SPATIAL VARIATION OF SOIL METHANE AND NITROUS OXIDE EMISSIONS IN SUBARCTIC ENVIRONMENTS OF CHURCHILL, MANITOBA

BY

JACQUELINE A. CHURCHILL

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Department of Soil Science
University of Manitoba
Winnipeg, Manitoba

ABSTRACT

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Global warming, associated with elevated levels of greenhouse gases is expected to alter hydrologic regimes, permafrost extent and vegetation composition in the Hudson Bay Lowlands (HBL). Greenhouse gas (respiration, CH_4 and N_2O; GHG) emissions and soil gas concentrations were determined over the growing seasons of 2005 and 2006 from numerous habitats within three dominate ecosystems within the HBL, a polygonized-peat plateau, northern fringe boreal forest and palsa fen, near Churchill, Manitoba. Nitrous oxide emissions and soil concentrations were near zero however, a trend for very slight production of N_2O was observed at dry aerobic sample positions while very slight consumption occurred at very wet sample locations. "Hot-spots" of intense CH_4 emissions and soil concentrations occurred in the sedge-dominated areas of high moisture and plant productivity, whereas areas of low moisture and plant productivity resulted in slight CH_4 consumption. Of all the ecosystems studied, the palsa fen had the greatest CH_4 production, with carbon losses from CH_4 occurring at rates of approximately 50 g C m^{-2} during the growing season. A peat plateau ecosystem site was also used to compare GHG emissions using a similar vegetation type (*Cladina stellaris*) and under differing soil conditions. Based on the results, slight gradients in soil conditions such as moisture content, peat accumulation and active layer depths altered respiration emissions but did not significantly affect CH_4 and N_2O fluxes. The differences in GHG emissions were not

as great as those between different plant community types, which suggest plant community types could be used to predict GHG emissions in similar environments.

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FOREWORD

This thesis has been prepared in manuscript format following the guidelines established by the Department of Soil Science at the University of Manitoba. The reference style used in this document is from the Canadian Journal of Soil Science. Chapters 2, 3 and 4 may be submitted to a peer-reviewed journal, to be decided in the future. For all papers, I will be the lead author and co-authorship will be decided according to contribution.

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LIST OF ABBREVIATIONS

α – probability level
μg – microgram
μL – microliter
μS – microseimen
ANOVA – analysis of variance
BD – bulk density
C – carbon
CCG – coarse cherty gravelly
CG – cherty gravelly
CH_4 – methane
cm – centimeter
CNSC – Churchill Northern Studies Centre
CO_2 – carbon dioxide
CS – coarse sand
CV – coefficient of variation
d – day
DO – dissolved oxygen
DOC – dissolved organic carbon
EC – electrical conductivity
epm – excersions per minute
Fen – eutrophic palsa fen site
FS – fine sand
g – gram
G – gauge
GC – gas chromatograph
GF/F – glass-fiber filter
GHG – greenhouse gas
GLM – generalized linear model
GMC – gravimetric moisture content
Gt – gigaton
HBL – Hudson Bay Lowlands
Hummock – peat mound dominated by moss and vascular plant species at the Fen site
Ice Wedge – ice crack formed in between polygon peat mounds dominated by vascular plants and moss species at the Peat site
km – kilometer
L – liter
Lower Sedge – peat lowland at the Peat site covered with moss, sedge and vascular plants
m – meter
mg – milligram
mL – milliliter
mm – millimeter
Moss (*Hylocomium*) – *Hylocomium splendens/Tomenthypnum nitens* covered mounds within the Spruce/Larch forest at the Spruce site
Moss (*Sphagnum*) – *Sphagnum* mounds within the Spruce/Larch forest at the Spruce site

ms – millisecond
MS – medium sand
mV – millivolts
n – number of replicates
n – number of moles of gas [mol]
N – nitrogen
NEE – net ecosystem exchange
N_2 – nitrogen
N_2O – nitrous oxide
NO – nitric oxide
NO_3^- – nitrate
NMHC – non-methane hydrocarbons
NOWES – Northern Wetlands Study
O_2 – oxygen
O_3 – ozone
ORP – oxidation-reduction potential
p – pressure [Pa]
P – probability level
Peat – polygonized-peat plateau site
pH – potential of hydrogen
Polygon Top – tundra polygon peat mound dominated by lichen species at the Peat site
Pond Edge – submerged peat ledge in the edge of Frisbee pond at the Peat site
Pool – pools of standing water located in between Hummocks at the Fen site
ppm – parts per million
psi – pound per square inch
PVC – polyvinyl chloride
r – correlation coefficient
R – gas constant [8.3143 m^3 Pa K^{-1} mol^{-1}]
R^2 – coefficient of determination
Riparian – wet area surrounding Frisbee pond at the Peat site and dominated by *Carex aquatilis* and *Hypnum* species
s – second
SAS – Statistical Analysis Software
SD – standard deviation
SE – standard error
Sedge-Lawn – wet peat mat areas dominated by *Carex aquatilis* and *Drepanocladus vernicosus* at the Fen site
Sedge-Moat – a moat like depression with dominant *Carex* and *Tomenthypnum nitens*, surrounding the edge of Lake Stanley at the Spruce site
SpCond – specific conductivity
Spruce – white spruce/ larch forest site
Subset – the 32 or 36 sampling locations sampled weekly at the Peat and Spruce sites
T – temperature in kelvin [K]
TDR – time domain reflectometery
$Temp_{2.5}$ – soil temperature at 2.5 cm depth
$Temp_{15}$ – soil temperature at 15 cm depth
$Temp_{air}$ – air temperature at approximately 1.25 m above ground

Tg – teragram
Upper Lichen – *Cladina stellaris* covered peat upland at the Spruce site
Upper Sedge – peat upland at the Peat site covered with moss, sedge and vascular plants
UV – ultra violet
V – volume [m^3]
VCS – very coarse sand
VMC – volumetric moisture content
VOC – volatile organic compounds
yr – year

1. INTRODUCTION

1.1. Greenhouse Gases and Climate Change

Methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) play an important role in atmospheric processes and their emissions to the atmosphere are controlled by both natural and anthropogenic factors. The atmospheric concentrations of these gases have increased rapidly over the last hundred years, due to anthropogenic activities, namely the burning of fossil fuels, deforestation and food production (IPCC, 2001). Carbon dioxide is the most abundant of the greenhouse gases in the atmosphere, however, CH_4 and N_2O are more effective at absorbing infrared radiation. Methane and N_2O have warming potentials of 23 and nearly 300 times greater than CO_2, over a period of 100 years. About one-third of CH_4 emissions and two-thirds of N_2O emissions, come from soils (Smith et al., 2003). Methane and N_2O, also occur in the atmosphere long enough to be transported into the Earth's stratosphere, where they can lead to ozone destruction (IPCC, 2001).

Global warming is expected to occur as concentrations of greenhouse gases in the atmosphere increase. Changes such as an increase in air temperature, as well as changes in the amount and timing of precipitation, especially in high latitude regions, are expected consequences of global warming (Phoenix and Lee, 2004). These changes could result in increased melting of glaciers, rising sea levels, changes and reduction in sea ice, all of which could result in major changes in natural and agricultural environments (IPCC, 2007). The expected future changes in climate due to global warming, are not thought to occur at the same rates all over the globe. The most pronounced changes are expected at high latitudes, in subarctic and arctic environments. Therefore, in order to be able to predict if climate change will alter greenhouse gas (GHG) emissions, we must be able to understand the processes leading to current CH_4, N_2O and CO_2 emissions. This understanding can then be used to predict if warming will increase or decrease the rate of GHG emissions and extrapolate these concepts to a regional, and ultimately, a global scale.

1.2. Importance of Subarctic Terrestrial Environments in Understanding Climate Change: The Hudson Bay Lowland Region

Southwestern Hudson Bay and its coastal zone are sensitive habitats for a large range of flora and fauna and contain the second largest contiguous peat accumulation (Rouse et al., 2002) and third largest wetland in the world (Ricketts et al., 1999; ArcticNet, 2007). The Hudson Bay Lowland (HBL) region is made up of subarctic and boreal ecosystems and is an important repository of organic carbon in Canada and the world (Rouse et al., 2002). General circulation models predict warming of 2 to 6^{o}C, or as much as 8^{o}C in the high arctic by 2070, with the greatest warming in the winter months (Phoenix and Lee, 2004). Precipitation is also predicted to increase by an annual mean of 11%, with the most significant changes occurring at high latitudes in the winter. Arctic ecosystems are highly influenced by temperature and increases can lead to changes in permafrost extent, active layer depth, snow cover, plant community composition, hydrology and soil processes (Phoenix and Lee, 2004). These changes may cause an alteration in the amount and rate of emissions of CO_2, CH_4 and N_2O. Therefore, subarctic and boreal ecosystems, like the HBL, are expected to be among the most sensitive to changing future climatic conditions (Christensen et al., 2004).

Peatlands cover over 365,000 km^2 of Alberta, Saskatchewan and Manitoba (Turetsky et al., 2002). They also occupy about 12% of Canada's land area with 97% occurring in the boreal and subarctic regions (Tarnocai, 2006) and contain approximately one-third of the world's soil carbon pool (Pastor et al., 2003). Globally peatlands contain between 400 and 500 Gt of carbon (Roulet, 2000). Northern peatlands play an important role in global cycling of carbon through the exchange of CO_2 with the atmosphere, emissions of CH_4, emissions of volatile organic compounds (VOC) from vegetation as well as production and export of dissolved organic carbon (DOC) (Moore et al., 1998; IPCC, 2001). Water saturated peat soils have been found to be large sinks for atmospheric CO_2 and are large carbon stores. Carbon accumulation in undrained boreal and subarctic peatlands is estimated at a rate of 13 to 20 g m^{-2} yr^{-1} (Maljanen et al., 2004). It is believed pristine peatlands produce negligible N_2O but emit carbon as CH_4 (Maljanen et al., 2004). However, detailed carbon balance studies often reveal that individual peatlands can switch between years from being net carbon sinks to net carbon sources (Turetsky et al., 2002). If climatic conditions change, factors that may alter carbon dynamics such as, increasing active layer depths leading to increased anaerobic zones for CH_4 production, melting of permafrost, release of hydrates to atmosphere and loss of plant communities not suited to temperature and moisture changes may occur. These changes could cause peatlands to switch to being net carbon sources to the atmosphere resulting in increased atmospheric concentrations of CH_4 and CO_2 and ultimately further warming. This phenomenon is referred to as a GHG positive feedback mechanism (Turetsky et al., 2002). Therefore, a detailed study of GHG emissions at multiple sites and within numerous different habitat types combined with environmental, soil and plant community composition data in the peatlands near Churchill, Manitoba could provide invaluable insight into carbon cycling and climate change feedback mechanisms in this environment.

Many subarctic terrestrial environments, such as the peatland sites at Churchill, are underlain by permafrost. Churchill is in a transition zone between having continuous and discontinuous permafrost (Camill, 2005). Permafrost provides major variations in physical soil formation, which affects surface micro-topography and influences plant community structure. Permafrost also determines the hydrological and nutritional status of soil conditions, which is important for vegetation distribution, ecosystem carbon balance and the emissions of greenhouse gases (Christensen et al., 2004). Discontinuous permafrost has recently been shown to be melting across western Canada creating new vegetation communities (Turetsky et al., 2002). Increasing active layer depth is generally associated with wetter conditions and has been found to result in the vegetation shifting from elevated dry-shrub dominated to wet-graminoid dominated in a subartic region in Sweden, which resulted in increased methane emissions ranging from 22 to 66% from 1970 to 2000 (Christensen et al., 2004). Climate change appears, in that study, to have induced changes in vegetation distribution that may be used as indicators of significant and rapid GHG emissions (Christensen et al., 2004). Of the greenhouse gases, CH_4 is of great interest, as subarctic and boreal ecosystems emit CH_4 in significant amounts to the atmosphere. Methane emissions are related to temperature, hydrology and alterations in permafrost coverage and vegetation. For example, as soil moisture increases due to melting permafrost or increased precipitation, oxygen concentrations decrease and CH_4 production can increase. Therefore, changes in these factors could have a dramatic impact on emissions.

1.3. Importance of Determining Greenhouse Gas Emissions at Local Scale for Climate Change Models

The interactions between variables of global change like greenhouse gases, temperature and precipitation have been rarely examined with most experiments being short term (Phoenix and Lee, 2004). Areas that are sensitive to global warming are very important to study, as they will act as model sites to provide insight into the effects of climate change not only in the subarctic, but around the world. Northern wetland areas are often viewed as one-dimensional ecosystems or are broken down into only a few community types for estimates of global carbon cycling (Bridgham et al., 1998). This can result in inaccurate models of GHG emissions from wetland ecosystems as they have been found to have huge variability both spatially and temporally due a wide variety of factors (Rouse et al., 1995). It is important to know the spatial dependency of GHG emissions to variations in plant community composition, hydrology and soil conditions within landscapes. Net ecosystem exchange (NEE) of greenhouse gases can be determined using micro-meteorological techniques, however these techniques do not provide insight in spatial dependency of GHG emissions within landscapes and plant habitats.

Plant communities can be useful predictors of CH_4 emissions and can be important in assessing the variability in a landscape in order to scale measurements to regions and to predict effects of changing conditions on GHG emissions. Vegetation cover could be a very useful factor when modeling these ecosystems as it is easier to map using remote sensing techniques compared to environmental factors, such as water table depth and soil temperature (Bubier et al., 1995). Much is known regarding net CO_2 exchange, however much less is known about CH_4 and N_2O, despite the fact that the warming potential of both CH_4 and N_2O is greater than CO_2, at 23 and nearly 300 times respectively, over a period of 100 years (Smith et al., 2003). Therefore, many more long term studies with work on spatial dependency of GHG emissions in subarctic and arctic regions are necessary to provide information on the effects of global warming on CH_4 and N_2O emissions in these landscapes.

1.4. ArcticNet

ArcticNet is a Network of Centres of Excellence of Canada that brings researchers from all disciplines together with members of northern communities, government agencies and the private sector to study the impacts of climate change in the coastal Canadian Arctic. ArcticNet's central objective is "to contribute to the development and dissemination of the knowledge needed to formulate adaptation strategies and national policies to help Canadians face the impacts and opportunities of climate change and globalization in the Arctic". There are 4 main themes within ArcticNet, each containing multiple sub-themes. Theme 1 deals with climate change impacts in the High Canadian Arctic. Theme 2 is responsible for food, water and resources in the Terrestrial Eastern Canadian Arctic. Theme 3 studies land-ocean interactions in the subarctic Hudson Bay and managing this environment in a new climate. Theme 4 deals with knowledge transfer, polices and strategies with regards to adapting to change in the Canadian Arctic (ArcticNet, 2007).

This thesis project is part of ArcticNet theme 3.2, which studies the Hudson Bay Coastal zone in a changing climate. The southwestern region of Hudson Bay and its coastal zone are expected to experience large temperature increases and changes in precipitation amount and patterns, which are associated with rising GHG levels. Due to climatic forcing, changes could occur in Hudson Bay, such as rising sea levels, or changes in the extent of sea ice, which could alter conditions in the coastal terrestrial environment as a result. Changes in hydrology, permafrost extent, nutrient cycling and vegetation communities would be expected if changes occur in Hudson Bay. The goal of ArcticNet theme 3.2 is to better understand the linkages between Hudson Bay and its coastal zone, and in particular how the state of Hudson Bay may affect the biogeophysical and biogeochemical processes with respect to water and carbon within the terrestrial and aquatic systems of the HBL (ArcticNet, 2007). This thesis project aims to establish patterns for GHG emissions in various sites and multiple habitat types in the terrestrial coastal zone of Hudson Bay, in relation to environmental and soil conditons data, such as soil and air temperatures, soil moisture content, active layer depth and plant community composition. These relations will be useful in predicting future impacts on emissions in the HBL. Results will be critical to modeling and scaling GHG emissions in the Churchill area, HBL and other subarctic ecosystems.

This thesis project is one of many established under ArcticNet which all allow invaluable insight into determining the impacts of climate change to all people, especially those in arctic and subarctic regions and formulating strategies to minimize the effects of such changes.

1.5. Thesis Objectives and Structure

The specific objectives of this thesis were:

1) To determine the relation between major environmental conditions and plant habitats to GHG emissions (Chapter 2).
2) To determine if zones of GHG production or consumption occur within the soil and if soil gas concentrations can be related to surface gas fluxes, in different plant habitats and under different environmental conditions (Chapter 3).
3) To determine if variations in soil conditions affect GHG emissions within a similar plant community (Chapter 4).

Field studies and laboratory analysis were conducted in order to meet the above objectives and the data collected for this thesis occurred in order to establish patterns in GHG emissions and create the potential for modeling and scaling of GHG emissions in the HBL near Churchill, Manitoba. Chapter 2 discusses how spatial variation in GHG emissions occurred in specific plant habitats, which differ in environmental parameters and dominant plant communities, at a Polygonized-Peat Plateau (Peat), White Spruce/Larch Forest (Spruce) and Palsa Fen (Fen). The chapter highlights which areas are producing and consuming CH_4 and the importance of accounting for these different habitats if accurate regional models of GHG emissions in the HBL are to be produced. It also establishes that slight trends for N_2O production and consumption do occur in northern peatlands and explains how GHG emissions vary with respect to environmental and soil conditions and plant community structure, over a large environmental gradient. Chapter 3 deals with *in situ* GHG concentrations at depths in the soil and relates these to surface fluxes within different plant habitats. These findings will be important to suggest if changing climatic conditions altering active layer depths, permafrost extent and hydrology, in subarctic peatland regions affect GHG emissions. Chapter 4 was established to test the influence of variation in soil conditions to GHG emissions within a common plant type. It examines if soil conditions are important to consider when upscaling or predicting GHG emissions. The study adds to that of Chapter 2 to provide an assessment if plant communities alone can be used to upscale and predict regional GHG emissions. Plant communities could be used as predictors of CH_4 emissions as remote sensing techniques are easier to use on plants than soil conditions. Chapter 5 is an overall synthesis discussing the general findings of the thesis including a discussion on the necessity of considering specific plant habitats and vegetation mapping for scaling of

GHG estimates for HBL and a direction for future research, suggested by the findings of this thesis.

