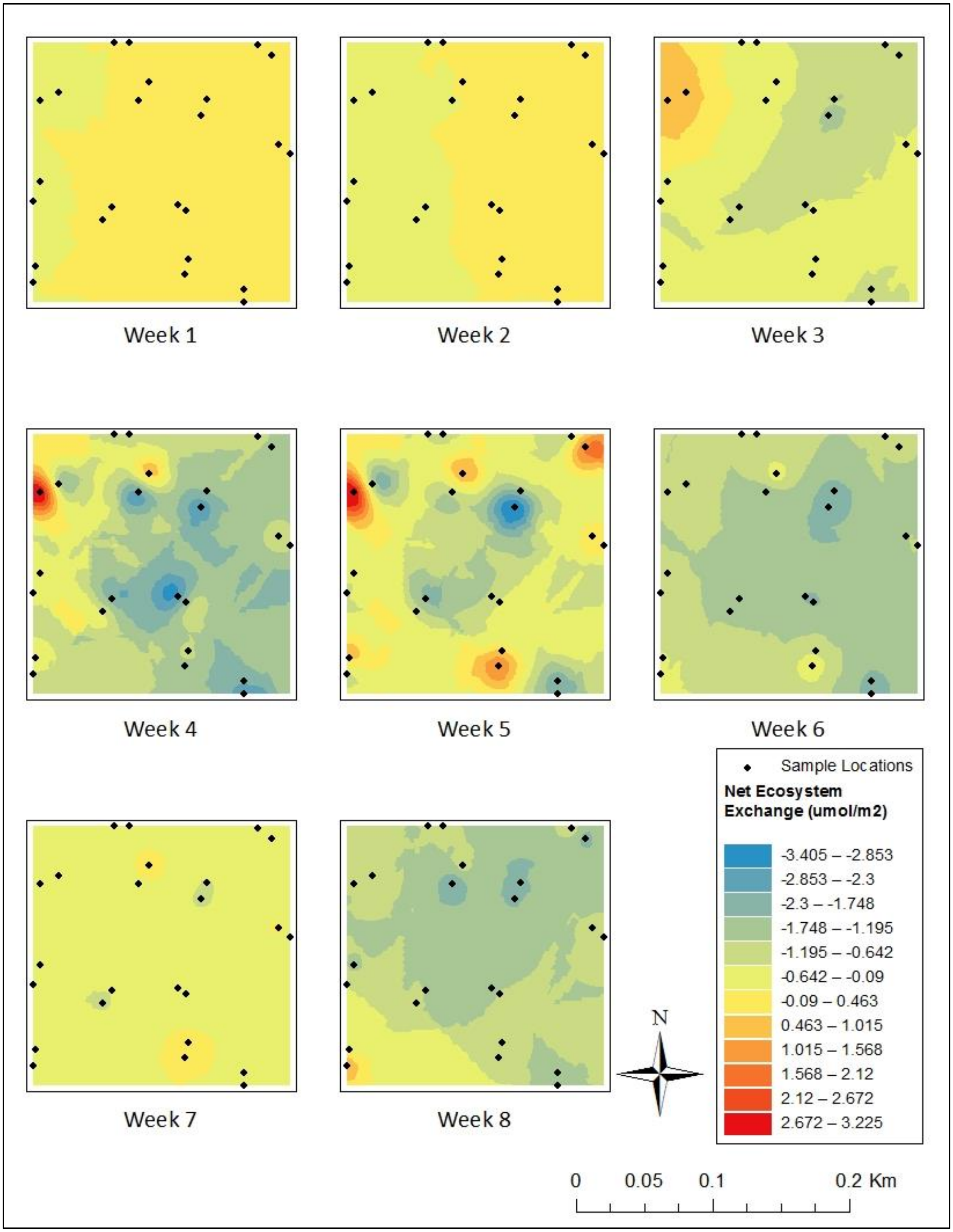

Figure 14: Net Ecosystem Exchange Kriging Results

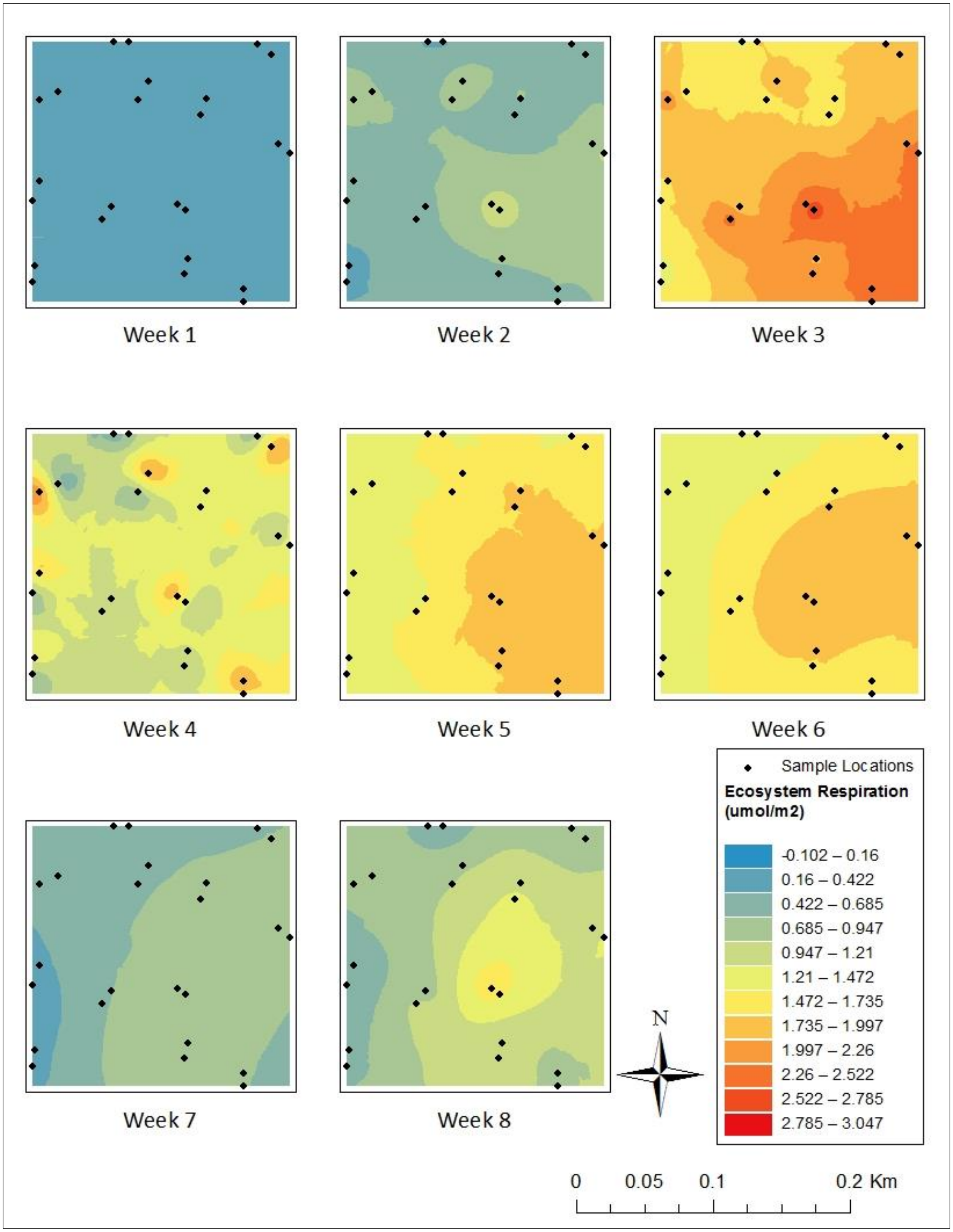

Figure 15: Ecosystem Respiration Kriging Results

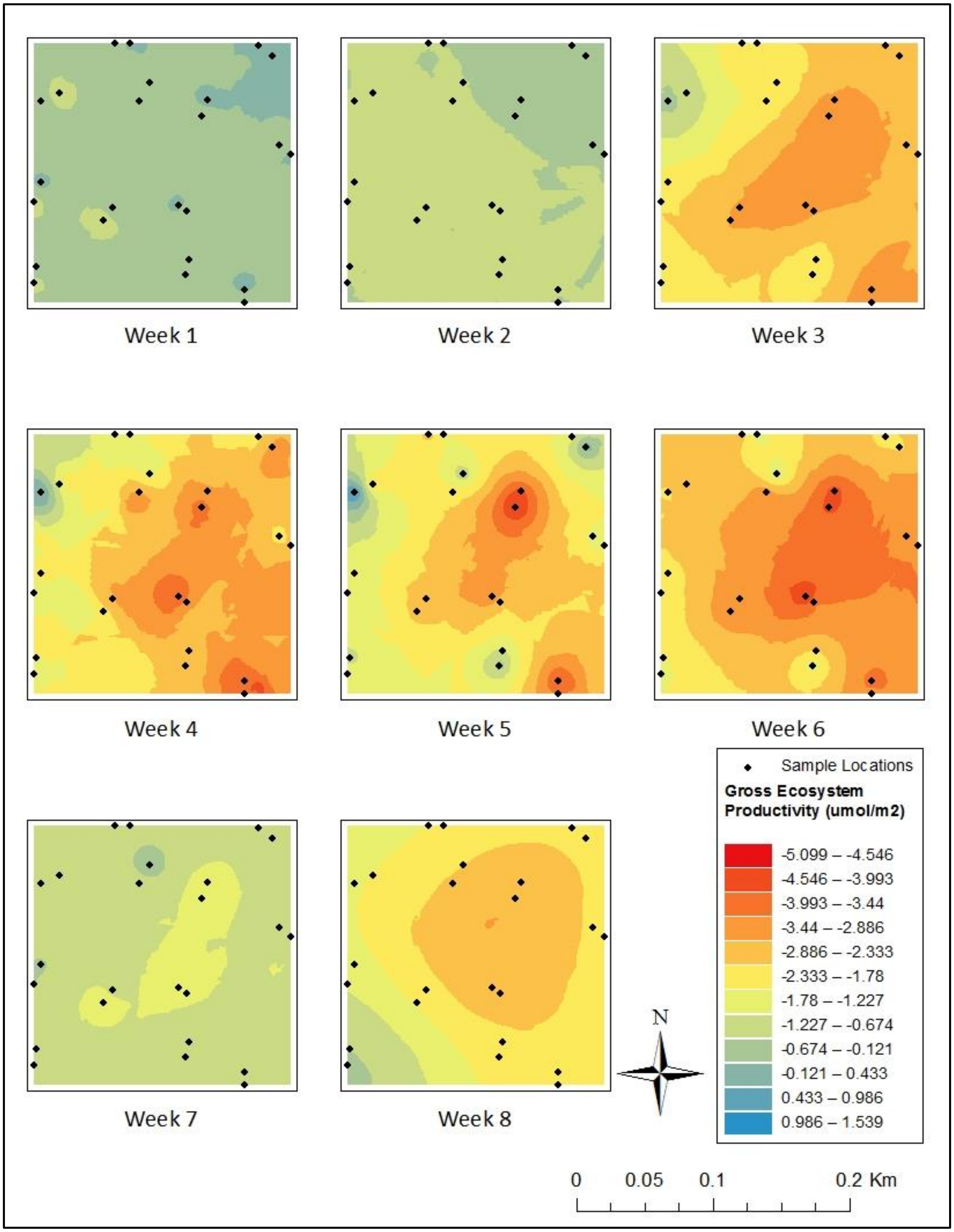

Figure 16: Gross Ecosystem Productivity Kriging Results

3.4.3. Environmental Influences on CO_2 Flux

To determine if CO_2 flux from the wet sedge was influenced by its physical conditions and/or the weather, a stepwise MLR was performed on the data. The results of this test indicated which physical variables had a statistically significant correlation to ER and GEP. Since NEE is the sum of ER and GEP, the results of the NEE MLR were considered unnecessary to present.

A MLR was performed using the biophysical variables' point pair averages for each week (case A), and again using the quadrant averages for each week (case B). The results of both tests are provided in Table 7, with R^2 being the proportion of variability of ER or GEP that was explained by the physical variable(s) (Laerd Statistics, n.d.-d). In both cases, the most dominant predictor for ER was AT, followed by SR and then SM for case A and vice versa for case B. The use of quadrant averages over the 8 "weeks" resulted in higher R^2 values and lower standard errors of the estimate (SEE), with AT accounting for 69.4% of the variability in ER on its own (Table 7 b). Adding SM and SR increased the R^2 of ER to 0.900. In case A, AL depth was also a significant predictor of ER, but only increased the predictability of ER by less than 2% (Table 7).

The two most significant predictors for GEP were the same in both cases, with SR being most dominant and followed by SM. In case B, SR alone could explain 72.5% of the variability in GEP, and adding SM to the model increased predictability to 81.4% (Table 7), indicating that SR accounted for much more of the GEP variability than SM. In case A, a ST at a 5 cm depth also qualified as having statistical significance for GEP prediction, although it only increased the R^2 by less than 2%.

Table 7: Stepwise MLR Results

A) Point Pair Results						
Variable	**Predictor**	**R^2 adj.**	**SEE**	**F**	**Sig.**	**df**
ER	AT	0.589	0.39096	137.102	0.0000	1,94
	SR, AT	0.703	0.33246	113.297	0.0000	2,93
	SM, SR, AT	0.744	0.30829	93.22	0.0000	3,92
	SM, SR, AT, AL Depth	0.761	0.29831	76.485	0.0000	4,91
GEP	SR	0.459	0.85738	81.705	0.0000	1,94
	SM, SR	0.594	0.74295	70.497	0.0000	2,93
	SM, SR, ST (5cm)	0.608	0.73038	50.039	0.0000	3,92
B) Quadrant Average Results						
Variable	**Predictor**	**R^2 adj.**	**SEE**	**F**	**Sig.**	**df**
ER	AT	0.6940	0.31345	71.22	0.000	1,30
	AT, SM	0.8260	0.23602	74.764	0.000	2,29
	SR, AT, SM	0.9000	0.17902	94.108	0.000	3,28
GEP	SR	0.7250	0.50060	82.891	0.000	1,30
	SR, SM	0.8140	0.41161	68.993	0.000	2,29

The results of the MLR test also provided the coefficients of each independent (physical) variable for the prediction model of the dependent (CO_2 Flux) variable (Table 8). From looking at the sign of the coefficients, it can be stated that AT, SR, and SM all had positive influences on ER in both case A and B. Similarly, since the more negative the CO_2 flux the greater the GEP, negative coefficients for GEP indicated a positive influence on GEP. Thus, as SR, SM, and ST (5 cm) increased, more GEP occured (Table 8). Specifically these results (case B) are stating that for every unit increase in SR (W m^{-2}) GEP increased by 0.004^{th} of a unit (μmol m-^{2} s^{-1}). Likewise, for every unit increase in AT (K), ER increased by 0.07^{th} of a μmol m-^{2} s^{-1}. Unexpectedly in case A, AL had a negative but slight correlation with ER which is discussed in the following section.

Table 8: Stepwise MLR Results: Predictor Coefficients of CO_2 Flux

A) Point Pair Results				
Flux	**Predictor**	**Coefficient**	**Std. Error**	**Sig.**
ER	(Constant)	-15.531	2.373	0.000
	SM	0.005	0.002	0.003
	SR	0.002	0.000	0.000
	AT	0.057	0.009	0.000
	AL Depth	-0.005	0.002	0.008
GEP	(Constant)	24.002	10.948	0.031
	SM	-0.025	0.004	0.000
	SR	-0.004	0.000	0.000
	ST (5 cm)	-0.081	0.040	0.043
B) Quadrant Average Results				
Flux	**Predictor**	**Coefficient**	**Std. Error**	**Sig.**
ER	(Constant)	-19.7	2.395	0.000
	SR	0.001	0.000	0.000
	AT	0.07	0.009	0.000
	SM	0.013	0.003	0.000
GEP	(Constant)	1.577	0.451	0.002
	SR	-0.004	0.000	0.000
	SM	-0.024	0.006	0.000

The influences of the wet sedge's physical conditions on CO_2 flux that were discernable from the stepwise MLR results were also apparent when plotting ER and GEP with their most statistically significant predictors. In Figure 17*: Comparison of GEP and Solar Radiation's Temporal Trends* the relationship between GEP and SR was quite clear. As SR increased, GEP increased in magnitude (negativity) and declined as SR weakened almost simultaneously, indicating SR had a near instantaneous effect on GEP. The same appeared true for SR's influence on ER, displayed in Figure 18: as SR intensified ER increased shortly afterwards, having a clear relationship for being the second most significant predictor of ER. The most significant predictor of ER, AT, is plotted with ER in Figure 19. This plot portrayed both ER and AT to have very similar temporal trends, again suggesting AT had an instantaneous influence on ER.