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2. GREENHOUSE GAS EMISSIONS IN RELATION TO PLANT HABITATS AND ENVIRONMENTAL CONDITIONS IN THE SUBARCTIC ENVIRONMENT OF CHURCHILL, MANITOBA

2.1. Abstract

Global warming, associated with elevated levels of greenhouse gases, is expected to alter hydrologic regimes, permafrost extent and vegetation composition in the Hudson Bay Lowlands (HBL). The objective of this study was to determine the relationship between greenhouse gas (GHG) emissions to plant habitats and major environmental conditions. Transects of sample positions, were set out at a Polygonized-Peat Plateau (Peat) and a White Spruce/Larch Forest (Spruce) in 2005, encompassing the dominate plant habitats in each ecosystem. Static-vented chambers were used on a select set of sample positions (32 in 2005; 36 in 2006; referred to as subset) to detect GHG emissions (respiration, CH_4, N_2O). The subset was sampled on a weekly basis from the beginning of June through August, in both 2005 and 2006. In the fall of 2005, a study site at a eutrophic Palsa Fen (Fen) was established and monitored in 2006. The entire transect at the Peat site was sampled six times, to obtain more representative sampling of the gradients in plant communities and environmental conditions. Habitats such as riparian areas, submerged peat ledges in ponds and sedge areas, continually showed high CH_4 production, due to the increased moisture content and large amounts of plant biomass. Conversely, CH_4 consumption was related to low moisture content in areas with lichen dominated plant biomass, such as polygon tops. Increased soil moisture and temperature coincided with increased respiration. Analysis of results from 2005 and 2006 for the Peat site indicated GHG emission estimates were comparable using the subset sample positions and the more numerous sample positions of the entire transect. Greenhouse gas

emissions were found to vary considerably between plant habitats. “Hot-spots” of intense CH_4 emissions occurred in the sedge-dominated areas of high moisture and plant productivity, while areas of low moisture and plant productivity resulted in low rates of CH_4 consumption. Conversely, areas of high moisture and plant productivity were sinks for N_2O and low moisture and plant productivity areas were a source of N_2O, albeit at very low rates. The findings indicate the importance of determining the contribution of specific plant habitats to regional emissions, particularly if climate change is expected to alter moisture and plant community composition in arctic and subarctic environments.

2.2. Introduction

Southwestern Hudson Bay and its coastal zone contain the second largest contiguous peat accumulation (Rouse et al., 2002) and third largest wetland in the world (Ricketts et al., 1999; ArcticNet, 2007). A wetland is an area of land with the water table at, near or above the surface or which is saturated for a long enough period to promote features such as wet-altered soils and water tolerant vegetation. Wetlands include organic wetlands or “peatlands,” and mineral wetlands (National Wetlands Working Group, 1997). Particularly important, in these regions is the exchange of carbon due to the large amount of organic carbon stored (Christensen et al., 2003). Northern peatlands contribute about one-tenth of the total methane (CH_4) emissions to the atmosphere (Basiliko et al., 2004) while wetlands are the largest natural source contributor of CH_4 emissions (IPCC, 2001).

Changes such as an increase in temperature, as well as an increase in the amount and timing of precipitation, are expected results of global warming (Phoenix and Lee, 2004). These changes could result in increased melting of glaciers, rising sea levels, changes and reduction in sea ice and changes in permafrost extent, active layer depth, snow cover, plant community composition, hydrology and soil processes, which are expected in arctic and subarctic regions (IPCC, 2007).

In particular, changing CH_4 emissions are of great interest in arctic, subarctic and boreal ecosystems, as these systems can emit significant amounts of CH_4 into the atmosphere. Methane emissions are related to temperature, hydrology, water table depth, alterations in permafrost coverage and vegetation (Christensen et al., 2004). Changes in these factors are expected to have a dramatic impact on emissions, as they affect methanogens and methanotrophs ability to produce and consume CH_4, respectively (Moore et al., 1998). Methanogenesis is influenced more by changes in temperature than methanotrophy (Smith et al., 2003). Furthermore, the depth to the water table and active layer depth affects the rate of methanogenesis by affecting the amount of anaerobic soil conditions (Trettin et al., 2006). As temperature and moisture conditions change, as a result of global warming, CH_4 emissions are expected to further increase (Christensen et al., 2004). However, CH_4 consumption may occur in areas where increased temperature results in surface drying, lowering of the water table, increasing active layer and more aerobic conditions. Under such conditions, some arctic wetlands could change from CH_4 producing to CH_4 consuming systems, but in upland areas, drying could suppress CH_4 consumption due to water stress on soil microorganisms (Gulledge and Schimel, 1998).

Vegetation shifts from elevated dry-shrub dominated to wet-graminoid dominated have been found to cause an increase in CH_4 emissions ranging from 22 to 66% in a subarctic region in Sweden from 1970 to 2000 (Christensen et al., 2004). Increased plant growth, as a result of elevated carbon dioxide (CO_2) levels, can lead to higher CH_4 emissions (Moore et al., 1998). Vegetation type also alters CH_4 emissions, as methanogenesis depends heavily on the amount of available carbon in the vegetation.

Furthermore, Keppler et al. (2006) recently found that terrestrial plants incubated under aerobic conditions at an ambient temperature can produce CH_4 and that CH_4 released by living vegetation could range from 62 to 236 Tg yr^{-1}, on a global scale (1 Tg = 10^{12} g). Therefore, more studies like Keppler et al. (2006) will need to occur to determine the processes that cause CH_4 production in vegetation, and obtain more accurate estimates of how different vegetation types will contribute CH_4 to the atmosphere and eventually determine the effects of climate change on CH_4 production processes occurring in living plants.

There is great spatial variability in northern peatland and wetland ecosystems in plant habitats, water table depth, active layer depths, soil temperatures and soil moisture contents. This variability can lead to differing responses of CH_4 emissions, as a result of global warming. For example, non-floating peatlands and sedge-dominated peatlands are expected to have decreased CH_4 emissions, due to a lower water table having a greater impact on increasing CH_4 consumption and decreasing CH_4 production than increased temperatures. In contrast, floating peat, degrading pools, and peat palsa peatlands are expected to result in increased CH_4 emissions. The floating peat and degrading pools peatlands are more affected by increased temperatures as they are expected to have accelerated rates of methanogenesis which results as a consequence of water saturated and thus anaerobic conditions. The peat palsa peatlands are expected to increase CH_4 emissions as a result of accelerated methanogenesis induced by melting permafrost leading to increased moisture and anaerobic conditions (Moore et al., 1998). Permafrost melting is of great concern in palsa peatlands, as they are formed by perennial permafrost mounds (Gurney, 2001). This explains why the largest changes in CH_4 emissions are expected to be in the high boreal and low subarctic zones underlain by discontinuous or southern extent of continuous permafrost. As permafrost melts due to increased temperatures, these systems will likely switch from slight net CH_4 consumption to substantial net CH_4 production (Moore et al., 1998).

Churchill, Manitoba is located within the Hudson Bay Lowlands (HBL) which encompass areas surrounding Hudson Bay in northeastern Manitoba and northern Ontario. The area surrounding Churchill is complex, as it is in a transition zone between the boreal forest and the subarctic tundra, and between having continuous and extensive discontinuous permafrost (Tarnocai, 2006). Within 10 km, along Twin Lakes road in Churchill, peat plateaus, numerous ponds, a vast eutrophic Palsa fen and the northern edge of boreal forest are found (Figure 2.1). Each is comprised of numerous different plant habitats. Therefore, this area is highly spatially variable with respect to plant communities, environmental conditions and presumably greenhouse (GHG) emissions. Studies in northern latitudes must get away from being viewed as one-dimensional ecosystems, which has been the common practice in past literature (Bridgham et al., 1998). This can result in inaccurate models of GHG emissions from subarctic ecosystems as they have been found to have huge variability both spatially and temporally due a wide variety of factors (Rouse et al., 1995). The spatial dependency of GHG emissions to variations in plant community composition, hydrology and soil conditions within landscapes is extremely important. Net ecosystem exchange (NEE) of greenhouse gases can be determined using micro-meteorological techniques, however these techniques do not provide insight in spatial dependency of GHG emissions within landscapes and plant habitats. Therefore, in order to produce accurate models for large-scale regions like the HBL, specific plant habitats must be taken into account in the different ecosystems present in these vast subarctic peatlands.

Previous studies on CH_4 and CO_2 emissions around Churchill, Manitoba have primarily focused on wetlands, like fens (Rouse et al., 1995; Waddington et al., 1998; Griffis et al., 2000). There are fewer studies done in forested regions (Rouse et al., 2002), and none in peat plateau landscapes or the riparian areas surrounding ponds. However, the Northern Wetlands Study (NOWES) is an example of a large scale project completed in both the southern and northern portions of the HBL peatlands. This study was established to better define the role of northern wetlands with respect to the exchange of CO_2, CH_4, N_2O, O_3, and non-methane hydrocarbons (NMHC) between the wetland surface and the atmosphere (Glooschenko et al., 1994). Another example of a study on CH_4 from a peat plateau landscape was done near Thompson, Manitoba by Bubier et al. (1995). That study found that treed sites such as peat plateaus had a low seasonal average for CH_4 production ranging from 0 to 20 mg C m^{-2} d^{-1}. Bubier et al. (1995) also did collect data in different habitats within the site and found that dry hummocks and peat palsas occasionally showed slight CH_4 consumption, at levels as high as -1.5 mg C m^{-2} d^{-1} (Bubier et al., 1995). Also, many previous studies in the Churchill area account for landscapes as a whole, and have not broken up the landscapes into different sections or habitats. Rouse et al. (1995) was the only study on CH_4 in the Churchill area that did break up the wetland sites in the study into wet (standing water), mesic (moist hollow) and dry (hummock), however the results were not presented for the individual habitats, but rather for the entire landscape as a whole. The data from Rouse et al. (1995) were collected almost two decades ago, in 1989 and 1990, and gas was collected over 24-hour periods from static chambers (Rouse et al., 1995). Gas flux determination methods have been greatly improved since 1990. Recently there has been a study on long-term carbon storage and CO_2 exchange from tundra ponds around Churchill, Manitoba, however, CH_4

emissions from the ponds were not included in the study (Macrae et al., 2004). There have also been no previous studies looking at nitrous oxide (N_2O) emissions from terrestrial landscapes around the Churchill area. Therefore, a current study on CH_4, CO_2 and N_2O, which encompassed the fen, boreal forest and peat plateau sites and addressed spatial dependency of GHG emissions to plant habitats, including the riparian and pond edge habitats within sites was necessary to establish patterns in GHG emissions and create the potential for modeling and scaling of GHG emissions in the HBL near Churchill, Manitoba.

This study was carried out over two years, 2005 and 2006. In 2005, GHG emissions, environmental conditions and plant communities were obtained, for the main plant habitats at a Polygonized-Peat Plateau (Peat) and White Spruce/Larch Forest (Spruce) sites. In 2006, the number of sample locations at these sites was slightly increased to better capture results from specific plant habitats. A Palsa Fen site (Fen) was also added to the examined sites in order to gain further information on the difference in GHG emissions between plant habitats within a site and between sites. By adding the Fen site, a larger environmental gradient was established for GHG emissions, as moisture conditions are much greater at the Fen due to a high water table and constant standing water, than at the Peat and Spruce sites. The objective of this study was to determine the relation between major environmental conditions and plant habitats to GHG emissions. The ultimate goal of this work will be to provide a basis to accurately model current and future GHG emissions under a changing climate for the plant habitats around Churchill, Manitoba and the HBL.

2.3. Materials and Methods

2.3.1. Site Locations and Field Layout

Three study sites were established in 2005 in the vicinity of the town of Churchill, Manitoba. The sites were situated along Twin Lakes Road, which runs south of the Churchill Northern Studies Centre (CNSC) beginning about 23 km east of the town of Churchill (Figure 2.1). The sites were selected for their contrasting plant communities. A Polygonized-Peat Plateau (Peat) approximately two km southwest of the CNSC, a eutrophic Palsa Fen (National Wetlands Working Group, 1997) and a White Spruce/Larch Forest (Spruce) site located approximately 13 and 15 km south of the CNSC, respectively, were selected (Figure 2.1). The Peat, Spruce and Fen sites were located at 58.73^{o}N: 093.84^{o}W, 58.64^{o}N: 093.82^{o}W and 58.66^{o}N: 093.83^{o}W, respectively. The Peat site was comprised of tundra polygons which were formed as the ground cracked under extremely cold conditions. As meltwater entered into the cracks, it froze and formed vertical seams of ice, known as ice wedges. Over time, the ice wedges became thicker and deeper, and continually forced up the soil on each side, resulting in the formations of polygons (Pielou, 1994).

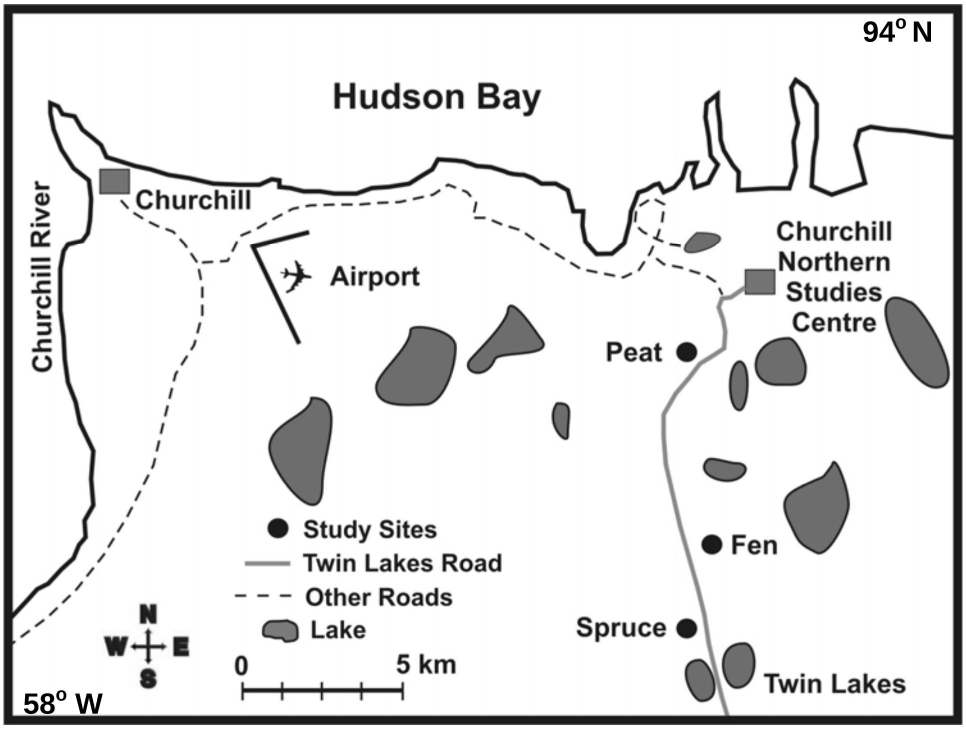

Figure 2.1. The three study sites in relation to the town of Churchill, the Churchill Northern Studies Centre and Twin Lakes Road.

At the Peat site, a transect of 92 sample positions were selected at 1.25 m spacing, along a trajectory running southeast to northwest. The Peat transect graded downslope successively from wet-sedge meadow, polygonized-peat plateau, bottom-land and into the edge of Frisbee pond. The White Spruce/Larch Forest (*Picea glauca/Larix laricina*) site had a transect of approximately 100 potential sample locations running east to west and grading downslope from a lichen dominated upland, *Sphagnum-Picea glauca* forest, to Sedge-Moat surrounding Lake Stanley. The Fen site was established in late September of 2005 and nine sample locations were selected (Figure 2.2).

Post snow melt in early June 2005, at all 92 sample positions at the Peat site and 32 positions at the Spruce site, a section of PVC pipe was inserted into the soil to act as a collar or base for deployment of cover to serve as a static-vented chamber for gas sampling. The chambers consisted of two parts, a collar and a cover. The collars were 10.2 cm (4 inches) internal diameter, 0.2 cm thick and either 6.5 cm or 12 cm in height and painted white to minimize heating from sunlight. Short collars were placed in most locations at the Peat and Spruce sites, with the long collars used when a tall plant canopy or thick lichen mat was encountered or for extra stability in moss mounds. Using a serrated knife to cut into the peat material, the collars were inserted into the ground by slowly twisting the beveled edge of each collar at least 2 cm into the soil. About 2 cm of each collar was left showing above the ground. The collars in the edge of Frisbee pond at the Peat site were constructed of two parts, a base and extension. The base was a segment of 10.2 cm internal diameter PVC pipe with a PVC pipe coupler attached to the upper end, inserted into the pond bottom until the frost layer was hit, and with 2 cm of the coupler extending out of the pond bottom. A 2.5 cm section of PVC pipe was inserted into the coupler 1.9 cm below the top edge. A collar extension of PVC pipe was inserted and overlapped 1.9 cm into the coupler. The extensions were also 10.2 cm internal diameter PVC pipe of varying length. The specific length of each collar extension was chosen based on the pond water level the day of sampling. Ideally, the collars in the pond's edge were a 2 to 4 cm above the pond water level and the collar extensions were inserted into the bases in the pond edge, either the day before or the day of sampling. The distance from the top edge of PVC extension to water level was recorded on each sample day.

The cover of a static-vented dark chamber consisted of a 10.2 cm PVC pipe cap with a 5.4 cm vent tube made of 0.3 cm (1/8 inch) Tygon® tubing (Cole-Parmer Canada, Anjou, QC) a rubber serum stopper (Suba Seal, #14.5, Sigma-Aldrich Canada, Oakville, ON) and a size #1 rubber stopper inserted into a drilled hole. The vent tube size was chosen based on chamber volume and other factors used in a vent calculation developed by Hutchinson and Mosier (1981). The vent's purpose was to ensure similar atmospheric pressure inside and outside the chamber. The serum stopper was used as the sampling port through which gas samples were obtained. Both the vent tube and serum stopper were sealed to the cover with silicone, while the rubber stopper was removable and inserted into the cap after it had been placed on the collar, to minimize pressure build up within the chamber headspace upon placement of the cover. A 3.8 cm sleeve of PVC pipe was inserted permanently into each cover to be 0.6 cm below the open end of the cover. Thus, placement of the cover resulted in a 0.6 cm overlap of cover on the collar. A cover and collar as a whole was tested in the laboratory for air tightness by submerging the chamber in water, pumping air into it and watching for the release of air bubbles. The chambers were also field tested in a bog in southern Manitoba before leaving for Churchill, to make sure that the protocol for gas collection was successful by detecting GHG concentrations from the samples taken and obtaining a linear increase in CO_2 within the chamber over a 30 minute period.