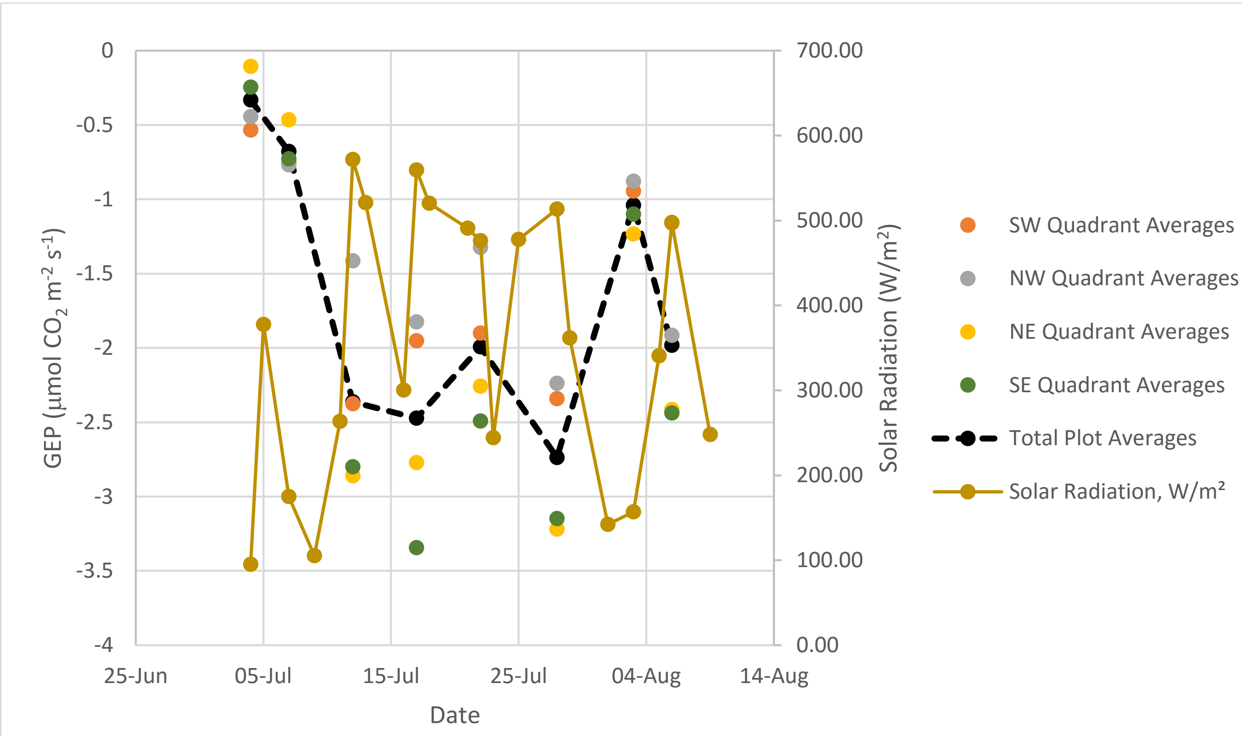

Figure 17: Comparison of GEP and Solar Radiation's Temporal Trends

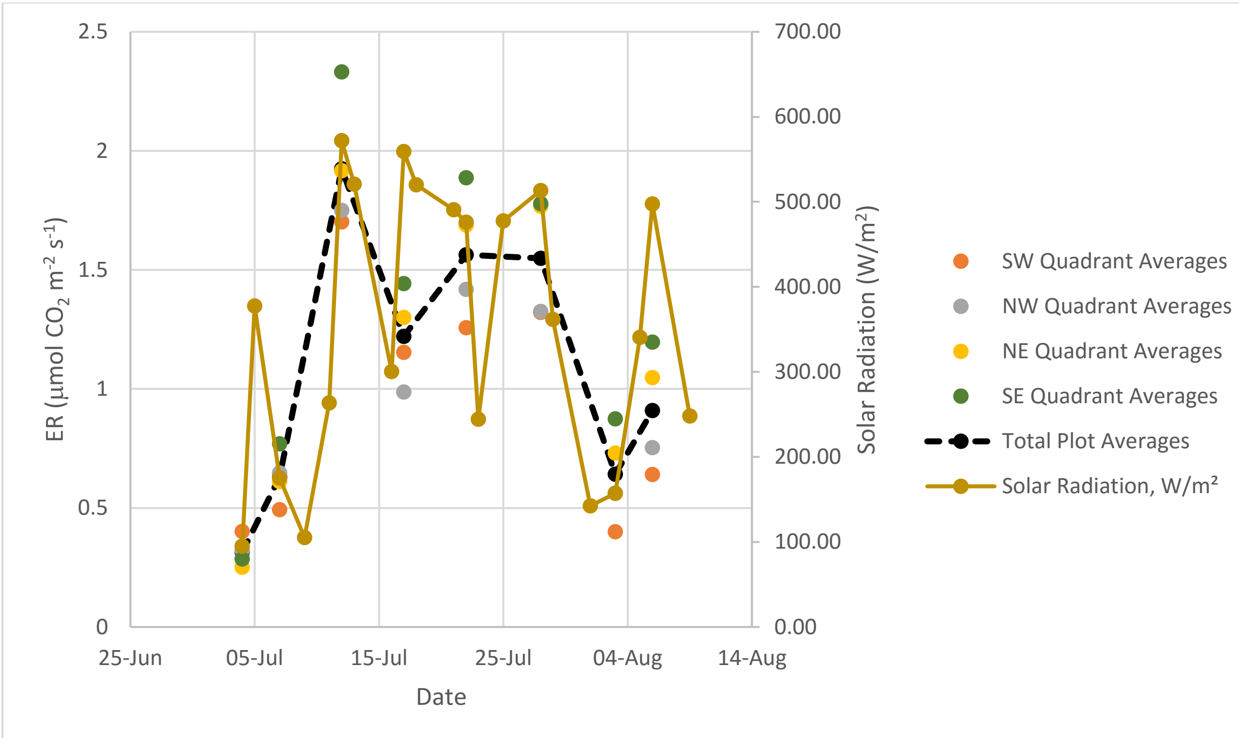

Figure 18: Comparison of ER and Solar Radiation's Temporal Trends

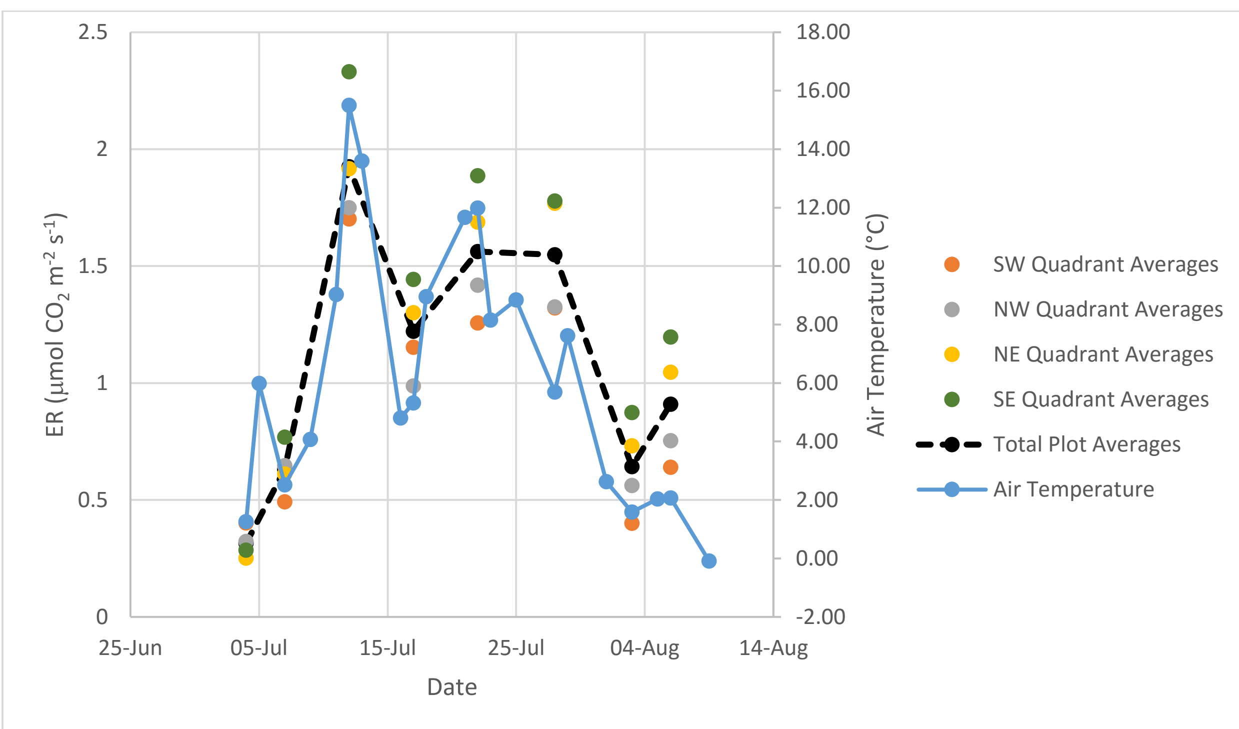

Figure 19: Comparison of ER and Air Temperature's Temporal Trends

3.5 Discussion

Wetlands in the high Arctic are predicted to have greater sensitivity to climate changes than southern wetlands due to having experienced larger temperature constraints from their originally colder climates and limited growing seasons (Sullivan et al., 2008). Studies focused on high Arctic wetlands are limited, making the effects of climate change on these sensitive yet significant carbon storages uncertain (Sullivan et al., 2008; Knoblauch et al., 2013). What are highly certain are the effects climate change will have on the Arctic's physical conditions, including increased surface temperature, deeper permafrost thaw, and the shrinkage of snowpacks (Callaghan et al., 2011; IPCC, 2013). The aim of this study is to provide greater knowledge on the interaction of biophysical variables in high Arctic wetlands so the fate of these carbon sinks can be better predicted.

3.5.1 Temporal Trends of Biophysical Variables

Assessing the trends of the biophysical variables over the wet sedge's growing season provided some initial information on the relationships and reactions of the variables to the weather and each other. In the results we found that ST closely followed AT over the sample season, with AL depth more generally following suit. For instance, both ST and AL depth began to drop/freeze as the AT dropped in August. Beamish et al. (2011) also found a strong correlation between ST and AT at the multiple sites they studied within the CB watershed. Increased temperatures in Chapin et al.'s 1995 study on Arctic tundra increased the surface temperatures and STs along with the AL depth. Ramsay et al. (2015) found ST to increase and fluctuate with both AT and SR.

Air temperature also seemed to have an indirect influence on SM, as SM seemed to coincide with the melt of the late lying snowpack located upslope of the wet sedge. The largest average increase in SM was seen during the snowpack's final weeks of melting in mid-July, during which there was nearly zero precipitation and high ATs. The average SM of the wet sedge began to plateau around the same time the snowpack disappeared. Beamish et al. (2011) also saw the greatest increase in SM around the same time in 2010 in CB, perhaps also corresponding with the rapid melt of surrounding snowpacks. These temporal observations suggest that the snowpack melt has a greater influence on the wet sedge's overall SM than precipitation during the growing season. Atkinson (2012) also found that precipitation events in CB did not appear to affect the gravimetric SM in dry, mesic, and wet tundra ecosystems during 2006's growth season. When Ramsay et al. (2015) studied this same wet sedge as our study in 2014, the SM averages saw little change over the growing season, which Ramsay et al. (2015) attributed to the "steady hydrological input" from the perennial snowbank rather than that season's precipitation. The wet sedge underwent a colder growing season in 2014 which did not see a complete melt of the perennial snowpack as we did in the 2015 sample season (Ramsay et al., 2015). Ramsay et al. (2015) suggested that this wet sedge's SM regime will be directly impacted by changes to its hydrological input, the perennial/late lying snowpack, also suggested by Atkinson and Treitz (2013). During the time period in which SM was measured in 2015, there did not appear to be a decrease in SM from the disappearance of the snowpack, however it is unknown what the SM of the wet sedge became in mid and late August. Moreover, although an immediate effect on SM may not have been observable from the snowpack depletion, if the snowpack begins to continually disappear in subsequent years the wet sedge may start to dry out (Ramsay et al., 2015). This could be due to the soil being less saturated when it freezes at the end of the growing seasons, thereby resulting in lower SM at the beginning of the next growing season with a smaller snowpack as the hydrological input.

All of the biophysical variables measured in this study remained statistically stable during the first two "weeks" in early July, after which statistically significant variation over the weeks occurred. This was true for all variables including NEE, ER, and GEP. All CO_2 flux types changed significantly after week 2, then insignificantly fluctuated from mid to late July followed by a significant drop in early August, similar to the AT and ST temporal trends. These temporal trends implied that the wet sedge stabilized during peak growth in late July, which Ramsay et al. also found to be the case when measuring ST, SM, and AL depth in this wet sedge in 2014. Ramsay et al. (2015) reported these findings as similar to Roulet and Woo (1986) and Nobrega and Grogan's (2008) results during their mid and low Arctic studies, which found NEE, GEP, and ER showed greater stability during peak growth with the most significant variation occurring during the early and late growth periods. A study performed on another wet tundra site in CB during the growing season of 2006, however, did not find any statistically significant temporal variation in CO_2 flux from July 5th to July 30th (Atkinson, 2012). Atkinson (2012) suggested this lack of variation may have been partly attributed to the cooler climate at high Arctic latitudes compared to mid and low Arctic sites. Although the results of this study differed from Atkinson's, this may be attributed to the warming of the high Arctic from 2006 to 2015, the year of our study. When comparing the different CO_2 flux types, ER and GEP appeared to vary nearly simultaneously, with GEP's variation being generally larger in magnitude, keeping NEE below but not far from zero and therefore remaining a CO_2 sink. Similarly, simultaneous temporal patterns between ER and GEP were also witnessed in Christensen et al.'s 2000 study on a high Arctic wetland (fen) in northeast Greenland, along with Boelman et al.'s 2003 study on Arctic wet sedge tundra. The similarity in GEP and ER's temporal trends are not uncommon as they are often found to offset one another since ecosystem traits that increase GEP, such as leaf area index, also have “large autotrophic respiratory costs” (Vourlitis et al. 2003). This similarity could also be explained by the MLR results of this study, discussed in Section 3.5.3, which show that GEP and ER were influenced most significantly by some of the same few physical variables.

3.5.2 Spatial Trends of Biophysical Variables

In the previous section the temporal trends and potential correlations were taken from the averages of the variables across the wet sedge. It was, however, important to assess the spatial aspect which, as evident in this study and Ramsay et al.’s 2015 study, informed us that there were spatial trends within the wetland that resulted in non-homogeneity. Thus, not all areas of the wet sedge displayed the temporal trends that the averages displayed. Spatial variability was assessed using multiple methods in this study: Using an ANOVA to inform us of statistical differences between quadrants, comparing quadrant means to observe non-statistically significant but reoccurring trends, and using the spatial interpolation method, kriging.

Of the physical variables, the ANOVA only stated there was slightly statistically significant variation within the wet sedge for SM, which the Tukey HSD post-hoc test showed it to be between the SE and NW quadrants. From comparing the quadrant SM means there was a clear E/W trend throughout the sample season, with the greatest SM consistently in the SE quadrant. Alternatively, AL depth appeared to have a W/E trend for most of the growing season, evident when comparing the quadrant means though not proven statistically. Interestingly, the SE quadrant, which consistently had the highest SM, almost just as consistently had the shallowest AL depth. This aligned with the fact that more energy is required to warm and thaw saturated soils than drier soils (Ramsay et al., 2015). The SW quadrant showed to have the greatest AL depth, with the NW quadrant having remained slightly greater than the NE quadrant. From the ANOVA and comparison of quadrant means, no spatial trend in ST could be observed.

Looking at the spatial data at a higher resolution than quadrant averages provided greater insight into the spatial variability within the wet sedge. Using this information from the spatially interpolated surfaces, it was evident that ST was highest around the N and W boundaries of the wet sedge, and cooler in the central and SE borders. Expectedly, AL depth appeared to be deeper in areas with warmer soils, which also looked to be the areas with drier soils. Since water requires more energy to heat than dry soil, it would be expected that the soils with greater moisture contents have lower temperatures (Ramsay et al. 2015). What was also observable from the kriged surfaces that could not be gathered from comparing quadrant means was the gradual spatial pattern of SM over the wet sedge compared to the more variable and broken spatial patterns of ST and AL depth. Ramsay et al. (2015) also found ST and AL depth to have more localized spatial trends compared to a more gradual SM spatial trend in this wet sedge in 2014. Additionally, Ramsay et al. observed the same E/W trend in SM in this wet sedge, suggesting that this trend in SM is a yearly occurrence during the growing season. The kriged surfaces showed us that in week 8, SM's gradual spatial trend has become more localized, which could have been be due to the soil water freezing and not read as moisture as the ATs and STs cooled in August. The localized, less gradual spatial trend in SM was also witnessed in the first "week" of the sample season, which Ramsay et al. (2015) also saw in the early summer of their CB sample season. Ramsay et al. predicted that the spatial patterns would start to break up again in August with the reduced temperatures and SR levels causing spatially inconsistent soil freezing. Finally, the warmer and deeper AL spots around the N and W borders of the wet sedge were also present in Ramsay et al.'s study (2015). Although wetlands are generally saturated, it would also be expected that the areas with greater AL depths would have lower SM values, as the soil water drains when the AL thickens. For SM to remain the same when the AL thickens, there has to be a constant and sufficient hydrological input (Ramsay et al., 2015). Thus, if the air continues to warm thereby increasing AL depth and the snowpack upon which this wet sedge relies continues to deplete every year, the wet sedge will likely dry out a bit more every year. However, as suggested by Ramsay et al. (2015), the depth of the organic layer and soil type across the wet sedge could affect SM if not homogeneous and should be looked into in future studies.

With regard to the wet sedge's CO_2 exchange, the ANOVA and Tukey HSD post-hoc tests indicated there was only statistically significant variation for ER between the SE and SW quadrants (p =0.025). Yet from comparing the quadrant means along with the kriged surface interpolations there was a continuous E/W trend for both ER and GEP after "week" 2. What could also be learned from this spatial analysis was that although we know on average the wet sedge remained a CO_2 sink over the sample period, it does not mean the whole wetland acted as a sink. There were several times over the growing season where the NW quadrant averaged to be a CO_2 source, which could have been caused by its differing characteristics from the rest of the wet sedge, including potential lower PVC from visual observation of the wet sedge, thicker AL depths, and drier soils. To accurately predict the CO_2 status of this wetland an even higher spatial resolution of CO_2 flux measurements may be required, as small spatial variations of ER and GEP within a wetland can cause significant spatial variations in NEE (Vourlitis et al., 2003). From observing the NEE kriged surfaces, it was clear that NEE did not have the same spatial trends of ER and GEP, and became highly variable within mid-July (weeks 4-5), with some high and low spots located very close to one another. This likely aligned with when ecosystem productivity was nearing its full potential, resulting in ER and GEP having greater sensitivity to spatial variances in environmental conditions. These large spatial differences were minimized in the beginning of the growing season and towards the end, which likely aligned with the periods before and after peak growth.