Due to changing active layer depths and water depths with the progression of the growing season, collars had to be adjusted periodically. In order to ensure accurate estimates of GHG emissions collar offsets were taken when the collars were first installed and anytime after the collars had been adjusted. Offsets were calculated as the average height from the top of the plant canopy to the top of the collar. This allowed chamber headspace to be calculated as the offset value plus the height of the cover, accounting for the 0.6 cm overlap between cover and collar. Any changes to the collars were done at least one day prior to sampling to minimize disturbance effects on gas emissions.

In early June 2005, 32 collars were chosen at the Peat and Spruce sites (subset). Eight collars were selected on each of the main plant habitats at different locations along the transects. The main plant habitats were chosen based on a visual inspection of the sites by Drs. Tenuta and Bello, and I. At the Peat site, the four main habitat types were the Upper Sedge, Polygon Tops, Ice Wedges and Lower Sedge. When sampling the entire 92 sample position transect at the Peat site three other habitat types were differentiated by visual inspection: Moss (*Dicranum*), Riparian and Pond Edge. At the Spruce site, the four main plant habitats were Upper Lichen, Moss (*Sphagnum*), Moss (*Hylocomium*) and Sedge-moat surrounding Lake Stanley. In 2006, the subset sampling positions at both the Peat and Spruce sites were expanded to contain 36 collars in order to include sample positions from specific plant habitats. At the Peat site, two sample positions from both Riparian and Pond Edge habitats were included. At the Spruce site, four collars were added to the Sedge-Moat habitat. The Fen site consisted of nine sample positions, with three positions for each of the three main plant habitats; Hummocks, Sedge-Lawns and Pools. The collars placed were 12 cm in height for the Hummocks and Sedge Lawns, and were 55 cm in height for the Pools to increase stability.

Elevation above sea level data for all sample positions at all sites was obtained during the 2005 and 2006 field seasons using a total station (TPS700, Leica Geosystems, Heerbrugg, Switzerland).

Figure 2.2. Aerial views of the Peat (A), Spruce (B) and Fen (C) sites. A line indicates the position of the transect at the Peat and Spruce sites.

2.3.2. Occurrence of Gas Flux Sampling

Static-vented dark chambers were used to determine GHG fluxes (respiration, CH_4 and N_2O) from gas collected in the chamber headspace at 0, 10, 20 and 30 minute intervals. In 2005, the Peat and Spruce site 32-sample-positions subsets were sampled every week from about snow melt (June 8) until late summer (August 18), with one sampling on September 26. The Fen site was sampled once on September 26, 2005. In 2006, the Fen site and the Peat and Spruce 36-sample-positions subsets were sampled on a weekly basis from about snow melt (May 24) to late summer (August 25). The 92 sample positions along the transect at the Peat site included seven plant habitats in 2005 and 2006 (Upper Sedge, Polygon Top, Ice Wedge, Moss (*Dicranum*), Lower Sedge, Riparian and Pond Edge). In both 2005 and 2006, all positions were sampled once in June, July and August, to provide periodic estimates of GHG emissions from more sample positions for each plant habitat and gain information on emissions from larger environmental and plant community gradients. The subset sample positions had 8 replicates for the Upper Sedge, Polygon Top, Ice Wedge and Lower Sedge habitats in 2005 and 2 replicates added for the Riparian and Pond Edge in 2006. While the transect had 9, 31, 14, 11, 20, 4 and 3 replicate positions for the Upper Sedge, Polygon Top, Ice Wedge, Moss (*Dicranum*), Lower Sedge, Riparian and Pond Edge, respectively.

2.3.3. Gas Flux Analysis

Ten-mL Becton-Dickenson syringes (Fisher Scientific, Edmonton, AB), fitted with Becton-Dickenson 23G 2.5-cm needles (Fisher Scientific, Edmonton, AB) were used to collect headspace gas from each chamber and the gas sampled placed into 6- or 3-mL Exetainer® vials (Labco Limited, Buckinghamshire, UK) that had been evacuated and had their septums covered with Mastercraft Kitchen and Bath Silicone (Canadian Tire Corporation, Winnipeg, MB). The vials were evacuated and flushed three times with helium gas to a final evacuated pressure of 500 millitorr. A 10-mL sample of headspace was placed into the 6-mL vials and a 7-mL sample was placed into the 3-mL vials. The vials were over pressurized with headspace gas to ensure the gas samples enter into the GC syringe without the surrounding air contaminating the sample. The septums of the Exetainer vials were covered using silicone multiple days before evacuating to maintain an air-tight seal. In 2006, three standard gas samples composed of 1195 ppm CO_2; 9.8 ppm CH_4 and 1.1 ppm N_2O and certified by the supplier (Praxair Distribution Inc., Edmonton, AB), were taken to the field to ensure that the samples taken were not affected by transport or storage.

All gas samples, including the standards, were transported to Winnipeg and stored at room temperature until analyzed. The samples were run on an automated gas chromatograph (Varian 3800, Mississauga, ON) (GC) fitted with an electron capture, flame ionization and thermal conductivity detectors at 300, 250 and 130^{o}C, respectively. The analyses on the GC were quality controlled using multi-point calibration, as well as, high and low standard checks run throughout each analysis of samples to ensure calibration drift does not occur. Using a Combi-PAL autosampler (CTC Analytics, Zwingen, Switzerland) paired to the GC, 2.5 mL of sample was injected from each vial and delivered to the GC in order to obtain CO_2, CH_4 and N_2O concentrations. The GC had two sample loops, one for CO_2 and CH_4 and one for N_2O analysis; both use a volume of 500 µL. Flux rates were calculated using the gas concentration, molecular mass of carbon or nitrogen, chamber area, chamber volume, air temperature at the time of sampling and atmospheric pressure using the Ideal Gas Law ($pV=nRT$). The mass of gas in the chamber's atmosphere (g gas-element) was determined and converted to mass of gas per chamber area (µg gas-element/m^2). From this, the flux rate of the gas-element (µg gas-element/m^2/s) was determined using the slope of a linear regression plot of µg gas-element/m^2 versus time. Data filtering for fluxes was done by examining plots of the gas concentrations over time. If concentrations were determined to be accurate on the GC, but were substantially different from the other points on the linear regression plot, these points were removed. A minimum of three of the four sampling points were used to calculate fluxes and an R^2 value of 0.85 or greater was usually obtained. In many cases for CH_4 and N_2O an R^2 value of 0.85 could not be reached without removing two or more points. In these cases, the points were not removed and a lower R^2 value was accepted. Positive flux values referred to GHG production or gas released into the atmosphere while negative flux values referred to GHG consumption or gas uptake from the atmosphere. Regression tests at a significance level of α=0.05 were done on the individual slopes for each gas to determine cut off points at which the flux is no longer different than zero. Approximately, 100 chamber fluxes from different sampling dates at the Peat site in 2006 were used for the determination. Flux values considered to be not significantly different from zero ranged between -0.00034 and 0.00026 μg N m^{-2} s^{-1}, -0.00089 and 0.0011 μg C m^{-2} s^{-1}, and 0 and 1.83 μg C m^{-2} s^{-1} , for N_2O, CH_4 and CO_2, respectively.

2.3.4. Environmental Conditions

Environmental conditions (soil temperature at 2.5 cm depth [$Temp_{2.5}$], soil temperature at 15 cm depth [$Temp_{15}$], air temperature [$Temp_{air}$], volumetric moisture content [VMC], and active layer depth) potentially controlling gas emissions were determined during the course of and after flux emission determinations were completed. Soil temperature was measured at 2.5 cm and 15 cm depths using digital thermometers with stainless-steel stem (Traceable Thermometers, Fisher Scientific, Edmonton, AB) and all temperature values were collected 20 minutes after the placement of covers on collars. Air temperature at approximately 1.25 m above ground level, was measured using the 2.5 cm digital thermometer probe shielded from sunlight at 20 minutes into sampling.

Soil moisture was determined using a portable time domain reflectometry (TDR) probe (HydroSense, Campbell Scientific, Edmonton, AB) to obtain volumetric moisture content (VMC) for the top 10 cm of the soil profile. The probe was calibrated for peat material in the laboratory following the 2005 field season by deriving a calibration equation using curve fitting methods to relate independently measured water contents to the TDR probe VMC readings. The data values collected in the field in 2005 and 2006 were adjusted according to the calibration.

Active layer depth was determined for each sampling position, on each sampling day using a thin metal rod which had 1 cm increments scored into it. The rod was inserted into the ground near each chamber to obtain the frost depth estimated to the nearest 1 cm and ultimately the active layer depth.

Precipitation measurements were obtained in 2005 using a tipping bucket rain gauge (Rain Collector II – Davis Instruments Corp., Hayward, CA) at both the Peat and Spruce sites. In 2006 only the Peat site was equipped with a tipping bucket. Gaps in rainfall data as well as average daily air temperatures were filled using data from the Environment Canada weather station located 10 km west of the CNSC and at the Churchill Airport (Churchill A) (Environment Canada, 2006).

2.3.5. Soil Sampling and Analysis

Four soil samples were taken near the location of each subset sample position every month of the study periods in 2005 and 2006. Soil samples were sampled from 0 to 5 cm using a serrated knife to cut a 2x2 cm block of peat material. On the last sample day in September 2005 and August 2006, a Mini-mized Macauley peat sampler was used to collect soil samples from various depths (0 to 5, 5 to 15, 15 to 25 and 25 to 35cm). All samples were frozen and later thawed for analyses. Degree of decomposition was determined for each sample using the Von Post decomposition scale, with 1 being the least decomposed and 10 being the most decomposed (Parent and Caron, 1993). The samples were then weighed and dried at 70^{o}C for 48 hours. After drying the samples, they were weighed again in order to calculate gravimetric moisture content (GMC). The 2005 soil samples were ground by hand using a mortar and pestle, while the 2006 samples were ground using an electric coffee grinder. The ground soil samples were then used for soil extractions.

Soil extractions were carried out using 1 g of soil to 25 mL deionized water and placed into a 50 mL conical disposable centrifuge tube (Fischer Scientific, Edmonton, AB). The tubes were shaken horizontally for 60 minutes on a reciprocating shaker at 150 epm. The samples were then poured through medium filter paper (Whatman Qualitative Grade 2 Circles, Fischer Scientific, Edmonton, AB) into scintillation vials (Fisherbrand 20mL, Fischer Scientific, Edmonton, AB). The electrical conductivity (EC) and pH of the extract solution was determined using a Conductivity Meter (Radiometer CDM2x and Conductivity Cell Radiometer CDC 304, Radiometer Canada, London, ON) and Orion 720A and 290A pH Meters (Cole-Parmer Canada, Anjou, QC) (Tables 2.1 to 2.3).

2.3.6. Soil Water Analysis

Monitoring wells were installed using an ice core sampler with a serrated teeth end, at the Peat and Spruce sites in late July 2005. The wells were constructed of 5.1 cm (2 inch) internal diameter PVC pipe cut with slits a few millimeters wide, sawed approximately every centimeter down the length of the pipe. Sixteen and 11 wells were installed along the transects at the Peat and Spruce sites, respectively. Water depths and measurements for temperature, specific conductivity, dissolved oxygen (DO) concentration, pH and oxidation reduction potential (ORP) (YSI 556 Multiprobe, YSI Environmental, Burlington, ON) were taken weekly from the beginning of June to the end of August in 2006 at a minimum water depth of 4 cm (Tables A.1 and A.2).

2.3.7. Plant Community Composition

Plant community composition as percent cover estimates by observation for taxa, for all sites and sample positions were started mid-season during the summer of 2005 and completed mid-season 2006. Percent cover estimates were taken inside each collar and also inside a 30.5cm (12 inch) internal diameter ring placed around the outside of each collar to estimate the percent cover within 10 cm surrounding each collar. Estimates of percent cover were taken outside each collar to account for the potential influence of nearby species on gas emissions due to roots, falling leaves and other sources. Plant species that could not be identified to the species level in the field were collected from an area away from the transect and placed in a plant press. These specimens were later identified to species or genus, or if rare occurrences, categorized as unknown. Plant dominance for a habitat type at each site, within and in the vicinity of the collars, were determined either as the sum of taxa providing percent cover values of at least 80% or the top three taxa based on percent cover values (Tables 2.1 to 2.3).

2.3.8. Statistical Analysis

Statistical analyses for all data were done using the Statistical Analysis Software (SAS) package version 9.1 (SAS Institute Inc., Cary, NC). The association between CH_4, N_2O and respiration, and measured environmental parameters were determined using Spearman rank correlation analysis at $P<0.05$ significance level. Spearman rank correlation analysis was chosen as it is a non-parametric method which tests both the direction and strength of the relationship between two variables and makes no assumptions about the frequency distribution of the variables. A generalized linear model (GLM) analysis of variance (ANOVA) was run on the average CH_4, N_2O and respiration fluxes for each plant habitat type at each site and for each field season, separately. A $P<0.05$ level of significance was used for the GLM ANOVA tests. Shapiro-Wilk and Levene tests were used to test normality and homogeneity of variance of the data sets, respectively. Any average flux data that was not normal or homogenous was transformed using log (base 10) or power-transformed, to improve both normality and homogeneity. In the cases where negative fluxes occurred, a common coefficient was added before the data transformation. Scheffe's Post Hoc analysis was used to compare fluxes between plant habitat type at a significance level of $P<0.05$. The effect of landscape position on CH_4 and N_2O flux data for the subset sample positions compared to the entire transect sample positions was determined using independent T-tests at a significance level of $P<0.05$.

Table 2.1. General site characteristics for the plant habitats at the Peat site, August 2006[1].

Habitat Type	Dominant Vegetation Inside Collar[2]	Dominant Vegetation 10 cm Surrounding Collar[2]	Soil Depth (cm)	von Post Decomposition Scale	Moisture (g H_2O/g soil)	EC (μS cm^{-1})	pH
			0-5	2.9 ± 0.1	537.4 ± 19.2	235.9 ± 13.3	6.7 ± 0.1
Upper	*Tomenthypnum nitens* (52)	*Tomenthypnum nitens* (40)	5-15	4.5 ± 0.2	536.4 ± 11.0	156.6 ± 11.6	6.7 ± 0.1
Sedge	*Cetraria nivalis* (7)	*Arctostaphylos alpine* (12)	15-25	5.1 ± 0.3	531.6 ± 15.3	148.9 ± 12.4	6.9 ± 0.1
	Arctostaphylos alpine (7)	Sedge A (11)	25-35	6.9 ± 0.2	552.5 ± 30.3	162.3 ± 12.7	6.8 ± 0.1
			0-5	2.8 ± 0.2	292.1 ± 11.3	110.9 ± 7.8	5.0 ± 0.1
Polygon	*Byroria nitigula* (39)	*Byroria nitigula* (25)	5-15	3.0 ± 0.0	306.2 ± 12.1	95.3 ± 8.4	5.0 ± 0.1
Top	*Cladina stellaris* (12)	*Ledum decumbens* (13)	15-25	3.5 ± 0.2	333.2 ± 10.5	93.3 ± 11.1	5.3 ± 0.1
	Cetraria nivalis (11)	*Cladina mitis* (13)	25-35	4.5 ± 0.3	298.5 ± 19.0	103.3 ± 11.9	5.4 ± 0.2
			0-5	2.6 ± 0.2	627.2 ± 79.2	197.3 ± 16.1	6.1 ± 0.3
Ice	*Aulacomnium turgidum* (12)	*Rubus chamaemorus* (17)	5-15	3.8 ± 0.4	657.9 ± 45.4	192.4 ± 10.4	6.0 ± 0.1
Wedge	*Cladina stellaris* (12)	*Dicranum elongatum* (11)	15-25	5.0 ± 0.5	599.1 ± 33.5	154.6 ± 9.9	6.4 ± 0.2
	Aulacomnium palustre (12)	*Aulacomnium palustre* (9)	25-35	5.8 ± 0.5	589.3 ± 44.0	143.4 ± 11.0	6.4 ± 0.1
			0-5	3.4 ± 0.4	471.5 ± 71.8	158.8 ± 17.2	6.3 ± 0.1
Lower	*Dicranum elongatum* (38)	*Dicranum elongatum* (22)	5-15	4.5 ± 0.5	601.3 ± 63.0	139.6 ± 10.5	6.6 ± 0.2
Sedge	*Cladina rangiferina* (15)	*Empetrum nigrum* (11)	15-25	5.9 ± 0.4	522.4 ± 70.8	128.1 ± 8.5	6.7 ± 0.1
	Tomenthypnum nitens (12)	*Rubus chamaemorus* (11)	25-35	6.9 ± 0.4	489.3 ± 82.7	138.5 ± 9.1	6.9 ± 0.3
			0-5	3.0	716.4 (583.1-849.6)	246.0 (240.0-252.0)	6.5 (6.2-6.8)
Riparian	*Hypnum sp.* (65)	*Carex aquatilis* (60)	5-15	3.5 (2.0-5.0)	967.3 (785.6-1149.0)	206.0 (160.0-252.0)	6.4 (6.3-6.4)
	Carex aquatilis (10)	*Hypnum sp.* (35)	15-25	5.0 (3.0-7.0)	879.1 (824.8-933.3)	153.0 (139.0-167.0)	6.7 (6.3-7.1)
			25-35	5.0 (3.0-7.0)	628.3 (501.0-755.6)	178.0 (127.0-229.0)	7.1 (7.0-7.2)
			0-5	3.5 (3.0-4.0)	650.6 (601.6-699.6)	319.5 (250.0-389.0)	6.6 (6.5-6.8)
Pond	Submerged Peat	Submerged Peat	5-15	4.5 (4.0-5.0)	933.0 (867.7-998.3)	352.0 (290.0-414.0)	6.6 (6.3-6.9)
Edge			15-25	5.0	480.0 (236.4-723.7)	286.5 (243.0-330.0)	7.0 (6.7-7.3)
			25-35	6.0	126.6 (71.1-182.1)	150.0 (148.0-152.0)	7.2 (6.7-7.7)

[1] Values shown are the mean of 8 replicate sample positions followed by ± 1 standard error of the mean except vegetation cover. Riparian and Pond Edge values are mean of 2 replicates followed by the range of values in parentheses. [2] Plant taxa and their average taxa percent cover shown in parentheses. Shown are either the three taxa providing a sum of >80% cover or the three dominant taxa.

Table 2.2. General site characteristics for the plant habitats at the Spruce site, August 2006[1].

Habitat Type	Dominant Vegetation Inside Collar[2]	Dominant Vegetation 10 cm Surrounding Collar[2]	Soil Depth (cm)	von Post Decomposition Scale	Moisture (g H_2O/g soil)	EC ($\mu S\ cm^{-1}$)	pH
			0-5	2.0 ± 0.0	388.7 ± 35.0	114.3 ± 6.8	4.7 ± 0.2
Upper Lichen	*Cladina stellaris* (83)	*Cladina stellaris* (64)	5-15	2.3 ± 0.2	483.9 ± 59.0	82.4 ± 8.8	4.9 ± 0.1
		Cladina rangiferina (14)	15-25	3.0 ± 0.2	443.3 ± 46.5	90.0 ± 16.4	5.2 ± 0.1
			25-35	3.9 ± 0.4	486.6 ± 41.2	82.3 ± 7.5	5.6 ± 0.1
			0-5	1.0 ± 0.0	753.4 ± 19.0	199.9 ± 13.6	4.4 ± 0.1
Moss	*Sphagnum sp.* (82)	*Sphagnum sp.* (74)	5-15	1.4 ± 0.3	663.0 ± 45.8	159.4 ± 19.6	4.9 ± 0.3
(*Sphagnum*)		*Rubus chamaemorus* (12)	15-25	1.8 ± 0.3	680.4 ± 50.9	162.3 ± 20.4	5.4 ± 0.4
			25-35	2.9 ± 0.5	608.6 ± 37.0	146.6 ± 21.4	6.1 ± 0.4
			0-5	1.9 ± 0.1	457.8 ± 36.4	203.4 ± 21.3	5.9 ± 0.2
Moss	*Hylocomium splendens* (59)	*Hylocomium splendens* (53)	5-15	2.8 ± 0.4	625.9 ± 82.9	160.5 ± 18.0	6.4 ± 0.1
(*Hylocomium*)	*Tomenthypnum nitens* (38)	*Tomenthypnum nitens* (34)	15-25	3.9 ± 0.6	622.0 ± 84.2	133.8 ± 15.1	6.6 ± 0.1
			25-35	5.9 ± 0.8	464.3 ± 75.6	111.6 ± 15.9	6.7 ± 0.1
			0-5	2.1 ± 0.1	1147.3 ± 111.2	342.9 ± 32.2	6.2 ± 0.1
Sedge-Moat	*Tomenthypnum nitens* (25)	*Tomenthypnum nitens* (23)	5-15	2.7 ± 0.2	1044.8 ± 76.5	242.3 ± 11.2	6.4 ± 0.1
	Sphagnum sp. (20)	*Carex sp. 2* (18)	15-25	3.6 ± 0.3	952.1 ± 57.8	243.4 ± 14.6	6.5 ± 0.1
	Salix planifolia (15)	*Sphagnum sp.* (14)	25-35	4.5 ± 0.4	947.1 ± 72.1	232.8 ± 11.8	6.6 ± 0.1

[1] Values shown are the mean of 8 replicate sample positions except for the Sedge-Moat values which are mean of 12 replicates and all followed by ± 1 standard error of the mean except vegetation cover. [2] Plant taxa and their average taxa percent cover shown in parentheses. Shown are either the three taxa providing a sum of >80% cover or the three dominant taxa.

Table 2.3. General site characteristics for the plant habitats at the Fen site, August 2006[1].

Habitat Type	Dominant Vegetation Inside Collar[2]	Dominant Vegetation 10 cm Surrounding Collar[2]	Soil Depth (cm)	von Post Decomposition Scale	Moisture (g H_2O/g soil)	EC (µS cm^{-1})	pH
			0-5	3.0 ± 0.0	487.3 ± 38.7	225.0 ± 27.2	5.9 ± 0.3
Hummock	*Aulacomnium turgidum* (33)	*Aulacomnium turgidum* (29)	5-15	5.3 ± 0.3	530.1 ± 59.3	174.3 ± 11.9	6.8 ± 0.4
	Dicranum elongatum (25)	*Carex aquatilis* (11)	15-25	6.0 ± 0.6	493.5 ± 14.4	161.7 ± 7.3	6.9 ± 0.4
	Andromeda polifolia (7)	*Dicranum elongatum* (9)	25-35	7.0 ± 0.0	556.0 ± 56.0	169.3 ± 13.0	7.4 ± 0.2
			0-5	4.3 ± 0.7	742.8 ± 54.0	193.3 ± 19.1	6.7 ± 0.3
Sedge-Lawn	*Drepanocladus vernicosus* (45)	*Carex aquatilis* (54)	5-15	5.0 ± 0.0	599.1 ± 109.6	195.7 ± 6.8	7.2 ± 0.2
	Carex aquatilis (33)	*Drepanocladus vernicosus* (42)	15-25	5.7 ± 0.7	715.4 ± 59.0	158.3 ± 23.8	7.2 ± 0.1
			25-35	7.0 ± 0.6	536.6 ± 210.8	172.3 ± 11.7	6.8 ± 0.6
			0-5	2.7 ± 0.3	1040.2 ± 77.7	353.7 ± 58.4	7.3 ± 0.1
Pool	Organic Sediment	Organic Sediment	5-15	3.0 ± 0.0	42.1 ± 10.3	137.7 ± 12.9	8.5 ± 0.1
			15-25	Mineral Soil	17.2 ± 0.9	111.7 ± 8.3	8.4 ± 0.2
			25-35	Mineral Soil	15.1 ± 0.5	108.0 ± 9.5	8.2 ± 0.5

[1] Values shown are the mean of 3 replicate sample positions and all followed by ± 1 standard error of the mean except vegetation cover. [2] Plant taxa and their average taxa percent cover shown in parentheses. Shown are either the three taxa providing a sum of >80% cover or the three dominant taxa.

2.4. Results

2.4.1. Weather Conditions

Daily precipitation and average daily air temperature were relatively similar for the field seasons of 2005 and 2006, in Churchill (Figure 2.3). Both seasons had wet summers, however the summer of 2006 had more precipitation throughout the field season. The wet conditions in 2006 occurred because of two major rain storms in July on days 193 and 195 which provided 48.6 and 68.7 mm of rain, respectively. The months of June were very similar both years with respect to rainfall, as June 2005 had 21.3 mm and June 2006 had 26.1 mm. In 2006, both July and August had much larger amounts of precipitation than the same months in 2005. July and August 2005 had 89.4 and 63 mm, respectively, while in 2006 there was 159.9 and 90.2 mm of rainfall. Except for the month of June, precipitation values were typically greater than 30 year average values for Churchill with 44.3, 56.0 and 68.3 mm of precipitation normally occurring in June, July and August, respectively (Environment Canada, 2006). With respect to air temperature, both 2005 and 2006 had very similar average temperatures for the field season months of June, July and August and were slightly higher than the 30 year daily average air temperature of 10.1 ^{o}C for the same months (Environment Canada, 2006). The summer of 2005 had an average temperature of 11.7 ^{o}C while 2006 had an average temperature of 12.1 ^{o}C.

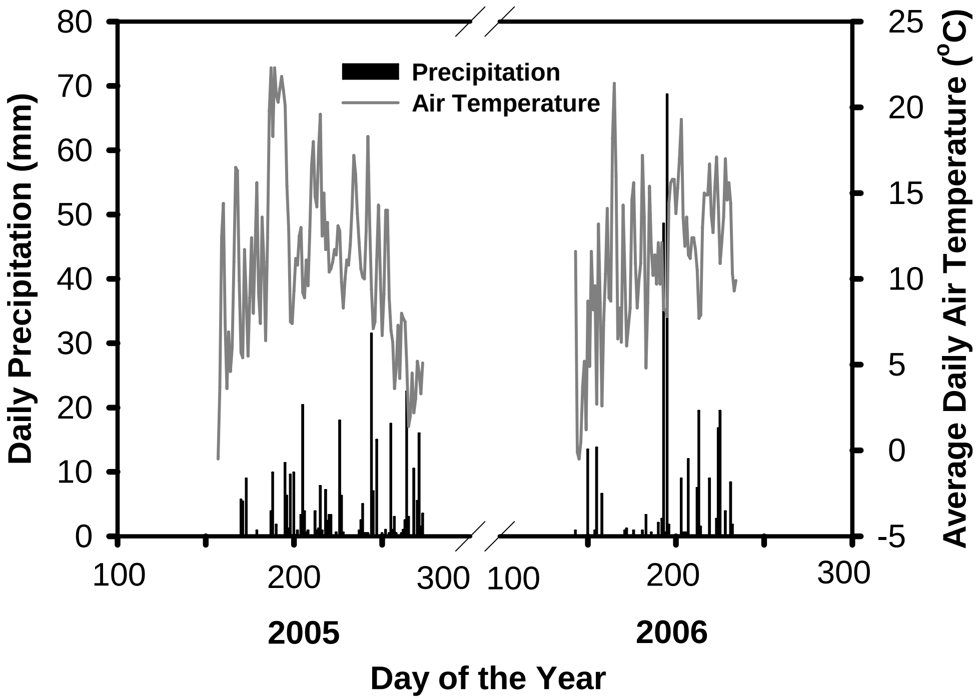

Figure 2.3. Daily precipitation and average daily air temperature for Churchill, Manitoba for the study periods in 2005 and 2006. Average daily air temperature from Environment Canada weather station at the Churchill Airport (Churchill A).

2.4.2. Temporal Variation in Greenhouse Gas Emissions

At the Peat site, in 2005 the subset of 32 sample positions along the transect revealed slight CH_4 production in the wetter plant habitats, such as the Ice Wedge and Upper and Lower Sedge areas. Consistently greater CH_4 fluxes were from the Upper Sedge, the Lower Sedge and Ice Wedge plant habitats had intermediate levels but were continually a source of CH_4 and the Polygon Top was an increasing sink for CH_4, as the season progressed (Figure 2.4a). In 2006, the trends for CH_4 emissions from the plant habitats were similar to 2005. The added plant habitats of Riparian and Pond Edge had comparably very high CH_4 emissions (Figure 2.5a). There were no consistent trends for differing N_2O emissions between plant habitats, as all positions gave very low N_2O

emission values (Figures 2.4b and 2.5b). However, there was a weak trend for slight negative N_2O emissions in 2006 from the Lower Sedge and slight positive emissions from the Polygon Top plant habitat (Figure 2.5b)

In 2005, large CH_4 fluxes, ranging from 0.043 to 0.227 µg C m^{-2} s^{-1}, occurred in the saturated Sedge-Moat habitat surrounding Lake Stanley at the Spruce site. There was a trend for the Upper Lichen habitat to have slightly negative CH_4 fluxes, while the other Moss habitats had fluxes generally around zero (Figure 2.4c). Fluxes in 2006 were comparable to 2005, however notably the CH_4 flux values for the Sedge-Moat were higher than the range for 2005, as average daily emissions ranged from 0.121 to 0.799 µg C m^{-2} s^{-1} (Figure 2.5c). There was no obvious trend for N_2O emissions with plant habitats as all produced near zero flux emission rates (Figures 2.4 d and 2.5d).

Methane fluxes were dramatically higher for the plant habitats at the Fen compared to the other sites. All habitats at the Fen site in 2006 showed CH_4 being emitted. The Sedge-Lawns had the greatest CH_4 emissions of all the sites, with values ranging from 0.237 to 17.0 µg C m^{-2} s^{-1}, followed by the Pools, with values as high as 4.78 µg C m^{-2} s^{-1}, and the Hummocks with values as high as 1.90 µg C m^{-2} s^{-1} (Figure 2.5e). In general, the Fen had low, near zero N_2O emissions (Figure 2.5f).

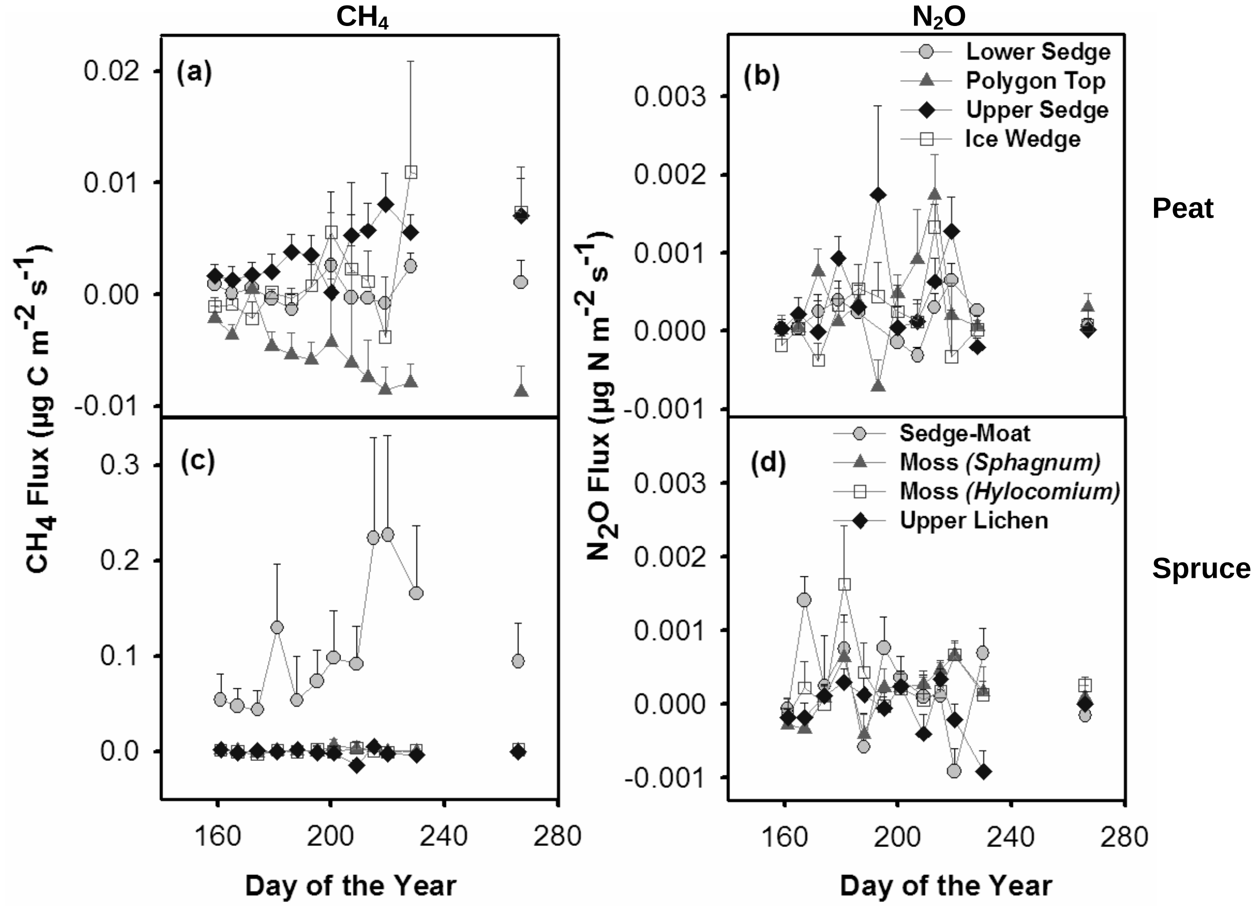

Figure 2.4. CH_4 and N_2O fluxes, for plant habitats at the Peat and Spruce sites in 2005; (a) CH_4-Peat site, (b) N_2O-Peat site, (c) CH_4-Spruce site, and (d) N_2O-Spruce site (mean of n=8, +1 SE shown). Note: Flux values not significantly different from zero ranged from -0.00089 and 0.0011 μg C m^{-2} s^{-1} for CH_4 and -0.00034 and 0.00026 μg N m^{-2} s^{-1} for N_2O.

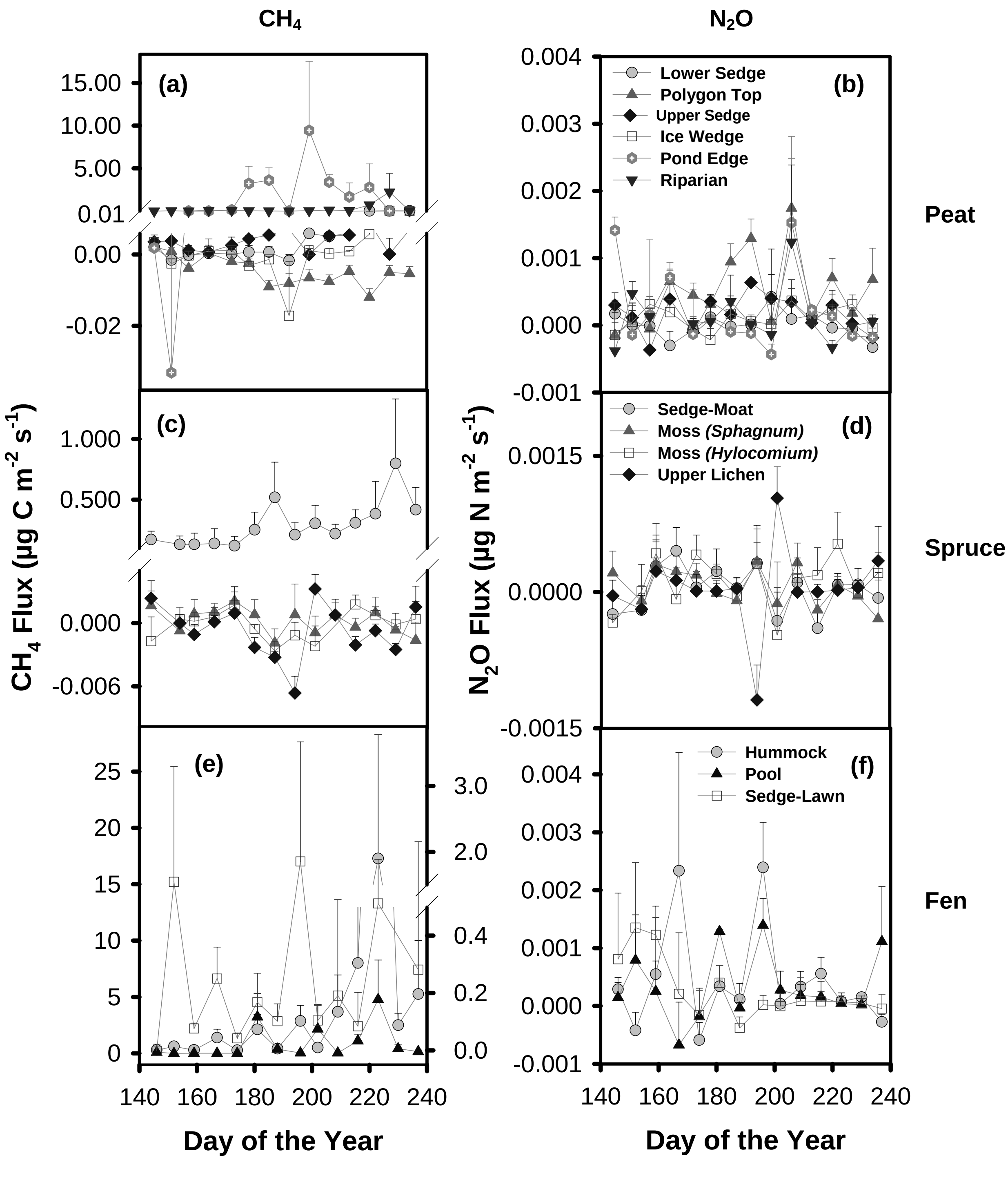

Figure 2.5. CH_4 and N_2O fluxes, for plant habitats at the Peat, Spruce and Fen sites in 2006; (a) CH_4-Peat site, (b) N_2O-Peat site, (c) CH_4-Spruce site, (d) N_2O-Spruce site, (e) CH_4-Fen site and (f) N_2O-Fen site (mean of n=8 for all except Riparian and Pond Edge: n=2; Sedge-Moat: n=12; Hummock, Pool and Sedge-Lawn: n=3, +1 SE shown). Note: Figure (e) Fen Hummock CH_4 flux data on right axis.