From assessing the spatial trends of all the biophysical variables, we could begin to see potential correlations between the physical variables and CO_2 flux. Looking at the first two "weeks" when the wet sedge was just barely entering "sink" status for CO_2, we could see that the wet sedge had relatively dry and cool soils with shallow ALs as the growth season begun and thus plant production was lower (Ramsay et al., 2015). However, in "week" 3 ER spikes, which appeared to be associated with the sudden increase in ST while large areas in the wet sedge remained relatively dry and plant productivity had not yet peaked. In fact, during this week SM appeared to decrease in some areas, likely due to increased evapotranspiration allowing more aerobic microbial and root respiration to occur in the soil (Billings et al., 1982). As the wet sedge became more saturated in the peak growth period, ER dropped and stabilized while GEP peaked. Ecosystem respiration responding positively to higher temperatures and lower SMs has been suggested in past Arctic tundra carbon exchange studies (Billings et al., 1982; Weller et al., 1995; Ellis and Rochefort, 2006; Harazono et al., 2006; Sullivan et al., 2008; Olivas, 2010). Moreover, the E/W spatial trend observed for both ER and GEP aligned with the E/W trend for SM. Hence, although drier soils have been found to have greater ER, plant productivity can be limited by low SM content in Arctic soils, ultimately limiting both GEP and the plant respiration aspect of ER (Boelman et al., 2003; Fisher et al., 2009). To test if these correlations between CO_2 flux and the physical variables of the wet sedge were statistically significant, a MLR was performed and the results discussed in the following section.

3.5.3 Environmental Influences on CO_2 Flux

The stepwise MLR analysis stated that ER was most dominantly influenced by AT, followed by SR, SM, and in case A (using pair averages) AL depth. These were the variables whose influences on ER were considered statistically significant. In both cases, the top predictor for ER was AT which explained from 59-69% of ER's variability, and SR and SM were in the top 3 predictors, both explaining from 4-13% of ER's variability. Last, in case A, AL depth accounted for just below 2% of the ER variability. Soil moisture and SR made it into the top three statistically significant predictors of GEP as well, this time SR being the most dominant predictor with an influence from 45-72%. Soil moisture's influence on GEP accounted for around 9-13% of its variability, followed by ST at 5 cm depth explaining between 1-2% of the variance. All of these variables had positive correlations to ER and GEP, except AL depth, indicating that as they increase, ER and/or GEP increase. Although NEE is a function of ER and GEP, when tested in the MLR analysis, it also had its top three predictors as SR, AT, and SM, and ST at 5cm depth as a 4th predictor. Net ecosystem exchange correlated positively with AT and negatively with SR, SM, and ST, suggesting the latter three's influences on GEP were stronger than their influences on ER, with the opposite being true for AT. This is since a positive NEE indicated a release of CO_2 from the ground (ER>GEP) and a negative NEE indicated the uptake of CO_2 from the atmosphere (GEP>ER).

When using regression modelling, Atkinson (2012) found that when modelling CO_2 flux, both AT and ST were the best predictors. This finding agreed with results from other high Arctic studies on wet tundra, which showed the key CO_2 flux predictors were temperature and SM (Atkinson, 2012). Even the use of NDVI models for CO_2 exchange were found to improve when AT and PAR, directly related to SR, were included (Atkinson, 2012). Another CB study which looked at CO_2 flux found ER to be significantly influenced by AT and less so by ST, noting that this was similar to the results of like studies on other high Arctic wetlands outside of CB (Wagner et al., n.d.). Wagner et al. (n.d.) did not find a correlation between ER and SM, and only found a correlation between AL depth and ER in a mid-moisture site, not the wet sedge studied. However, perhaps the slight AL depth influence on ER in this study came from the areas that showed more mid-moisture characteristics, such as in the far west portion of the wet sedge. This further strengthens the need to consider organic layer depth and soil type when performing this type of study. Beamish et al. (2011) who looked at the influence of physical variables on CO_2 flux across a variety of disturbed sites in CB, also found a strong correlation between AT, ST, and CO_2 flux. Moreover, Fisher et al. (2009) found temperature (air and soil) and SM had a significant, positive influences on CO_2 production at a wet sedge site in CB. As mentioned previously, Fisher et al. (2009) suggest that the positive correlation between CO_2 production and SM may be attributed to SM being a limiting control on plant productivity and as a result also on decomposition of plants to organic matter which contributes to soil respiration. This may explain why SM has a positive influence on both GEP and ER.

Related studies performed in high Arctic wet tundra sites outside CB had similar findings to this study and the other CB studies mentioned. Looking at fens in northeast Greenland, Christensen et al. (2000) found AT and AL depth to correlate positively with photosynthesis and with NEE, as well as a positive and significant correlation between ST, AL depth, and ER. These results are the same as our results except for the correlation of AL depth to CO_2 flux and between ST and ER. Christensen et al. (2000) recognized that the strong influence of temperature, AL depth and water level on photosynthesis and potentially ER may be mixed with a simultaneous increase in biomass production. The separation of these variables' effects on CO_2 flux increases the complexity of this analysis and should be looked into in future studies. Although in this study AL depth did not have a strong or positive correlation to ER, the majority of past studies, whether recent or over 15 years ago, found and/or predict that increased thawing of the permafrost will increase CO_2 release from the ground (Weller et al., 1995; Christensen et al., 2000; Knoblauch et al., 2013). This increase in ER from greater AL depths was attributed to increased microbial degradation, which would create the potential to turn the Arctic tundra from CO_2 sinks to CO_2 sources (Weller et al., 1995; Knoblauch et al., 2013). In conjunction with AL depth, many studies also found the correlation between CO_2 production and SM or water table depth (Weller et al., 1995; Christensen et al., 2000; Welker et al., 2004; Ellis and Rochefort, 2006; Sullivan et al., 2008; Olivas, 2010). In conclusion, the results of this study agreed with the findings in multiple past, similar studies. All the physical variables found to statistically significantly influence CO_2 exchange in this study are supported in past studies. These results strengthen the concern for the fate of the vast carbon reservoirs within high Arctic wetlands from the influences their environmental conditions, which are being threatened by climate change, have on their CO_2 exchange.

3.6 Conclusions

The purpose of this study was to help predict the effect climate change will have on the CO_2 status of Arctic wetlands from the changes to their environmental conditions. The significant global carbon sink status of Arctic wetlands (Christensen et al., 2000; Callaghan et al., 2001; Ellis and Rochefort, 2006; Sullivan et al., 2008; Preuss et al., 2013) make them crucial ecosystems to research. Furthermore, this research aimed to reduce the error caused by generalizing Arctic ecosystems from a few single sample locations by using a high spatial resolution of data over a substantial time period that encapsulatied the majority of the growth season. The importance of using a high spatial resolution of data was proven in this study from the clear heterogeneity of all the biophysical variables measured within the wet sedge.

Temporal analysis of the biophysical variables showed a clear influence of AT on ST and AL depth, supporting the fact that warming Arctic surface temperatures are deepening permafrost thaw (IPCC, 2013). Air temperature looked to have an indirect effect on SM from melting the snowpack which the wet sedge's SM appeared to rely upon for its hydrological input. The temporal trend of AT, SM, and snowpack melt showed to correlate more with each other than the influence of rainfall on SM in the summer of 2015. This was also observed in Ramsay et al.'s study (2015) on the same wet sedge in the summer of 2014 and Atkinson's (2012) study on another wet sedge at the CBAWO in 2006. However, unlike in 2014, the perennial snowpack completely melted near the beginning of the peak growth season (late July), which has rarely been witnessed since the CBAWO began operation in 2003 (Atkinson, 2015). From spatial analysis of the data, the drier, warmer soils in the wet sedge had deeper AL depths while the wetter and saturated soils were generally cooler with shallower ALs. From these observations it may be concluded that the wet sedge is at risk of drying out from a shrinking hydrological input and increased AL depths from warming surface temperatures.

ER and GEP appeared to have similar temporal and spatial trends that likely coincided with trends in vegetation (PVC and production) (Vourlitis et al., 1993; Boelman et al., 2003) as plant respiration can make up a significant portion of ER (Boelman et al., 2003). However, what spatial analysis emphasized was the non-uniformity of NEE across the wet sedge, causing some areas to act as CO_2 sources while the wet sedge on average remained a CO_2 sink over the sample season. The NW quadrant averaged to be a CO_2 source multiple times over the growing season, which was characteristically the quadrant with drier, warmer, and deeper soils. This, along with other temporal observations implies that ER rates are accelerated by warmer temperatures and is higher in drier, deeper soils without a compensating increase in GEP. Statistical analysis showed, on the other hand, that SM positively influenced both GEP and ER. The positive correlation with ER could again be attributed to greater vegetation in areas with higher SMs causing more plant respiration (Boelman et al., 2003). However, the most statistically significant predictor of ER was AT which had a positive influence, supporting the fact that Arctic warming may accelerate ER rates (Vourlitis et al., 1993; Weller et al., 1995; Welker et al., 2004; Knoblauch et al., 2013). Air temperature was not a statistically significant predictor of GEP. Instead, SR had the statistically highest influence on GEP, followed by SM. SM's statistical influence on GEP was greater than its influence on ER, indicating that GEP would be more affected by drying soils than ER. Solar radiation also had a statistically significant influence on ER, but again was lower than SR's influence on GEP. Therefore, if Arctic surface temperatures continue to rise while SM decreases from thickening ALs and disappearing hydrological inputs, ER rates may overcome GEP rates, converting these vital CO_2 sinks to CO_2 sources.