2.4.3. Average Growing Season Greenhouse Gas Emissions

There was generally a greater average seasonal CH_4 flux in 2006 than 2005 for the plant habitats at the Peat and Spruce sites. Average N_2O fluxes for all sites in both years were very low ranging from -0.00006 to 0.00238 µg N m^{-2} s^{-1}, with the majority falling below detectable limits.

At the Peat site in 2005, the wetter plant habitats (Upper Sedge, Ice Wedge and Lower Sedge) had the largest average CH_4 emissions, while the Polygon Top habitat had a negative average flux which was found to be significantly different from the other plant habitats. Average growing season respiration was greatest for the Ice Wedge habitat, with intermediate levels occurring for the Upper and Lower Sedge and the Polygon Top habitat had the lowest average flux with a value of 3.4 µg C m^{-2} s^{-1}. Similar trends for CH_4 emissions and respiration were found in 2006. The added Riparian and Pond Edge habitats had the greatest average CH_4 flux values of 0.3 and 1.7 µg C m^{-2} s^{-1}, respectively. The Pond Edge also had the lowest average flux with a value of 1.2 µg C m^{-2} s^{-1} (Tables 2.4 and 2.5).

Similar trends for average gas fluxes for the different plant habitats at the Spruce site occurred in both 2005 and 2006. The Sedge-Moat habitat had the greatest CH_4 average flux values of 0.1 and 0.3 µg C m^{-2} s^{-1} for 2005 and 2006, respectively, and was found to be significantly different from the other habitat types. Slight positive CH_4 fluxes were found for the Moss habitats and slight negative CH_4 emissions occurred in the Upper Lichen plant habitat in both field seasons. The Upper Lichen habitat also had the lowest average respiration while the Sedge-Moat plant habitat had the largest average respiration, in both field seasons (Tables 2.4 and 2.5).

At the Fen site in 2006, CH_4 average flux was greatest for the Sedge-Lawn plant habitats at 5.1 μg C m^{-2} s^{-1} and significantly lower for the Hummock and Pool habitats. The average respiration was significantly lowest in the Pools at 0.8 μg C m^{-2} s^{-1}, with the Hummocks and Sedge-Lawns having comparatively large respiration values of 8.5 and 8.1 μg C m^{-2} s^{-1}, respectively (Table 2.5).

Average CH_4 and N_2O flux variability for each plant habitat, at all sites, was high compared to that of respiration, with coefficient of variations (CV) as large as 1051%. Plant habitats with a smaller range of environmental conditions and plant communities, like the Polygon Top, Riparian and Pond Edge habitats, tended to have less CH_4 and N_2O average emission variation than habitats encompassing a broader gradient of conditions, like the Lower Sedge habitat.

Table 2.4. Average CH_4, N_2O and respiration (CO_2) flux for plant habitats at the Peat (days 159 to 267) and Spruce (days 161 to 266) sites in 2005.

		CH_4 Flux ($\mu g\ C\ m^{-2}\ s^{-1}$)			N_2O Flux ($\mu g\ N\ m^{-2}\ s^{-1}$)			Respiration ($\mu g\ CO_2\text{-}C\ m^{-2}\ s^{-1}$)		
Site	**Habitat Type**	**Mean**	**SD**	**%CV**	**Mean**	**SD**	**%CV**	**Mean**	**SD**	**%CV**
Peat	Upper Sedge	0.0038 a	0.0039	102	0.00043 a	0.00042	99	5.5 ba	1.3	23
108 days	Polygon Top	-0.0053 b	0.0042	79	0.00036 a	0.00041	114	3.4 b	1.6	48
	Ice Wedge	0.0017 a	0.0045	272	0.00019 a	0.00027	143	7.6 a	3.7	49
	Lower Sedge	0.0004 a	0.0026	612	0.00016 a	0.00017	107	5.8 ba	3.8	66
Spruce	Upper Lichen	-0.0017 a	0.0029	166	-0.00006 a	0.00021	339	5.0 b	1.3	26
105 days	Moss (*Sphagnum*)	0.0013 a	0.0021	170	0.00015 a	0.00015	100	5.5 b	2.2	40
	Moss (*Hylocomium*)	0.0003 a	0.0017	626	0.00030 a	0.00033	110	9.8 ba	4.7	48
	Sedge-Moat	0.1082 b	0.1318	122	0.00023 a	0.00028	124	13.4 a	6.2	46

Values shown are the mean of 8 replicate sample positions, 12 sample days with total sample data of n=96, ± 1 standard deviation (SD) of the mean and the percent coefficient of variation (CV). Mean values followed by the same letter (within column and site) are not significantly different using Scheffe's test ($P<0.05$). Note: Spruce site CH_4 flux data were not homogenous.

Table 2.5. Average CH_4, N_2O and respiration (CO_2) flux for plant habitats at the Peat (days 145 to 234), Spruce (days 144 to 236) and Fen (days 146 to 237) sites in 2006.

		CH_4 Flux ($\mu g\ C\ m^{-2}\ s^{-1}$)			**N_2O Flux ($\mu g\ N\ m^{-2}\ s^{-1}$)**			**Respiration ($\mu g\ CO_2\text{-}C\ m^{-2}\ s^{-1}$)**		
Site	**Habitat Type**	**Mean**	**SD**	**%CV**	**Mean**	**SD**	**%CV**	**Mean**	**SD**	**%CV**
Peat	Upper Sedge	0.0040 a	0.0053	132	0.00017 ba	0.00022	129	4.6 a	1.1	24
89 days	Polygon Top	-0.0045 b	0.0033	74	0.00050 a	0.00040	79	3.4 a	2.0	58
	Ice Wedge	0.0043 a	0.0104	243	0.00010 b	0.00019	193	6.1 a	2.3	37
	Lower Sedge	0.0079 a	0.0122	254	0.00001 b	0.00013	1050	7.4 a	5.5	75
	Riparian	0.2570	0.2431	95	0.00238	0.00357	150	6.0	2.2	37
	Pond Edge	1.7340	1.3795	80	0.00022	0.00003	14	1.2	0.5	39
Spruce	Upper Lichen	-0.0007 a	0.0009	126	0.00003 a	0.00021	652	3.5 a	1.0	29
92 days	Moss (*Sphagnum*)	0.0002 a	0.0007	386	0.00006 a	0.00096	171	5.7 ba	2.6	45
	Moss (*Hylocomium*)	0.0033 a	0.0056	173	0.00011 a	0.00023	216	6.8 bc	2.6	39
	Sedge-Moat	0.2934 b	0.4452	152	0.00003 a	0.00031	1051	13.4 c	6.8	51
Fen	Hummock	0.2 b	0.3	155	0.00042 a	0.00006	14	8.54 a	0.66	8
91 days	Pool	0.9 b	0.7	75	0.00034 a	0.00020	59	0.80 b	0.06	8
	Sedge-Lawn	5.1 a	0.3	7	0.00027 a	0.00048	182	8.12 a	2.95	36

Values shown for the Peat site are the mean of 8 replicate sample positions, 14 sample days with total sample data of n=112, except for the Riparian and Pond Edge values which are mean of 2 replicate sample positions, 14 sample days with total sample data of n=28. Values shown for the Spruce site are the mean of 8 replicate sample positions, 14 sample days with total sample data of n=112, except for the Sedge-Moat which is mean of 12 replicate sample positions, 14 sample days with total sample data of n=168. Values shown for the Fen site are the mean of 3 replicate sample positions, 14 sample days with total sample data of n=42. Values of ± 1 standard deviation (SD) of the mean and the percent coefficient of variation (CV) are also shown. Mean values followed by the same letter (within column and site) are not significantly different using Scheffe's test ($P<0.05$). Riparian and Pond Edge not included in Scheffe's test due to limited number of replicates

2.4.4. Temporal Environmental Conditions

Respiration occurred at all plant habitats and was used to assess general microbial activity and autotrophic plant respiration. At the Peat site in 2005, respiration was continually greater for the Ice Wedge, Upper and Lower Sedge habitats compared to the Polygon Top (Figure 2.6a). In 2006, similar trends were observed for respiration. The added Riparian habitat had respiration values similar to the Ice Wedge, Upper and Lower Sedge plant habitats while the Pond Edge habitat consistently had the lowest respiration levels (Figure 2.7a). At the Spruce site, respiration trends were the same for both 2005 and 2006. The greatest respiration values occurred for the Sedge-Moat plant habitat ranging from 6 to 23 μg C m^{-2} s^{-1} in 2005 (Figure 2.6b) and 4 to 21 μg C m^{-2} s^{-1} in 2006 (Figure 2.7b) and were lowest for the Upper Lichen habitat. In 2006, the Fen site had similar levels of respiration for the Hummock and Sedge-Lawn plant habitats, while the Pool habitat had comparatively low levels (Figure 2.7c).

Respiration followed soil temperature trends at both 2.5 and 15 cm. All plant habitats at the Peat and Fen sites had very similar soil temperatures at 2.5 cm in 2005 and 2006 (Figures 2.6c, 2.7d and 2.7f). The Upper Lichen habitat at the Spruce site constantly had a lower soil temperature at 2.5 cm than the other three plant habitats in both field seasons (Figures 2.6d and 2.7e).

Soil volumetric moisture content (VMC) was greatest at the Peat site for the Upper Sedge, followed by the Ice Wedge and Lower Sedge habitats in 2005 and 2006. The lowest VMC was found for the Polygon Top habitat ranging from 21 to 44% in 2005 (Figure 2.6e) and 31 to 41% in 2006 (Figure 2.7g). The greatest moisture content at the Spruce site in both years was found for the Sedge-Moat with the lowest VMC values occurring for the Moss habitats (Figures 2.6f and 2.7h). The Sedge-Lawn habitat at the Fen had the highest moisture content of all habitats at all sites with VMC values of 91 to 99% (Figure 2.7i).

Active layer depths at the Peat site were similar for all plant habitats. In 2005, the Polygon Top habitat had the thinnest active layer while the Lower Sedge had the deepest active layer at a maximum of 69 cm (Figure 2.6g). The plant habitats at the Peat site in 2005 had very similar active layer depths due to the interference of a cobble layer found at a similar depth in the soil profile at the site. In 2006, areas near the sample locations were found in which the cobble layer did not interfere with active layer depth measurements and therefore even though similar active layer depth trends were found in 2006, the values are more reliable. The added Riparian and Pond Edge plant habitats consistently had slightly greater active layers than the other habitats (Figure 2.7j). At the Spruce site, the Sedge-Moat habitat had very large active layer depths compared to the other habitats at this site in both field seasons, with maximum values of 118 cm in 2005 (Figure 2.6h) and 151 cm in 2006 (Figure 2.7k). The plant habitats at the Fen, were similar with respect to active layer depth, reaching a maximum depth of 175 cm for the Pool habitat, late in the growing season (Figure 2.7l).

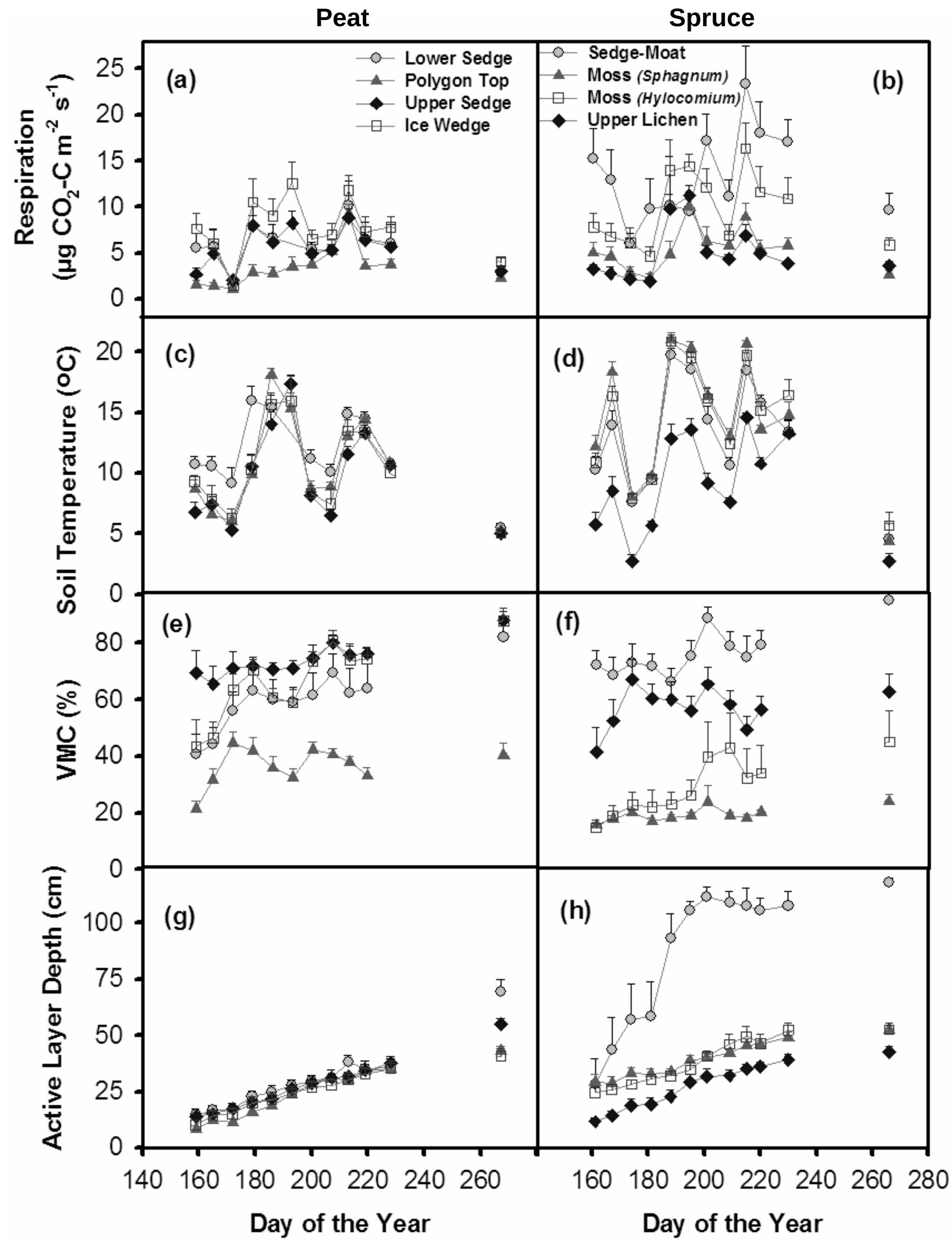

Figure 2.6. Respiration (CO_2), soil temperature at 2.5 cm, soil volumetric moisture content (VMC) and active layer depth, for plant habitats at the Peat and Spruce sites in 2005; (a) CO_2-Peat site, (b) CO_2-Spruce site, (c) 2.5 cm temperature-Peat site, (d) 2.5 cm temperature-Spruce site, (e) VMC-Peat site, (f) VMC-Spruce site, (g) active layer depth-Peat site and (h) active layer depth-Spruce site (mean of n=8; +1 SE shown). Note: Flux values not significantly different from zero ranged from 0 and 1.83 µg C m^{-2} s^{-1} for CO_2.

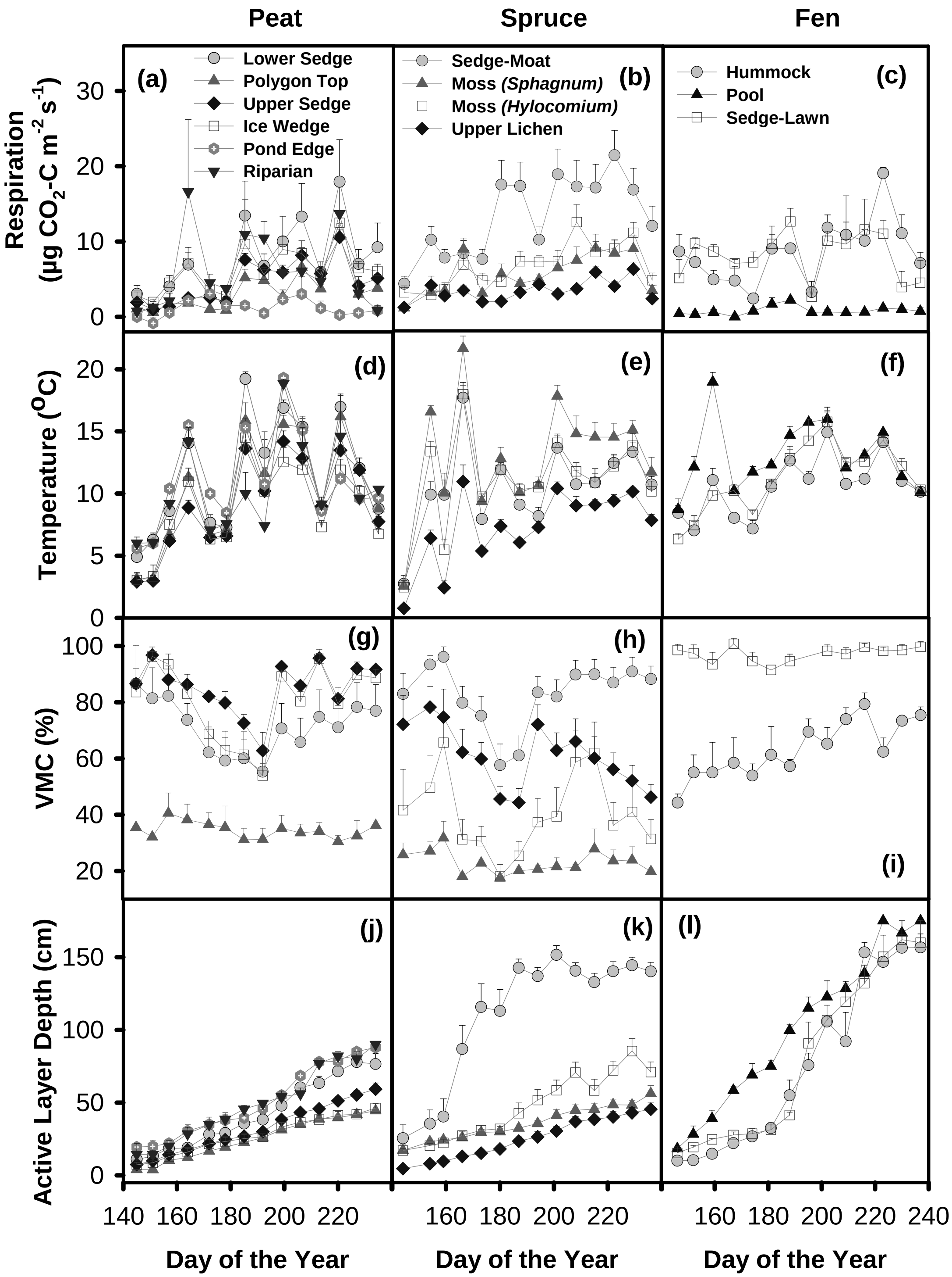

Figure 2.7. Respiration (CO_2), soil/water temperature at 2.5 cm, soil volumetric moisture content (VMC) and active layer depth, for plant habitats at the Peat, Spruce and Fen sites in 2006; (a,b,c) CO_2-Peat, Spruce and Fen sites (d,e,f) 2.5 cm temperature-Peat, Spruce and Fen sites, (g,h,i) VMC-Peat, Spruce and Fen sites and (j,k,l) active layer depth-Peat, Spruce and Fen sites (mean of n=8 for all except Riparian and Pond Edge: n=2; Sedge-Moat: n=12; Hummock, Pool and Sedge-Lawn: n=3, +1 SE shown). All Riparian values and Sedge-Lawn day 195 for VMC not included due to standing water.