Continued high spatial and temporal resolution monitoring of important Arctic ecosystems like the wet sedge in this study is recommended to gain knowledge on the long term effects climate change is having on the Arctic environment. It is important to return to the same study sites to monitor these effects so yearly data and its corresponding weather can be assessed. Moreover, the spatial heterogeneity within the wet sedge proven from the spatial analysis in this report emphasizes the benefit that comes with using high spatial resolutions of data. It would further improve accuracy in estimates on the GHG exchange in Arctic ecosystems if even higher spatial resolutions of data were used when feasible. Finally, distinguishing which environmental variables have direct and indirect influences on CO_2 exchange would provide greater understanding on the key controlling factors of CO_2 flux. Ramsay et al., (2015) also recommends recording soil type and the organic layer depth of sample site locations so their influence on other biophysical variables like SM and CO_2 flux can be accounted for.

4. Discussion

4.1 Results Acceptations/Rejections of Hypotheses

The main objective of this study was to ultimately use temporal and spatial analysis to identify environmental influence on CO_2 exchange in a high Arctic wetland. The abiotic factors assessed were ST, SM, and AL depth, along with weather variables AT, precipitation, and SR. First, the temporal analysis of the environmental variables (ST, SM, AL depth, AT, and SR) showed ST's trend to be a close replication of AT's fluctuations over the growing season. AL depth increased at a fairly steady, more gradual rate with ST's and AT's increase. The average SM of the wet sedge gradually increased until it plateaued in mid/late July, around the same time the snowpack, its hydrological input, melted entirely. From graphical analysis the SM appeared to be more influenced by the melt of the snowpack than the precipitation events. Spatial analysis of the abiotic factors showed that the whole of the wet sedge did not respond to the weather as one, but was dependent on the area studied. For example, the SM of the N half of the wet sedge, closest to the snowpack, remained fairly steady throughout the sample season, while the S half was the area to show the most change while the snowpack was melting. However, the mixed ANOVA indicated that the differences between the quadrants' temporal trends were not statistically significant. SM also showed to decrease from W to E, with a nearly opposing trend in ST and AL depth. These trends were observed from a combination of comparing quadrant means, an ANOVA, and spatial interpolations. Using these analysis methods there was a clear E/W trend for both GEP and ER, resulting in no discernable spatial trend for NEE. GEP and ER followed a similar temporal trend to ST and AT, increasing in mid/late July then dropping in early August as the weather cooled.

A MLR analysis allowed us to determine which environmental variables had a statistically significant influence on CO_2 exchange. This analysis indicated that GEP was most dominantly influenced by SR, followed by SM and then slightly but significantly influenced by ST at a 5 cm depth. ER's top predictor was AT followed by SR and SM, and was slightly but significantly influenced by AL depth. Weather conditions, therefore, seemed to be the dominant predictors of CO_2 flux, yet the abiotic factors of the wet sedge still had significant influence on the sedge's CO_2 exchange. Referring back to the Hypotheses outlined in Chapter 1, we compared how these results agreed with the Hypotheses and the findings from past, similar studies.

The clear correlation between ST, AL depth, and AT support Hypothesis 1: *ST and AL depth will increase with AT over the growing season.* From the temporal graphs and kriged surfaces of the data, we can see that both ST and AL depth increased as the AT rose throughout July and cooled in early August. ST more closely followed the fluctuations in AT in mid/late July, while AL depth steadily increased until early August. From the kriged surfaces we could see that not all areas of the wet sedge warmed at the same rate, but all areas appeared to increase in ST and AL depth to some extent. Ramsay et al. (2015) had similar observations of the wet sedge in 2014, with less ST fluctuations in late July when they found the wet sedge stabilized, similar to ST's trend in late July of 2015. Chapin et al. also found ST and thaw depth increased with ATs in their 1995 study, when the climate was expectedly cooler. Although Ramsay et al.'s (2015) sample season did not extend into August, they predicted that as the temperatures dropped in August the wet sedge would begin to freeze and create a "broken thaw pattern".

The steady average increase in SM until mid/late July after which SM appeared to stabilize does not quite support Hypothesis 2: *SM will remain stable over the growing season from receiving meltwater from the perennial snowpack, and have an E/W trend of decreasing*

SM. This hypothesis was mostly derived from Ramsay et al.'s study performed in 2014 on the same wet sedge, who saw minor temporal variations in SM over the growing season, attributing this to the constant hydrological input from the perennial snowpack. This could be due to the difference in weather from 2014 to 2015, with the warmer temperatures in 2015 causing the perennial snowpack to uncommonly melt completely shortly after mid-July. However, the ANOVA showed that SM only had statistically significant variation in SM in week 3, during which there was a spike in AT and little precipitation compared to the few "weeks" beforehand. So statistically speaking, the SM had minimal variation over the sample season. Moreover, the wet sedge's SM did not appear to be very influenced by the rainfall. There were no noticeable increases in SM that aligned with the large precipitation events, agreeing in part with this Hypothesis and Ramsay et al.'s (2015) conclusions that that majority of the wet sedge's SM comes from the perennial snowpack.

From the spatial aspect of our analysis, it was evident that not all areas of the wet sedge had the same temporal trends of SM. The NE quadrant remained the most consistent over the growing season while the SE quadrant saw the greatest increase in SM, and the west half showed a slower, steadier increase. Ramsay et al. (2015) had drew the same observations from their spatial analysis, finding not all areas of the wet sedge had a relatively stable SM value, with the NE area decreasing in value while the SE corner increased during peak growth. Another similar finding from our two studies was the general E/W trend in SM across the wet sedge, supporting the latter half of Hypothesis 2. SM was the only environmental variable to have a statistically significant variation within the wet sedge, specifically between the SE and NW quadrants. The significant difference between these two quadrants was evident when looking at the spatially interpolated surfaces of SM. It was also evident from these kriged surfaces that SM was generally higher in the E of the wet sedge and decreased towards the W, with the exception of the NE corner. Therefore, hypothesis 2 is accepted by the lack of statistically significant variation in SM over the sampling season, along with a clear E/W trend observable from kriged surfaces and the ANOVA which showed statistically significant variation from the SE to the NW of the wet sedge.

Active layer depth's opposing spatial trend to SM's E/W trend supports Hypothesis 3: *Areas with highest SM contents will coincide with areas of shallower AL depths*. Although AL depth did not show to have statistically significant variation within the wet sedge, it is clear from the kriged surfaces and a comparison of quadrant means that AL depth is generally lower in the E and greater in the W. In actuality, the quadrant with the average greatest SM content, SE, had the lowest AL depth in our 2015 sample season. The contrasting hot and cold spots also evident from the kriged surfaces showed a clear and negative correlation between SM and AL depth. The deepest AL spots, found along the N and W borders of the wet sedge, had the driest soils, which were also apparent in Ramsay et al.'s 2014 study (2015). Since less energy is required to warm and thaw soils with lower SM contents, these findings are in agreement with the literature (Ramsay et al., 2015).

Another finding of this study in agreement with the literature was the similarity of GEP and ER's temporal trends throughout our sample season. This is not only apparent from GEP and ER's temporal plots, but from the statistical analysis of temporal variation. The mixed ANOVA results indicated that NEE, ER, and GEP were statistically stable the first two "weeks" with a statistically significant variation in week three followed by a relatively stable middle period, then significantly fluctuated towards the end of the season. These results support Hypothesis 4: *ER and GEP will follow similar temporal trends over the growing season* developed from

Christensen et al. (2000), Boelman et al. (2003), and Vourlitis et al. (2003) who also found fairly simultaneous changes of GEP and ER in their studies. Atkinson (2012) did not find NEE, GEP, or ER to vary statistically significantly in the high Arctic wet sedge he studied in 2006. Atkinson (2012) did, however, note that other studies in the low and mid Arctic seemed to have statistically significant variation in all CO_2 flux components in the early and late growth periods, surrounding a stable peak growth period, which aligned with our results. Vourlitis et al. (2003) state the reason for simultaneous ER and GEP temporal trends as due to biophysical factors that positively influence both, such as specific leaf area and tissue nutrient content. However, GEP's fluctuations, although similar in pattern to ER, were greater in magnitude along with GEP's average flux rate, which kept the wet sedge a sink for CO_2 over our sample season.