2.4.5. Association of CH_4 Emissions and Environmental Parameters

The relation between CH_4 fluxes and measured parameters for each sample position was determined across sample days using Spearman rank correlation analysis. Analysis for the Peat and Spruce sites was completed using data of the two study years combined. At the Peat site when all the plant habitats were analyzed together, CH_4 flux was positively correlated with all parameters except respiration, and soil temperature at 2.5 and 15 cm depths were strongly correlated with CH_4 flux. When considering each habitat individually, soil temperature at 2.5 cm was consistently the highest or second highest associated parameter to CH_4 flux. Active layer depth was strongly correlated to CH_4 flux for the Polygon Top. Soil temperature was strongly correlated to CH_4 flux in the Riparian and Pond Edge habitats. At the Spruce site, all plant habitats considered together produced strongest correlations to active layer depth and soil temperature at 15 cm. Nitrous oxide flux was the only parameter not significantly correlated to CH_4 fluxes. Similar to the Peat site, a strong correlation was found for each plant habitat between CH_4 flux and soil temperature. Associations of note were Moss (*Hylocomium*) to active layer depth and Sedge-Moat to respiration. For the Fen site, respiration and soil temperature at 15 cm depth was most strongly correlated to CH_4 flux across all plant habitats. For the Hummock habitat soil temperatures were strongly correlated while the Pool and Sedge-Lawn plant habitats had respiration correlated to CH_4 flux (Table 2.6). Scattergrams were produced for all parameters found to be significantly correlated with CH_4 flux ($P<0.05$). Interestingly, even though moisture content was generally not found to be correlated with CH_4 fluxes for the individual plant habitats at all sites, the scattergrams showed CH_4 fluxes to only be high at very high VMC levels (Figure 2.8). The negative CH_4 fluxes found at high moisture contents in the Sedge-Lawn plant habitat at the Fen site, all occurred in the wet conditions found in the months of July and August. In some instances the rising water table caused the sample positions in the Sedge-Lawn to almost be under water, resulting in extra pressure needed to place the cover on the collar. The pressure and saturated conditions likely caused an initial burst on CH_4 to fill the chamber. High initial CH_4 concentrations were found only within the Sedge-Lawn habitat and lead to decreasing trends and ultimately negative CH_4 fluxes for select sample positions on specific days.

Table 2.6. Spearman rank correlation analysis for CH_4 with N_2O flux, respiration (CO_2) and measured environmental parameters for the different plant habitats at the Peat, Spruce and Fen sites in 2005 and 2006.

		Parameter						
Plant Habitat	**n**	**N_2O**	**Respiration**	**$Temp_{2.5}$**	**$Temp_{15}$**	**$Temp_{air}$**	**VMC**	**Active Layer Depth**
Peat								
Upper Sedge	208	**0.25 ****	**0.18 ***	**0.69 *****	**0.62 *****	**0.54 *****	-0.18	**0.49 *****
Polygon Top	208	**0.39 *****	**-0.52 *****	**0.52 *****	**0.59 *****	**0.39 *****	-0.11	**0.60 *****
Ice Wedge	208	**0.22 ***	0.01	**0.70 *****	**0.64 *****	**0.54 *****	0.01	**0.53 *****
Lower Sedge	208	0.02	**0.19 ***	**0.53 *****	**0.58 *****	**0.46 *****	**0.34 *****	**0.43 *****
Riparian	28	-0.01	0.15	**0.52 ***	0.25	**0.67 ****	-0.28	0.22
Pond Edge	28	0.11	**0.60 ****	**0.50 ***	**-**	0.41	-	0.18
All Habitats	888	**0.15 *****	0.06	**0.51 *****	**0.53 *****	**0.44 *****	**0.22 *****	**0.44 *****
Spruce								
Upper Lichen	208	-0.04	-0.18	**0.47 *****	**0.55 *****	**0.37 *****	0.17	**0.43 *****
Moss (*Sphagnum*)	208	0.001	-0.08	**0.50 *****	**0.43 *****	**0.43 *****	0.14	**0.25 ****
Moss (*Hylocomium*)	208	0.03	-0.05	**0.39 *****	**0.51 *****	**0.31 *****	**0.26 ****	**0.48 *****
Sedge-Moat	264	-0.02	**0.52 *****	**0.41 *****	**0.51 *****	**0.22 ****	**-0.39 *****	**0.37 *****
All Habitats	888	0.02	**0.31 *****	**0.43 *****	**0.49 *****	**0.27 *****	**0.19 *****	**0.52 *****
Fen								
Hummock	42	0.001	0.31	**0.61 *****	**0.58 *****	0.19	0.04	**0.43 ***
Pool	42	0.31	**0.48 ***	0.27	-	0.28	-	0.25
Sedge-Lawn	42	-0.32	**0.41 ***	0.16	0.05	0.24	0.03	-0.15
All Habitats	126	-0.08	**0.29 ****	-0.05	**0.30 ***	0.13	-0.03	-0.06

*, ** and *** indicate the correlation is significant at $P<0.01$, 0.001 and 0.0001 level of significance, respectively. At the Peat site there were 8 replicates for each habitat except for the Riparian and Pond Edge habitats, which had 2 replicates. At the Spruce site there were 8 replicates for each habitat except for the Sedge-Moat in 2006, which had 12 replicates. At the Fen site there were 3 replicates for each habitat. Note: VMC = soil volumetric moisture content. Dash indicates analysis not available.

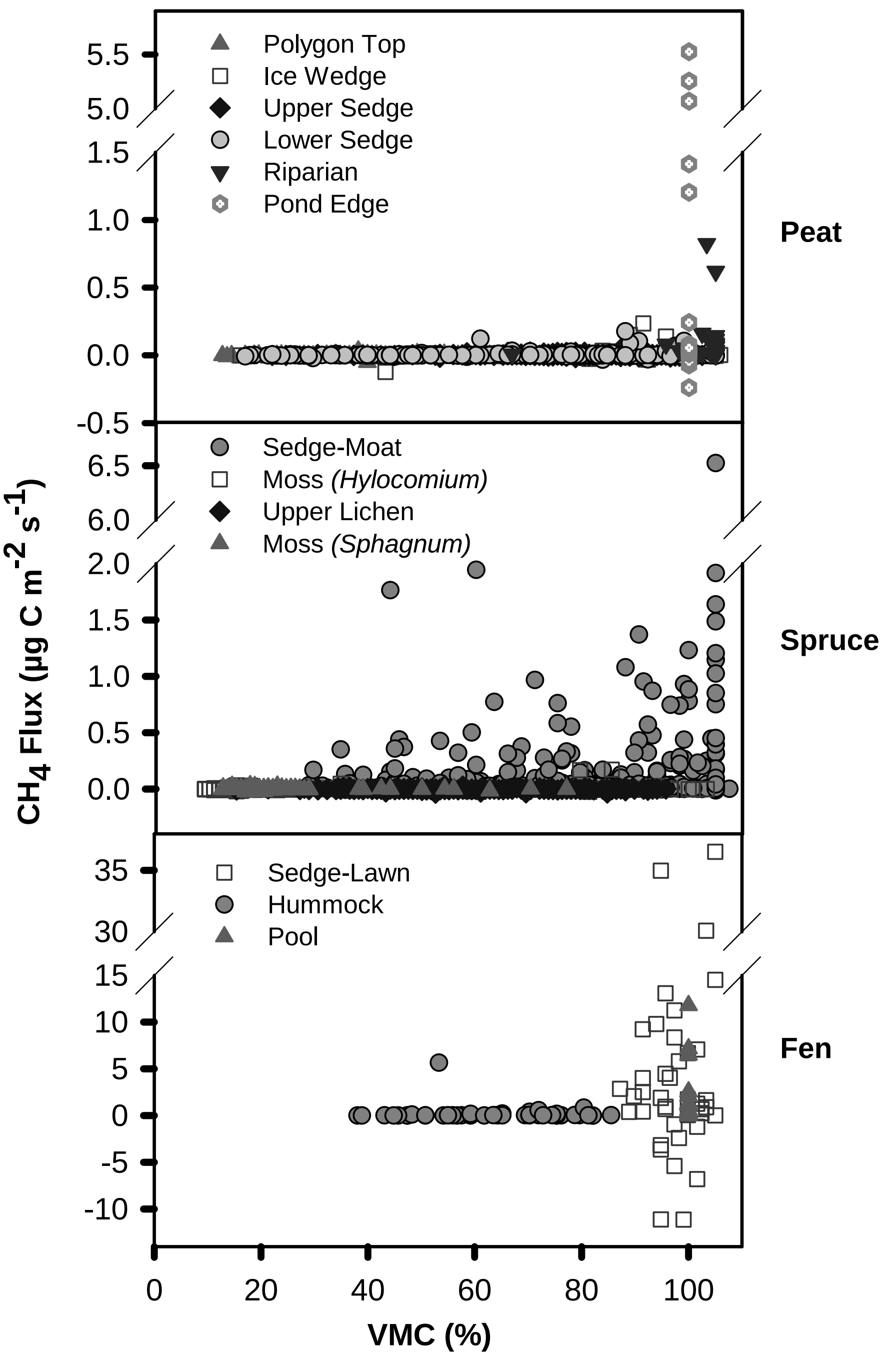

Figure 2.8. Scatterplots of CH_4 and volumetric moisture content (VMC) for plant habitats at the Peat, Spruce and Fen sites in 2005 and 2006 (n=208 for Upper Sedge, Polygon Top, Ice Wedge and Lower Sedge habitats, n=28 for Riparian and Pond Edge habitats; n=208 for Upper Lichen, Moss (*Sphagnum*) and Moss (*Hylocomium*) habitats, n=264 for the Sedge-Moat habitat and n=42 for Fen habitats).

2.4.6. Entire Transect at the Peat Site

The transect results for CH_4 and N_2O fluxes supported the results found using the subset sample positons. Methane fluxes were slightly negative in the drier, higher elevation Polygon Top habitat while stronger positive CH_4 fluxes occurred in the wet habitats (Upper Sedge, Ice Wedge, Lower Sedge, Riparian and Pond Edge) (Tables A.7 and A.8). For example, using one set of data for the transect in August 2006, the relationship of the gas emissions to habitat type can clearly be seen based on elevation, as well as environmental parameters such as soil temperature (Figure 2.9). These findings are generally typical of those produced by the transect, however, the pattern of N_2O production for the first half of the transect and consumption for the last half, was not as strong in the other samplings though evident in four of the six sampling days. The transect findings are supported by a statistical comparison of the use of the subset sample positions to the entire transect sample positions for both field seasons and all plant habitats. T-tests produced P values which were always greater than 0.05, ranging from 0.1 to 0.99, indicating that there was no significant difference between the subset and entire transect sampling positions for a plant habitat. Also, no strong trends appeared when comparing the subset versus entire transect sampling positions percent coefficient of variation (CV) for average CH_4 and N_2O emissions for each plant habitat (Tables 2.7 and 2.8). Therefore, even with less replicates being used for the weekly subset sampling, the results for CH_4 and N_2O emissions for each plant habitat, were found to be similar to using more replicates in the entire 92 transect.

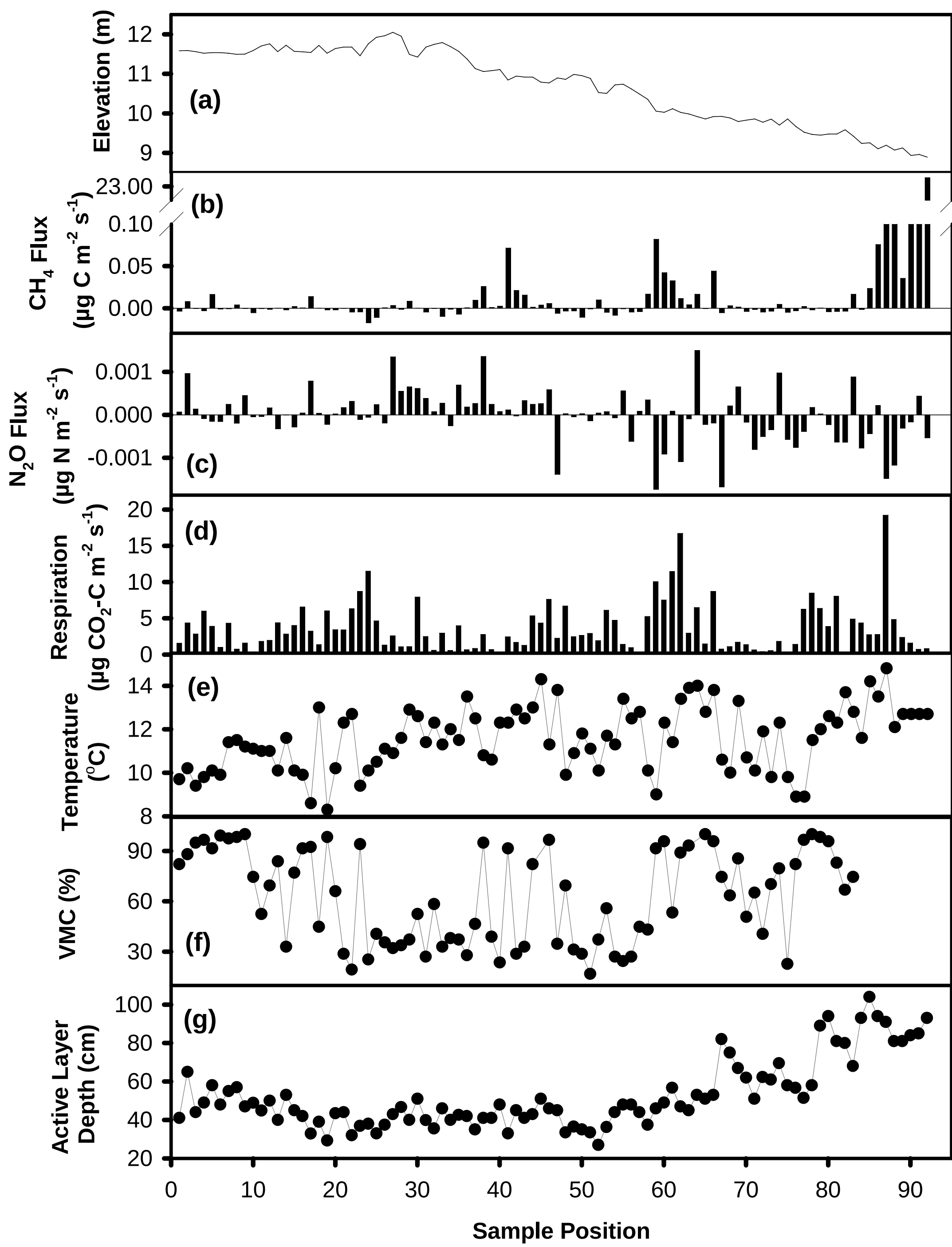

Figure 2.9. Entire transect results for each sample position at the Peat site in August 2006. (a) Chamber elevation above sea level, (b) CH_4 flux, (c) N_2O flux, (d) respiration (CO_2), (e) soil/water temperature at 2.5 cm, (f) volumetric moisture content (VMC) and (g) active layer depth. VMC values for chambers 45, 64 and 84-89 not included due to standing water.

Table 2.7. Comparison of subset or entire transect sample positions to estimates of CH_4 and N_2O emissions at the Peat site in 2005.

		Subset Positions CH_4 Flux (ng C m^{-2} s^{-1})				Transect CH_4 Flux (ng C m^{-2} s^{-1})				
Day of the Year	Habitat Type	n	Mean	SD	%CV	n	Mean	SD	%CV	P Value
168	Upper Sedge	8	1.20	1.80	150	9	3.30	6.70	203	0.37
	Polygon Top	8	-2.00	1.80	90	31	2.00	6.10	305	0.10
	Ice Wedge	8	4.00	1.30	33	14	2.00	1.30	65	0.71
	Lower Sedge	8	0.09	2.70	31395	20	-0.29	3.00	1034	0.81
197	Upper Sedge	8	6.50	6.50	100	9	6.50	6.10	94	0.99
	Polygon Top	8	-5.00	12.30	246	31	-2.00	15.70	785	0.70
	Ice Wedge	8	-1.00	17.80	1780	14	1.60	16.80	1050	0.70
	Lower Sedge	8	-1.00	9.60	960	20	-3.00	12.80	427	0.71
217	Upper Sedge	8	6.90	14.50	210	9	6.60	13.60	206	0.97
	Polygon Top	8	-6.00	5.40	90	31	-2.00	6.30	315	0.10
	Ice Wedge	8	4.60	9.50	207	14	3.00	7.90	263	0.67
	Lower Sedge	8	1.30	1.10	85	20	1.30	2.30	177	0.92
		N_2O Flux (ng N m^{-2} s^{-1})				N_2O Flux (ng N m^{-2} s^{-1})				
168	Upper Sedge	8	0.04	0.40	909	9	0.02	0.40	1653	0.91
	Polygon Top	8	-0.19	0.40	211	31	0.001	0.70	77778	0.47
	Ice Wedge	8	-0.15	1.20	800	14	-0.14	0.90	643	0.98
	Lower Sedge	8	-0.43	1.10	256	20	-0.24	1.00	417	0.66
197	Upper Sedge	8	1.40	1.80	129	9	1.30	1.70	131	0.88
	Polygon Top	8	0.40	0.70	175	31	0.40	1.00	250	0.84
	Ice Wedge	8	0.10	0.80	800	14	0.50	1.20	240	0.39
	Lower Sedge	8	0.40	1.00	250	20	0.20	1.20	600	0.71
217	Upper Sedge	8	2.60	1.10	42	9	2.40	1.20	50	0.73
	Polygon Top	8	1.00	0.60	60	31	1.20	1.00	83	0.49
	Ice Wedge	8	1.00	1.80	180	14	1.10	1.90	173	0.95
	Lower Sedge	8	1.00	0.70	70	20	0.90	0.60	67	0.94

Values shown are the number of replicate sampling positions in each landscape position (n), mean, standard deviation (SD), the percent coefficient of variation (CV) and P value for CH_4 and N_2O fluxes. Independent T-tests were done to produce the P values and $P<0.05$ indicate a significant difference in average values between the subset and transect sample positions.

Table 2.8. Comparison of subset or entire transect sample positions to estimates of CH_4 and N_2O emissions at the Peat site in 2006.

Day of the Year	Habitat Type	Subset Positions CH_4 Flux (ng C m^{-2} s^{-1}) n	Mean	SD	%CV	Transect CH_4 Flux (ng C m^{-2} s^{-1}) n	Mean	SD	%CV	P Value
163	Upper Sedge	8	3.50	2.40	69	9	3.90	2.60	67	0.74
	Polygon Top	8	-6.00	5.90	98	31	-3.00	4.90	163	0.19
	Ice Wedge	8	-2.00	4.00	200	14	-2.00	3.40	170	0.84
	Lower Sedge	8	-0.38	1.90	500	20	-0.97	2.10	216	0.50
	Riparian	2	64.70	30.60	47	4	37.20	36.30	98	0.42
	Pond Edge	2	27.20	21.00	77	3	34.30	19.30	56	0.72
198	Upper Sedge	8	0.90	4.10	456	9	2.00	5.20	260	0.63
	Polygon Top	8	-7.00	4.20	60	31	-4.00	4.90	123	0.15
	Ice Wedge	8	-0.58	1.60	276	14	-1.00	1.60	160	0.24
	Lower Sedge	8	2.00	3.00	150	20	1.60	2.60	163	0.74
	Riparian	2	55.90	66.50	119	4	33.40	47.20	141	0.65
	Pond Edge	2	934.20	1047.20	112	3	636.50	902.40	142	0.75
226	Upper Sedge	8	0.30	3.90	1300	9	2.10	6.50	310	0.51
	Polygon Top	8	-3.00	5.30	177	31	-2.00	6.80	340	0.81
	Ice Wedge	8	27.40	34.50	126	14	18.60	27.60	148	0.52
	Lower Sedge	8	9.80	17.20	176	20	3.20	12.70	397	0.27
	Riparian	2	55.60	28.30	51	4	156.00	158.80	102	0.45
	Pond Edge	2	4272.80	5863.00	137	3	10622.00	11753.00	111	0.54
		N_2O Flux (ng N m^{-2} s^{-1})				N_2O Flux (ng N m^{-2} s^{-1})				
163	Upper Sedge	8	-0.21	0.30	143	9	-0.23	0.30	130	0.91
	Polygon Top	8	-0.31	0.80	258	31	0.20	0.90	450	0.18
	Ice Wedge	8	-0.35	0.50	143	14	-0.45	0.50	111	0.63
	Lower Sedge	8	0.50	0.70	140	20	0.30	0.90	300	0.44
	Riparian	2	-0.08	0.10	125	4	0.20	0.30	150	0.32
	Pond Edge	2	0.20	0.20	100	3	0.70	0.80	114	0.51
198	Upper Sedge	8	0.80	0.70	88	9	0.80	0.60	75	0.94
	Polygon Top	8	0.40	0.70	175	31	0.30	0.60	200	0.88
	Ice Wedge	8	0.30	0.40	133	14	0.30	0.40	133	0.95
	Lower Sedge	8	0.30	0.60	200	20	0.20	0.40	200	0.69
	Riparian	2	0.10	0.04	40	4	0.20	0.30	150	0.54
	Pond Edge	2	0.70	0.20	29	3	0.60	0.20	33	0.60
226	Upper Sedge	8	0.20	0.40	200	9	0.10	0.40	400	0.84
	Polygon Top	8	0.20	0.50	250	31	0.10	0.40	400	0.55
	Ice Wedge	8	-0.15	0.90	600	14	0.10	0.70	700	0.52
	Lower Sedge	8	0.04	0.80	2000	20	-0.24	0.70	292	0.37
	Riparian	2	-0.05	0.40	800	4	-0.69	0.80	116	0.35
	Pond Edge	2	0.10	0.40	400	3	-0.09	0.50	556	0.64

Values shown are the number of replicate sampling positions in each landscape position (n), mean, standard deviation (SD), the percent coefficient of variation (CV) and P value for CH_4 and N_2O fluxes. Independent T-tests were done to produce the P values and $P<0.05$ indicate a significant difference in average values between the subset and transect sample positions.

2.5. Discussion

Global estimates for greenhouse gas (GHG) emissions, especially methane (CH_4), for peatlands and wetlands are uncertain due to a lack of data from specific habitats. There is great spatial variability in northern ecosystems in factors such as vegetation cover and water table depth (Moore et al, 1998). As the results show, this variability leads not only to variability within sites but between sites and spatial variability for plant habitats within all sites is much greater for CH_4 and nitrous oxide (N_2O) emissions. Most models do not included the spatial variability that occurs in these landscapes due to differences in vegetation, environmental factors and topography (Hirota et al., 2004). Therefore, landscape-scale evaluation of GHG fluxes, as well as soil and environmental factors, are key in establishing relationships and patterns needed for modeling purposes (Pennock et al., 1992).

The majority of studies regarding CH_4 emissions are conducted in fen or bog wetlands. There are limited studies for other subarctic peatland areas, such as peat plateaus and forests and few studies that take different landscape or habitat types into account. Therefore, a huge percentage of subarctic peatlands is being ignored in global estimates of GHG emissions. The objective of this study was to determine the relation between major environmental conditions and plant habitats to GHG emissions. The ultimate goal of this work will be to provide a basis to accurately model current and future GHG emissions under a changing climate for the plant habitats around Churchill, Manitoba and the Hudson Bay Lowlands (HBL).

2.5.1. Plant Habitats as Sources and Sinks of CH_4

Soils have the ability to both produce and consume CH_4. Anaerobic bacteria called methanogens produce CH_4 and are common in wetlands and other saturated soil environments. The major controls on CH_4 production, or methanogenesis, are temperature, soil moisture and water table depths, soil aeration and carbon availability in organic matter. When soil moisture contents or water table depths are low, aerobic conditions are favored, decreasing or preventing methanogensis (Trettin et al., 2006). Methanotrophy, or CH_4 consumption or oxidation occurs through aerobic soil bacteria, known as methanotrophs and occurs in all types of environments (Smith et al., 2003). Soil in the tropics, tundra, grasslands, forests, agricultural fields and deserts have shown to consume CH_4 at similar rates, generally between 0.5 to 2 mg CH_4 m^{-2} d^{-1}, with the soils in tundra regions having higher rates of consumption at around 3 mg CH_4 m^{-2} d^{-1} (King, 1999). Methanotrophy is affected primarily by soil moisture content and secondly by temperature, with dry conditions leading to increased CH_4 consumption (Smith et al. 2003).

This study found CH_4 production was generally greater for plant habitats in 2006 compared to the same habitats in 2005, which is likely due to 2006 being a wetter year than 2005. At the Peat site, slight CH_4 consumption occurred on the Polygon Top habitat for both field seasons and these fluxes were found to be significantly different from the other plant habitats at the Peat site (Tables 2.4 and 2.5). Slight CH_4 consumption also occurred in the Upper Lichen plant habitat at the Spruce site. Methane consumption was due to a range of factors, such as the dry conditions at the Polygon Top plant habitat, the lower soil temperatures at the Upper Lichen habitat and the vegetation type present in these environments. Dry conditions create a more aerobic environment, which result in CH_4 being oxidized by methanotrophs (Smith et al., 2003), while low soil temperatures, caused by the high albedo of the dominant *Cladina stellaris* lichen mats, as well as the thickness of the mats themselves, would not allow the sun's energy to penetrate and ultimately warm the soil. Microbial activity tends to decrease with lower temperatures (Trettin et al., 2006). Recent studies have also found vegetation to be a major factor influencing the variability of CH_4 emissions (Joabsson et al., 1999; Joabsson and Christensen, 2001; Hirota et al., 2004). Areas that had dominant macrolichen communities, such as the Polygon Top and Upper Lichen plant habitats were found to be CH_4 sinks. Macrolichens are abundant in subarctic and arctic environments and can contribute to nutrient cycling and biomass to the arctic carbon sink (Cornelissen et al., 2001).

Slight CH_4 production occurred in the wetter habitat types of the Peat site, such as the Ice Wedge and Upper and Lower Sedge (Tables 2.4 and 2.5), while comparatively large CH_4 production was found in the saturated Riparian and Pond Edge habitats of the Peat site and Sedge-Moat plant habitat of the Spruce site. Also, all plant habitats at the Fen site in 2006 were relatively large CH_4 sources, with the Sedge-Lawn plan habitat being significantly the largest CH_4 source of all plant habitats at all sites. The Hummocks were the driest plant habitat type at the Fen, although still relatively wet when compared to the habitats at the other sites, and had the least CH_4 production at the Fen site (Table 2.5). The Hummocks are also very porous which would allow the vast amounts of CH_4 produced at depth near the water table to move readily through the soil of the Hummock and be emitted at the surface. The large peaks of CH_4 production that occurred at the Fen throughout the field season were due to increases in both precipitation and/or temperature on or around the day of sampling. Methane production at the various plant habitats was due to increased soil moisture, high water table levels as well as the dominant vegetation types. Waterlogged conditions, with a water table near the surface create anaerobic conditions necessary for the microbial breakdown of organic compounds and CH_4 production. For methanogensis or CH_4 production to occur, low redox conditions created by prolonged saturated conditions and labile carbon are a necessity (Smith et al., 2003). Indication of anaerobic, low redox conditions were found when measuring dissolved oxygen (DO) concentration and oxidation-reduction potential (ORP) of soil water from monitoring wells in the different plant habitats. Low DO and ORP values were found for the wetter habitats at the Peat site and Spruce sites (Table A.1 and A.2). For example, the Upper Sedge plant habitat had ORP values ranging from -166 to 12 mV and the Sedge-Moat had ORP values ranging from -102 to 100 mV, with the majority being negative in both habitats. These values give evidence of the conditions necessary for CH_4 production to occur. Also, habitats such as the Riparian, Sedge-Moat and Sedge-Lawn of the Peat, Spruce and Fen sites respectively, are dominated by sedges (*Carex spp.*) which allows increased CH_4 production. Studies have found that sites dominated by sedges, generally *Carex*, were usually saturated and produced high CH_4 emissions. Sedges play an active role in increasing CH_4 emissions as they have the ability to transport CH_4 through their plant structures, avoiding the oxidation zone in the peat. Also, sedges are a source of labile carbon to the surrounding soil for methanogenesis (Bubier et al., 1995). Much of the CH_4 emissions from peatlands have been found to come from organic matter deposited by sedges in anoxic peat layers (Trettin et al., 2006). Therefore, due to the increased spatial variability in peatland ecosystems resulting in vast differences in environmental conditions and vegetation communities, sources and sinks of CH_4 can occur only a few meters away from each other in the landscape. As a result, it becomes increasingly important to determine the contribution of specific plant habitats to local, regional and global CH_4 budgets.

2.5.2. Nitrous Oxide Emissions

At all sites and plant habitats in 2005 and 2006, N_2O production or consumption was negligible, as the majority of values fell within the range of flux values considered to be the same as zero, which is common in peatlands (Tables 2.4 and 2.5). In many peatland environments, N_2O flux has been found to be insignificant (Maljanen et al., 2004). The Peat and Spruce subset sampling positions resulted in a lack of consistent trends for differing N_2O emissions between plant habitats, as all positions gave very low N_2O emission values. Slight N_2O production and consumption occurred throughout the length of the entire transect at the Peat site with N_2O consumption generally occurring in wet regions (Figure 2.9). However, only a few of these N_2O consumption values were found to be within detectable limits. Nitrous oxide values not significantly different from zero ranged from of -0.00034 and 0.00026 μg N m^{-2} $s^{-}1$.

Soils can act as sinks for N_2O, but depend on the potential for N_2O reduction to nitrogen (N_2), the ability of N_2O to diffuse through the soil and dissolve into soil water. Nitrous oxide consumption primarily depends on numerous soil properties, such as mineral nitrogen and labile organic carbon and nitrogen availability, soil oxygen (O_2) and water contents, soil temperature, pH and redox conditions. Increased water filled pore space and limited nitrate (NO_3^-) availability are generally the primary factors promoting N_2O uptake into the soil. Nitrous oxide consumption has been found under a range of conditions in many different environments, such as spruce and deciduous forests, grasslands, savannah, pasture, cropped agricultural fields (rice, maize, wheat) and natural and converted peatlands (Chapuis-Lardy et al., 2007). However, all studies in which *in situ* N_2O uptake was found occurred in temperate, tropical, natural and agricultural systems. No previous studies have found N_2O consumption in northern peatland soils. Often, N_2O consumption has been neglected in literature, with many of the values being considered error and subsequently discarded from further calculations of net emissions (Chapuis-Lardy et al., 2007). In our study, all N_2O production and consumption values were included in average and cumulative flux calculations. The average N_2O flux values were very small and were not found to be significantly different between any of the plant habitats, except for the Peat site in 2006.

2.5.3. CO_2 Greenhouse Gas Equivalent Emissions of CH_4 and N_2O

Considerable rates of CH_4 production were found in many plant habitats at the different sites, as well as CH_4 consumption in dry, lichen dominated habitats. Also, even though N_2O emissions were very small, slight trends for both production and consumption were found in different plant habitats. Therefore, the findings from this study suggest GHG emissions in specific plant habitats within peatland environments can be large sources to the atmosphere and certain habitats can be sinks, although generally not at as great rates. Methane and N_2O are of particular interest as they have very high warming potentials of 23 and nearly 300 times greater than carbon dioxide (CO_2), over a period of 100 years as they are more effective at absorbing infrared radiation (Smith et al., 2003). Therefore, even at small rates in the atmosphere, both CH_4 and N_2O have large scale impacts on global warming especially due to the fact that peatlands cover such a large area of land. For example, peatlands cover over 365,000 km^2 of Alberta, Saskatchewan and Manitoba (Turetsky et al., 2002) and occupy about 12% of Canada's land area with 97% occurring in the boreal and subarctic regions (Tarnocai, 2006). These large regions will likely be extremely important to global CH_4 and N_2O emissions.

Furthermore, CH_4 may be extremely important to net carbon and GHG exchanges especially in northern peatland ecosystems. For example, a previous study by Rouse et al. (2002) in the same fen and similar forest sites near Churchill, Manitoba, found that carbon was lost in the form of CH_4 emissions but values were small and therefore not considered to be a as significant as CO_2 to the net carbon budget. However, Rouse et al. (2002) only found the fen and forest on average to be losing carbon at an annual rate of 5.1 and 0.8 g C m^{-2} yr^{-1}, respectively (Rouse et al., 2002). Whereas using this study, if the CH_4 results from the individual habitats at the specific sites were considered together, not accounting for the aerial extent of each plant habitat, carbon losses from CH_4 would be substantially greater at rates of approximately 50 and 2 g C m^{-2} for the fen and forest during the growing season. Also, when considering CH_4 in equivalent terms to CO_2 in the anaerobic sedge-dominated "hot-spots" of CH_4 production found in this study, the levels of CH_4 produced were at similar and usually greater levels compared to the CO_2 produced in the same plant habitats. At these levels the importance of CH_4 becomes increasingly important in subarctic peatland environments, and in many sites and plant habitats CH_4 would even surpass CO_2 as the predominate GHG affecting net carbon and GHG exchanges.

2.5.4. Implications to Upscaling and Modeling GHG Emissions

Upscaling and modeling greenhouse emissions are very important in order to obtain an idea of the amount of emissions produced or consumed over seasons, years or decades and determine the contribution GHG emissions from specific habitats. Cumulative values for CH_4, N_2O and respiration using linear interpolation for all sites were calculated to give an estimate of fluxes over the entire growing seasons of 2005 and 2006. Cumulative CH_4 consumption values as large as -58 mg C m^{-2} over the period of 108 days were found in dry aerobic, lichen dominated areas while very large cumulative production values were found in wet anaerobic areas dominated by sedges. For example, the Riparian and Pond Edge habitats had cumulative CH_4 flux values for the period from day 145 to 234 (89 days) of 2,155 and 14,572 mg C m^{-2}, respectively and the Sedge-Moat of the Spruce site had a cumulative flux of 2,323 mg C m^{-2} for days 144 to 236 (92) in 2006 (Tables A.3 and A.4). Also, the Fen site had very large cumulative CH_4 production values for days 146 to 237 (91 days) which were lowest for the Hummock habitat at 1,679 mg C m^{-2} and greatest for the Sedge-Lawns at 40,707 mg C m^{-2} (Table A.5). Nitrous oxide cumulative flux values at all sites were small, ranging from only 1 to 4 mg N m^{-2} and respiration values were greatest in plant habitats with increased soil moisture and dominant vascular plants such as sedges (Tables A.3 to A.5).

Furthermore, it is also necessary to compare the findings from this study to previous research in similar or the same environments. Most past studies on CH_4 emissions for subarctic and arctic regions, have focused on wetlands, like fens and bogs. There are fewer studies done in forested regions, and even fewer in peat plateau landscapes or the riparian areas surrounding ponds. Also, very few studies have occurred that break up the landscapes into different sections or habitats (Bridgham et al., 1998). In order to compare the findings from this study to previous studies, the sites will be compared as a whole.