The MLR results on ER showed AT to be the strongest predictor, followed by SM and SR with a minor yet significant correlation to AL depth. These four environmental variables agree with some of the environmental influences on ER suggested in the literature which were the basis for Hypothesis 5: *CO_2 production (ER) will increase with AT, ST, AL depth, and lower SM.* One difference between this hypothesis and our results is SM's positive correlation to ER, as opposed to the majority of the literature which suggests ER will be greater in areas with drier soils since they have increased aerobic root and microbial respiration (Billings et al., 1982; Weller et al., 1995; Christensen et al., 2000; Ellis and Rochefort, 2006; Sullivan et al.. 2008; Olivas, 2010). Some studies suggested soil drying also increased photosynthesis (Christensen et al., 2000; Olivas, 2010), yet in this study SM was found to have a positive influence on GEP along with ER. This can also be seen from the spatially interpolated surfaces of the wet sedge, where ER and GEP appeared to have a general E/W trend of decreasing magnitude, similar to SM's spatial trend. Fisher et al. (2009) on the other hand, noted that SM is a key factor controlling plant productivity and in turn, production of organic matter to be stored in the soil, thereby influencing the amount of soil decomposition, a CO_2 source, that can occur. This means that if SM is insufficient for plant production, it can limit both GEP and ER (Fisher et al., 2009). However, when the MLR was performed for NEE, a statistically significant and negative correlation to SM was produced, indicating SM had a stronger influence on GEP since a negative NEE implied GEP was greater than ER. Moreover, our MLR results did not show a correlation between ST and ER, as predicted in this hypothesis and from the literature. Instead, ER was found to be positively influenced by SR, not included in this Hypothesis, which likely had a positive correlation with ST. Solar radiation's influence on ER, which was not as prevalent in the literature, could be tied with SR's correlation to AT, where generally days in CB with greater ATs were days with higher SR. Again, SR appeared to be negatively and significantly correlated to NEE, indicating SR had a stronger influence on GEP than ER. AT was the only significant predictor of NEE that had a positive influence, suggesting that AT's influence on ER was greater than GEP if an influence of AT on GEP existed. Air temperature's positive influence on ER was frequently presented in past studies and was often found to be in conjunction with SM's influence (Billings et al., 1982; Weller et al., 1995; Christensen et al., 2000; Harazono et al., 2006; Sullivan et al., 2008; Olivas, 2010). Finally, the MLR results only presented AL depth to have a slight and negative correlation to ER. This opposes the predicted positive influence AL would have on ER in Hypothesis 5, as suggested in the literature (Christensen et al., 2000; Ellis and Rochefort, 2006). AL depth's negative influence on ER in our results may have arisen from SM's stronger influence on ER, which also negatively correlates to AL depth found in our spatial analysis, where areas of higher SM were found to have lower AL depths.

4.2 The Carbon Cycle in Arctic Wetlands

The ultimate reason for this study was to help in the understanding of how the vast carbon stocks in Arctic wetlands are affected by their environmental conditions so the risk to these carbon stocks from climate change can be better predicted. Understanding the key controls on carbon flux in these ecosystems is crucial to accurately develop models for GHG exchange projections (Friborg et al., 2000). It is without question that surface ATs in the Arctic are rising and have been for decades at a greater rate than the rest of the world (Chapin et al., 1995; Crowley 2011; IPCC 2013). From our study there was a clear correlation between AT, ST, and depth to the permafrost, both increasing as ATs rose. These results indicated that as Arctic ATs continue to rise, STs will increase and ALs will thicken in high Arctic wetlands. These findings have been predicted and/or found in earlier Arctic studies (Weller et al., 1995; Overpeck et al., 1997; Sullivan et al., 2008; Knoblauch et al., 2013). The seasonably warm temperatures during the 2015 growing season at the CBAWO resulted in a complete melt of the perennial snowpack that acts as the hydrological input to the wet sedge in study, rarely witnessed since the opening of the CBAWO in 2003 (Atkinson, 2012; Atkinson, 2015; Ramsay et al., 2015). This confirms Callaghan et al.'s prediction in 2011 that climate change would cause the depletion or shrinkage of Arctic snowpacks. These semi-permanent or permanent snowpacks are important hydrological inputs for Arctic wetlands that are at risk of drying out and deteriorating as these snowpacks deplete (Callaghan et al., 2011). The coinciding melt of the snowpack and increase in the wet sedge's average SMs until the snowpack disappeared in late July showed the dependence our wet sedge in study has on the perennial snowpack for its soil water. The wet sedge's SM did not appear to be affected by the large precipitation events during our sample season of 2015. This potentially means the predicted increase in rainfall the Arctic has been and is expected to experience (IPCC, 2013) may not prevent these wetlands from drying out. Ramsay et al. (2015) found the same wet sedge's SM was not affected by the rainfall events in 2014 but attributed the relatively stable SM in the wet sedge to the steady hydrological input from the perennial snowpack, which did not completely melt that year. The combination of a smaller hydrological input (decreased snowpack volume) with deeper ALs may enhance soil drying as the hydrological input will likely become less able to replenish the SM as the soil water drains to deeper depths. This may be the cause for the negative correlation between AL depth and SM apparent from the spatial analysis of the wet sedge in this study, with deeper ALs also correlating with higher STs. Perhaps soil drying from a smaller hydrological input could create a positive feedback system within itself, with warming ATs causing deeper ALs and drier soils, which in turn take less energy to heat up than saturated soils (Ramsay et al., 2015). This could result in higher STs causing deeper soil thawing and thus deeper soil water drainage, reducing near-surface SM.

With less SM near the soil surface, plant growth and productivity could be limited thereby reducing photosynthesis, a key uptake method of CO_2 from the atmosphere (Welker et al., 2004; Ellis and Rochefort, 2006; Fisher et al., 2009). Warmer Arctic ATs and lowered water tables would increase root respiration by increasing evapotranspiration rates, as well as enhance aerobic microbial respiration (Billings et al., 1982; Weller et al., 1995; Welker et al., 2004). In addition, GEP would be largely reduced at the end of the growing season and beginning of the fall as shorter daylight hours limit photosynthesis, while microbial respiration from the prolonged warmer temperatures continues (Billings et al., 1982; Welker et al., 2004). As such, the net carbon storage in these ecosystems is likely to decrease with the accelerating ER and potential reduction in GEP, threatening to convert Arctic wetlands from carbon sinks to carbon sources (Billings et al., 1992; Welker et al., 2004; Ellis and Rochefort 2006). Multiple observations from our data support these theories. First, the NW quadrant of the wet sedge, characterised as the drier, warmer, and deeper (AL) quadrant, averaged to be a CO_2 source two of the eight "weeks" over the growing season, one just before and the other during peak growth (mid-late July). The wetter, cooler, and shallower E side of the wet sedge remained the strongest CO_2 sink section after week 2, marking the beginning of the growth season. Second, the highest average ER rates recorded in the wet sedge were during week 3, the only week in which there was a statistically significant change in SM which was a significant decrease. This coincided with a spike in AT and ST and a high SR recorded around July 12th, shortly before the peak growth period. The greatest GEP rates did not occur at this time, and although on average the wet sedge remained a CO_2 sink it was a weaker sink than at other times over the sample season, with the NW quadrant averaged as a source in week 3. Third, our statistical analysis showed that the top predictor of ER was AT, followed by SR and SM, while GEP's top predictors were SR and SM. Although SM was positively correlated to ER, its influence on GEP was more statistically significant, indicating a drop in SM would have a more substantial effect on GEP than ER. Solar radiation being GEP's most statistically significant predictor also emphasizes GEPs dependence on SR suggested in the literature. ER's positive and large statistically significant correlation to AT indicates that it would be much less affected by a drop in SR and SM than GEP would be. Hence, these findings from our results support the theory that drier, warmer, and potentially deeper thawed soils have greater ER rates without having as large of an effect on GEP. If wetlands like the wet sedge at the CBAWO warm, thaw, and dry out, this would likely cause a positive feedback effect on climate change from increased ER but decreased or stable GEP (Billings et al., 1992; Welker et al., 2004).

The drying of Arctic wetlands may increase CO_2 production, but this will not necessarily result in a net carbon loss from these ecosystems as soil drying reduces CH_4 production (Vourlitis et al., 1993; Friborg et al., 2000; Wagner et al., 2007; Knoblauch et al., 2013; Preuss et al., 2013). Wetlands are a significant source of CH_4 as their saturated conditions are favourable to methanogenic activity (Vourlitis et al., 1993; Christensen et al., 2000; Harding et al., 2001; Wagner et al., 2007; Knoblauch et al., 2013; Preuss et al., 2013) and therefore the net carbon exchange of Arctic wetlands is influenced by CH_4 production in these ecosystems. The warming and increased thaw of Arctic wetlands' soils with rising ATs have been shown to increase CH_4 production depending on the extent that or if SM decreases (Vourlitis et al., 1993). If SM does not decrease due to increased precipitation in the Arctic, CH_4 emissions will likely increase from warmer, deeper, yet still moist soils. From the literature, it appeared that the water table level has the strongest control on methanogenesis (Preuss et al., 2013), which is directly connected to AL depth and ST (Ramsay et al., 2015). Thus, AL depth and ST could have both positive and negative influences on CH_4 production. CH_4 must therefore be measured in conjunction with CO_2 to determine the net carbon exchange of these ecosystems.

Furthermore, N_2O emissions have also been suggested to increase with greater soil saturation and warmer temperatures (Wagner et al., n.d.; Callaghan et al., 2011), indicating production could decrease if Arctic wetlands like the wet sedge in focus dry out in the future. However, much research is required on N_2O exchange in Arctic ecosystems and their environmental controls to be able to make these sort of conclusions. Ultimately, to determine if the warming Arctic temperatures' effects on Arctic wetlands' GHG exchange will create a positive feedback effect, more research is required on all significant GHG gases produced/absorbed in these ecosystems.

4.3 Future Research Applications & Considerations

This research will aid in the understanding of how these ecosystems respond to changing environmental conditions within a given season and across multiple years, such as their response to decreasing SM content due to receding snow packs. With climate change occurring more rapidly in the Arctic than the rest of the world and development in the North gaining greater potential, there is a need to understand the Arctic environment and how it will respond to future changes. Several past studies have shown that the long term effects of warming ATs can vary from short term effects (Weller et al., 1995; Olivas, 2010). For instance, short term responses of ecosystems to rising temperatures and drier soils may be greater CO_2 emissions without higher photosynthesis rates, but new vegetation species could eventually invade these areas resulting in greater GEP (Weller et al., 1995). Therefore, continual monitoring of Arctic ecosystems like the wet sedge at the CBAWO should be performed to assess how the environmental conditions and carbon storage are being effected on a long term basis, which this projects aims to help accomplish. In addition to long term monitoring, an expansion of the sampling season in Arctic ecosystems to cover the autumn season would be ideal as wetlands' environmental conditions destabilize after peak growth (Atkinson, 2012; Ramsay et al., 2015). Past research has suggested that higher temperatures may cause ER to increase into the autumn season without concurrent increases in photosynthesis due to autumn's shorter daylight hours (Welker et al., 2004). Hence, the carbon exchange in Arctic's autumn season may have a substantial effect on the Arctic's carbon budget.

The CBAWO on Melville, Island, NU, where this study takes place, is a "comprehensive watershed research facility" that aims to study and monitor the long term impacts of climate change on the high Arctic environment (CNNRO, n.d.). Research here takes place across a pair of watersheds, comprised of rivers and streams, multiple types of ecosystems and tundra sites, and downstream lakes. The research conducted here ranges from terrestrial to aquatic studies on fresh water systems, along with the biogeochemical process in both. It monitors the weather at Cape Bounty and the state and processes occurring in the surface waters, vegetation, soil, and permafrost. The CBAWO began operation in 2003 and is a seasonally opened station, with studies conducted from anywhere between May until the end of August dependant on the specific research needs and feasibility. The MET tower and numerous data loggers recording SM and various environmental parameters are implemented and logging year round. All of the research conducted here contributes to a greater, overall monitoring of environmental change in the high Arctic due to global warming (CNNRO, n.d.), which this study will be a part of. This study will also contribute to base data for future studies looking at the carbon exchange in high Arctic ecosystems as the Arctic continues to warm and experience greater effects.

There has been one study by Wagner et al. (n.d.) that collected trace gas flux data from the same wet sedge in our study, only at a lower spatial resolution. Moreover, four CO_2 flux autochambers were installed by Queen's University at the same wet sedge meadow in 2015. The autochambers will likely be in operation over the growing seasons of the next several years, depending on funding. The combination of these CO_2 flux recordings with our CO_2 measurements will hopefully allow the change of CO_2 flux over time in this particular wetland to be observed. Furthermore, Ramsay et al. (2015) collected a very high resolution of data on abiotic factors at this wet sedge meadow during the growing season of 2014, which included AL depth, SM, and ST measurements. Ramsay et al. (2015) also tracked the same perennial snowpack's melting process in 2014. Using this data in conjunction with our data collected in the 2015 growing season, the variance and similarities in the environmental conditions of the wet sedge and how they may relate to the state of the perennial snowpack can be assessed.

Finally, although not included in this report, satellite imagery of this wet sedge has been taken several times over the last decade. Having a high spatial resolution of data to compare with satellite imagery, otherwise considered remotely sensed data, can provide the possibility of using remote sensing for monitoring environmental change in these remote areas. Comparing the *in situ* data to the remotely sensed data may allow the development of spatial models that examine trace gas flux patterns in relation to environmental parameters, like SM (Atkinson, 2012). This is part of a larger, long term research study being conducted at the CBAWO. Its goal is to aid in developing spatial and spectral models to understand the biophysical variables in Arctic ecosystems and their responses to environmental change and disturbance (Atkinson, 2015).

5. Conclusions

By furthering our understanding of the spatial and temporal variability of CO_2 flux within wet sedge ecosystems, the scientific community will be a small step closer to determining whether climate change in the Arctic is creating a positive or negative feedback system from its effect on the Arctic's carbon budget. It is crucial to know whether a positive feedback effect would be created, as this would accelerate climate change and its impacts not just in the Arctic but over the globe. To achieve this knowledge, high temporal and spatial resolutions of data are required within individual types of ecosystems so their variabilities are accounted for to minimize error when using the data for estimations such as GHG projections. Using a high spatial and temporal resolution of data in this study proved that heterogeneity did exist within the wet sedge, and its environmental conditions and CO_2 flux varied over time.

From analysing the temporal trends, ST and AL depth had a clear positive correlation with AT, increasing and decreasing as AT rose then dropped over the sample season. This implies that the AL depth will continue to thicken as temperatures rise in the Arctic, worsening permafrost degradation. Spatial analysis of the environmental variables showed that the areas with deeper AL depths generally had drier and warmer soils. The SM of the wet sedge also appeared to be more greatly influenced by the snowpack melt as its hydrological input than to precipitation, also observed in the summer of 2014 (Ramsay et al., 2015). However, the perennial snowpack disappeared at the beginning of peak growth (mid/end July) in 2015, which will lead to a smaller source of soil water for the following year. The disappearance of snowpacks, like the one in this study, in combination with thickening ALs enhance the risk of wetland deterioration through soil drying (Callaghan et al., 2011; Ramsay et al., 2015). Low SMs can limit vegetation productivity in these ecosystems, reducing GEP while ER is accelerated in warm and dry soils, potentially causing a positive feedback effect to climate change (Billings et al., 1992; Welker et al., 2004; Ellis and Rochefort, 2006). Although the statistical results from our study show ER to be positively influenced by SM, spatial and temporal analysis show that areas and time periods with warmer and drier soils largely increased ER without the same effect on GEP. ER was most significantly influenced by AT, while GEP had SR and SM as its top predictors. Thus, from our results increasing ATs and decreasing SMs may increase ER without increasing GEP, threatening the shift of Arctic wetlands from carbon sinks to carbon sources.

To accurately predict if Arctic wetlands like the wet sedge in this study will shift from carbon sinks to carbon sources, CH_4 and N_2O flux need to be researched. The environmental results of this study suggest that CH_4 production could decrease with drying soils as the key control of methanogensis has been found to be the water table level (Christensen et al., 2000; Preuss et al., 2013). However, warming soils also accelerate CH_4 production, so if an increase in ST occurs without a decrease in SM, CH_4 production and emissions will likely increase (Vourlitis et al., 1993). N_2O, although does not contain carbon, is a GHG that is produced in these wetlands that needs to be studied in order for climate change's effects on N_2O emissions to be understood. With this, longer sample seasons to capture autumn GHG exchange, and long term monitoring of Arctic wetlands, the threats climate change is impeding on these net GHG sinks can be better projected.

Appendix A: Tukey HSD Post-Hoc Test Results

Table 9: Tukey HSD Post-Hoc Results (p values) of Within Subjects Effects (Week). (Highlighted cells indicate p<0.05)

NEE	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
Week 1	-	1	1.000	.006	1.000	.000	.015	.001
Week 2		-	1.000	.006	1.000	.000	.036	.001
Week 3			-	.011	1.000	.084	1.000	.372
Week 4				-	.053	1.000	.123	1.000
Week 5					-	.045	1.000	1.000
Week 6						-	.000	1.000
Week 7							-	.021
Week 8								-
ER	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
Week 1	-	.071	.000	.000	.000	.000	.010	.000
Week 2		-	.000	.000	.000	.000	1.000	.007
Week 3			-	.000	.160	.099	.000	.000
Week 4				-	.370	.994	.000	.087
Week 5					-	1.000	.000	.000
Week 6						-	.000	.000
Week 7							-	.002
Week 8								-
GEP	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
Week 1	-	.084	.000	.000	.001	.000	.000	.000
Week 2		-	.000	.000	.013	.000	.048	.000
Week 3			-	1.000	1.000	1.000	.000	1.000
Week 4				-	1.000	1.000	.000	1.000
Week 5					-	.088	.092	1.000
Week 6						-	.000	.004
Week 7							-	.000
Week 8								-
ST (5 cm)	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
Week 1	-	.128	.000	.000	.000	.000	.086	.000
Week 2		-	.000	.000	.000	.000	.253	.000
Week 3			-	.000	1.000	1.000	.000	.000
Week 4				-	.000	.000	.000	.000
Week 5					-	1.000	.000	.000

Week 6						-	.000	.000
Week 7							-	.000
Week 8								-
ST (10 cm)	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
Week 1	-	1.000	.000	.000	.000	.000	1.000	.005
Week 2		-	.000	.000	.000	.000	1.000	.001
Week 3			-	.000	.000	.000	.000	.000
Week 4				-	.000	.000	.000	.000
Week 5					-	.029	.000	.000
Week 6						-	.000	.000
Week 7							-	.000
Week 8								-
SM	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
Week 1	-	1.000	1.000	.758	.262	.178	.345	.227
Week 2		-	1.000	.491	.078	.040	.164	.109
Week 3			-	.001	.000	.001	.008	.001
Week 4				-	.470	.385	1.000	.394
Week 5					-	1.000	1.000	1.000
Week 6						-	1.000	1.000
Week 7							-	1.000
Week 8								-
AL Depth	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
Week 1	-	1.000	.000	.000	.000	.000	.000	.000
Week 2		-	.039	.000	.000	.000	.000	.000
Week 3			-	.032	.000	.000	.000	.000
Week 4				-	.001	.000	.000	.000
Week 5					-	.024	.220	.000
Week 6						-	1.000	.610
Week 7							-	.814
Week 8								-

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