The results from the Peat site in 2005 produce CH_4 flux values of only 0.3 mg C m^{-2} d^{-1}. However, when Riparian and Pond Edge habitats are taken into account in 2006, the values for CH_4 production increase to 189 mg C m^{-2} d^{-1}. The 2006 values are much greater than found in previous literature and indicate the importance of collecting data in all habitats at a site. However, when calculating these values the aerial extent of each habitat was not considered. Over the period of May 15 to September 15, 1994, Bubier et al. (1995) found that treed sites, such as peat plateaus had a low seasonal average for CH_4 production ranging from 0 to 20 mg C m^{-2} d^{-1}. Bubier et al. (1995) did collect data in different habitats within the site and found that dry hummocks and peat palsas occasionally showed slight CH_4 consumption at levels as high as -1.5 mg C m^{-2} d^{-1}, which were slightly higher than the rates found in this study for the Polygon Top habitat alone (Bubier et al., 1995). The findings from this study and Bubier et al. (1995) indicate the importance of areas within patterned peatlands, polygonized-peat plateaus and other dry, aerobic and lichen dominated peatlands as potentially being important CH_4 sinks in northern ecosystems.

Collectively, the Spruce site had CH_4 production at values of 7 and 26 mg C m^{-2} d^{-1} in 2005 and 2006, respectively, not accounting for the aerial extent of the habitats. Previous studies near Churchill, Manitoba, at a similar spruce forest site, only a few kilometers away from the site used in this study, found that the system was producing CH_4, but the values were minimal. However, areas like the Sedge-Moat habitat surrounding ponds were not taken into account (Rouse et al., 2002). In contrast, an ecosystem modeling study for the growing season period from June to September, conducted in a old black spruce forest, near Thompson, Manitoba, found model results for CH_4 flux to be very similar to measured emissions rates of -0.5 mg C m^{-2} d^{-1} (Potter et al., 2001). These results suggest that the forest site is consuming CH_4, but emissions from specific habitat types within the forest were not measured.

The values for the Fen, when looking at the ecosystem as a whole but not accounting for the aerial extent of the habitats, are greater than previous literature values for the same area or similar fen wetlands reported by Rouse et al., 1995, Bubier et al., 1995 and Huttunen et al., 2003. On average, the Fen produced approximately 550 mg C m^{-2} d^{-1}. Values ranging from only 22 to 52 mg C m^{-2} d^{-1} for the period of late June to late August, 1989, and 62 to 133 mg C m^{-2} d^{-1} from late June to early September, in 1990 were found for the same Fen. The values for 1990 are more comparable to the results found in this study, as 1989 values were collected in a very dry summer, although in both 1989 and 1990 gases were collected from static chambers over a 24-hour period which would alter environmental conditions and concentration gradients within the chambers (Rouse et al., 1995). More recently, studies from June to September, 1994 and 1995 on eutrophic fens in the boreal zone of Finland have produced results of mean CH_4 emissions ranging from 160 to 170 mg C m^{-2} d^{-1} (Huttunen et al., 2003). Also, mean CH_4 flux rates ranging from 100 to 380 mg C m^{-2} d^{-1} were found in open graminoid fens near Thompson, Manitoba (Bubier et al., 1995).

Due to the large variability in GHG emissions between different sites and habitats, plant habitats could be useful predictors of GHG emissions as well as important in assessing the variability in a landscape, in order to scale from chamber based measurements to the entire landscape. Vegetation cover could be a very useful factor when modeling these ecosystems as it is easier to map using remote sensing techniques compared to environmental factors (Bubier et al., 1995) and is indicative of the environmental and soil conditions present in an ecosystem. All different landscapes, as well as the main plant habitats within each site must be studied in order to accurately predict amount of the GHG emissions from large areas such as northern peatlands and the HBL and ultimately produce global models of GHG emissions.

2.5.5. Implications to Predicting Climate Change Impacts on CH_4 and N_2O Emissions

Climate change is expected to alter numerous factors such as environmental conditions and plant community composition, in arctic and subarctic environments. Changes in these factors could drastically alter spatially dependent CH_4 and N_2O emissions. When CH_4 emissions were compared to the environmental parameters at the sites, air and soil temperatures were more highly positively correlated to the CH_4 fluxes for specific habitats than moisture content (Table 2.6). However, at both the Peat and Spruce site when all habitat types were considered together, soil moisture content was highly correlated with CH_4 flux. Active layer depths were also found to be strongly positively correlated with CH_4 emissions from the Peat and Spruce sites. These findings indicate the importance of permafrost, with respect to CH_4, in these environments. There are fewer correlations between environmental parameters and CH_4 at the Fen site, which is likely due to the limited replication and sampling occurring only in one field season. Correlations with temperature, moisture and active layer with CH_4 emissions were expected as CH_4 fluxes from northern peatlands have been found to vary with multiple factors such as temperature, moisture (level of anoxia), pH, nutrient availability, degree of CH_4 oxidation, vegetation and thermodynamic competition (Basiliko et al., 2003).

The findings are very significant, when related to a changing climate. With changes in temperatures and precipitation expected for subarctic regions, major shifts in CH_4 emissions will likely occur. The changes in CH_4 production will likely be even greater in areas underlain by permafrost (Tarnocai, 2006). Not only could increased precipitation lead to increased soil moisture in certain areas, but the melting of permafrost and changing hydrologic conditions may further increase this effect. Melting permafrost can also lead to a deepening active layer, which was found to be highly correlated with CH_4 emissions. Permafrost in Churchill is not predicted to disappear by 2100, but will change from continuous to a zone of discontinuous permafrost (Camill, 2005). As habitats become wetter and water table heights increase, more anaerobic conditions will result, creating the environment necessary for increased methaogenesis to occur.

Dominant vegetation influence on CH_4 emissions is very important in high latitude environments, such as the HBL, as plants in these regions have been found to be extremely sensitive to warming. This sensitivity can lead to changes in vegetation community structure and growth, which will ultimately influence GHG emissions. For example, as permafrost melts due to expected climatic warming, active layer depths could increase and wetter conditions may occur (Christensen et al., 2004) which could greatly impact peatland vegetation patterns as they are influenced by moisture gradients and water surface chemistry (Beilman, 2001). In a subarctic region in Sweden, vegetation has been found to shift from elevated dry-shrub dominated to wet-graminoid dominated where permafrost melting has occurred (Christensen et al., 2004). As increased nutrients enter the soil, graminoids and deciduous shrubs will be favored, likely replacing low nutrient uptake plants, such as mosses and evergreen shrubs (Jonasson et al., 2004). Macrolichens in subarctic environments, such as *Cladina spp.*, may decline if vascular plants increase in dominance due to a changing climate (Cornelissen et al., 2001). Also, there is evidence suggesting the northern migration of many herbs and shrubs is mainly due to climate change (Aerts et al., 2006). If shifts in plant communities occur, increased CH_4 production for many plant habitats will likely increase. Therefore, changes in climate will greatly impact all aspects of northern ecology, ultimately resulting in large scale changes in CH_4 and N_2O emissions.

2.6. Conclusion

Subarctic ecosystems such as peatlands and the HBL are of vast importance to GHG emissions. Greenhouse gas emissions were found to vary considerably with plant habitats at three study sites located in different environments and with a large range of environmental and plant community gradients. Plant habitats such as riparian and sedge areas and submerged peat ledges in ponds, continually showed high CH_4 production, due to the increased moisture content and the presence of dominate sedges like *Carex spp*. These were considered to be "hot-spots" of intense CH_4 emissions and when considered over long time periods and large land areas, could be large contributors of CH_4 emissions to the atmosphere from terrestrial subarctic environments. Methane consumption was related to low moisture content in areas with lichen dominated plant biomass, such as polygon tops. Conversely, areas of high moisture and plant productivity were slight sinks for N_2O and low moisture and plant productivity areas were slight sources of N_2O, albeit at very low rates.

The findings indicate the importance of determining the contribution of specific plant habitats to GHG emissions in areas like the HBL. Under changing climatic conditions which are expected to alter factors like temperature, moisture and plant community composition, it is likely that the areas of intense CH_4 emissions will increase and play an even more important role in the total emissions and carbon budgets for northern peatlands. Therefore, in order to accurately upscale GHG emissions to regional, national and ultimately global levels, many more long term habitat based studies in arctic and subarctic environments need to occur.

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3. SOIL GAS CONCENTRATIONS IN RELATION TO SURFACE GREENHOUSE GAS FLUXES, PLANT HABITATS AND ENVIRONMENTAL CONDITIONS IN THE SUBARCTIC ENVIRONMENT OF CHURCHILL, MANITOBA

3.1. Abstract

Knowing gas concentration in soil is important to gain knowledge about the extent of microbial processes within soil and how these processes will affect the greenhouse emissions at soil surfaces. This is particularly important in arctic and subarctic peatlands, as they have been found to be large carbon stores and are expected to be areas highly influenced by changes in temperature, precipitation and hydrology associated with climate change. The objective of this study was to determine if zones of greenhouse (GHG) production or consumption occur within soil and if soil gas concentrations can be related to surface gas fluxes, in different plant habitats and under different environmental conditions. Gas sampler probes were installed in late July 2005, next to selected GHG sample positions at two sites near Churchill, Manitoba; a Polygonized-Peat Plateau (Peat) and White Spruce/Larch Forest (Spruce). The probes were sampled in three times 2005 and four times in 2006. Methane, CO_2, N_2O and O_2 soil gas concentrations were determined on gas collected from the probes and surface fluxes of CH_4, N_2O and respiartion were determined using static-vented chambers. Results indicate that soil gas concentrations follow the same trends as GHG surface fluxes and can be related to different plant habitats and environmental conditions. Concentrations of CH_4 and CO_2 were generally much higher at deeper depths. Soil moisture tended to be the primary influence on soil gas concentrations as it affected soil O_2 concentrations. Wetter and subsequently more anoxic habitats (lower O_2 concentrations), such as the Upper Sedge

and Sedge-Moat habitats, had increased CH_4 and CO_2 concentrations compared to drier and more aerobic habitats, like the Polygon Top habitat. Soil N_2O concentrations followed similar trends compared to surface N_2O fluxes in which a trend for very slight production of N_2O was observed at dry aerobic sample positions and very slight consumption occurred at wet sample locations. In wet sample locations N_2O concentrations at deep depths were very small when compared to dry sample positions. In very wet conditions, soil N_2O concentrations at shallow depths near the surface were also lowered. It is critical to understand soil gas production and consumption in numerous plant habitats within peatlands to determine zones that will be potentially impacted by changing hydrologic regimes and will ultimately impact GHG surface flux emissions.

3.2. Introduction

Soil gas concentrations are vital in determining the processes occurring within soil and are particularly important in a changing climate, as conditions affecting soil microbial activities will likely change, resulting in altered greenhouse gas (GHG) emissions released from soil. About 40% and 65% of methane (CH_4) and nitrous oxide (N_2O) emissions, respectively, come from soil (Smith et al., 2003). The changes that could occur with respect to soil gas concentrations are extremely important in northern ecosystems like peatlands, as they contain approximately one-third of the world's soil carbon pool (Pastor et al., 2003) and contribute one-tenth of total CH_4 emissions to the atmosphere (Basiliko et al., 2004).

Knowing the controls on GHG production will allow an assessment of how climate change will affect CH_4 and carbon dioxide (CO_2) emissions from soils (Yavitt et al., 2005). Soil temperature and moisture content affect microorganisms and therefore directly affect GHG production and consumption (Smith et al., 2003). Wet conditions can limit microbial activity as CH_4 and oxygen (O_2) diffusion can be limited, while in dry conditions microbial processes are reduced due to water stress (Gulledge and Schimel, 1998). Under saturated conditions aerobic processes are limited, but anerobic process like CH_4 production increase (Yavitt et al., 2005). Gas diffusion rates will also be altered depending on soil moisture content as O_2 is less able to diffuse into saturated soils (Smith et al., 2003).

A major source of CO_2 to the atmosphere is from soil and plant respiration and respiration has been found to increase exponentially with temperature. In wet soils with higher water tables, respiration is restricted and the soil becomes more anaerobic as the soil pores become water-filled (Smith et al., 2003). These conditions favour CH_4 production. The major controls on CH_4 production, or methanogenesis, are temperature, moisture and carbon availability. Methanogenesis is also highly sensitivity to organic matter levels in the soil, which makes CH_4 production extremely important in arctic and subarctic environments where organic matter usually occurs at high levels due to decreased decomposition rates. Methanotrophy or CH_4 consumption is affected primarily by soil moisture content and secondly by temperature, with dry conditions leading to increased CH_4 consumption and aerated soils become sinks for CH_4 (Smith et al. 2003). Nitrous oxide production occurs by two main processes; nitrification and denitrification. These processes are greatly affected by both temperature and moisture and increases in both factors have been found to increase N_2O production (Smith et al., 2003). Soils can also act as sinks for N_2O, but depend on the potential for N_2O reduction to nitrogen (N_2), the ability of N_2O to diffuse through the soil and dissolute into soil water (Chapuis-Lardy et al., 2007). The previous chapter (Chapter 2) found indication of wet locations sometimes acting as a sink for N_2O, albeit in very low levels. Therefore, changes associated with global warming in arctic and subarctic environments, such as changing temperatures, permafrost extent, water table height and hydrology are extremely important with respect to soil gas concentrations, and ultimately the surface flux of greenhouse gases.

This study was carried out to investigate soil gas concentrations in different habitats in two dominate ecosystems; Polygonized-Peat Plateau (Peat) and White Spruce/Larch Forest (Spruce) in the Hudson Bay Lowlands (HBL) and Churchill area, over two consecutive years. In 2005 and 2006, the goal was to determine *in situ* soil gas concentrations and compare these to surface GHG fluxes, environmental conditions and plant communities, for the main habitat types at the Peat and Spruce sites. Varying CH_4 and N_2O fluxes were found within different plant habitats in the previous chapter. This study allows verification of the surface flux findings in Chapter 2, and further exploration of N_2O acting as a source/sink in differing environments using soil gas concentrations. No previous studies in arctic or subarctic ecosystems like the Churchill area or the HBL have incorporated *in situ* GHG soil concentration measurements. The only studies on GHG soil concentrations in peatlands and northern environments have involved soil incubation experiments in the laboratory (Basiliko et al., 2004; Berestovskaya et al., 2005; Yavitt et al., 2005; Yavitt et al., 2006). The objective of this study was to determine if zones of GHG production or consumption occur within the soil and if soil gas concentrations can be related to surface gas fluxes, in different plant habitats and under different environmental conditions.

3.3. Materials and Methods

3.3.1. Site Locations and Field Layout

Two study sites were established in 2005 in the vicinity of the town of Churchill, Manitoba. The sites are situated along Twin Lakes Road, which runs south of the Churchill Northern Studies Centre beginning about 23 km east of the town. The two sites selected to study were a Polygonized-Peat Plateau (Peat) site approximately two km southwest of the Churchill Northern Studies Centre (CNSC) and a White Spruce/Larch Forest (Spruce) site located approximately 15 km south of the CNSC. The sites used were the same as discussed in Chapter 2.

At both Peat and Spruce sites, gas sampler probes were installed in late July 2005, to determine soil atmosphere concentrations of CH_4, N_2O, CO_2 and O_2. The samplers were made of 1.9 cm (¾ inch) internal diameter PVC pipe with 0.5 cm diameter holes drilled, containing 1.3 cm (½ inch) internal diameter Peroxide Cured Silicone Tubing (Cole-Parmer Canada, Anjou, QC), which had a 0.2 cm thick wall allowing gases, but not water to diffuse through. Stainless steel tubing (Winnipeg Fluid System Technologies Inc., Winnipeg, MB) of 0.2 cm ($^{1}/_{16}$ inch) diameter was inserted into the top of the silicone tubing and was sealed in place using a rubber serum stopper (Suba Seal, #13, Sigma-Aldrich Canada, Oakville, ON), Mastercraft Window and Door Silicone, and Marine Fix Fast 2 Part Epoxy Paste (Canadian Tire Corporation, Winnipeg, MB). A Swagelok fitting reducing union (Winnipeg Fluid System Technologies Inc., Winnipeg, MB) fitted with a 0.95 cm ($^{3}/_{8}$ inch) M-9 rubber septa (Alltech Canada – Mandel Scientific Co. Inc., Guelph, ON) was inserted onto the end of the stainless steel tubing to serve as a sample port. The gas samplers were installed at two different depths; 5 to 9 cm and 23 to 32 cm. Holes were drilled into the soil using a cordless drill with a 1.9 cm diameter wood auger bit. The 5 to 9 cm depth gas samplers were inserted on a 45^{o} angle while the 23 to 32cm depth samplers were inserted vertically into the soil.

3.3.2. Greenhouse Gas Concentration Measurement and Analysis

The samples from the gas sampler probes were taken once a month during both field seasons using 20-mL Becton-Dickenson (B-D) syringes (Fisher Scientific, Edmonton, AB), fitted with Becton-Dickenson 23G-2.5 cm needles (Fisher Scientific, Edmonton, AB), attached to a one-way luer valve (Cole-Parmer Canada, Anjou, QC). The valves were turned to the "flow" position and the syringe was placed into the gas probe. A 1-mL sample was taken from the gas sampler and then expelled to flush the tubing and sample port dead space. The syringe was reinserted into the sample port and the syringe plunger pulled to the 20-mL mark. A wooden dowel was placed to prevent the syringe plunger from dropping due to the suction created within the gas sampler and allow the gas from the samplers to flow into the syringe. After approximately five minutes, the luer-valve was turned to the "off" position, the wooden dowel removed, the plunger allowed to drop, and the syringe removed from the sample port. The valve was then turned to the "flow" position and a 10-mL sample was placed into 6-mL Exetainer® vials (Labco Limited, Buckinghamshire, UK) that had been evacuated and had their septums covered with Mastercraft Kitchen and Bath Silicone (Canadian Tire Corporation, Winnipeg, MB). The vials were evacuated and flushed three times with helium gas to a final evacuated pressure of 500 millitorr. The vials were over-pressurized with headspace gas to ensure the gas samples enter into the GC syringe without the surrounding air contaminating the sample. The septums of the Exetainer vials were covered using silicone multiple days before evacuating to maintain an air-tight seal. In 2006, three standard gas samples composed of 1195 ppm CO_2; 9.8 ppm CH_4 and 1.1 ppm N_2O and certified by the supplier (Praxair Distribution Inc., Edmonton, AB), were taken to the field to ensure that the samples taken were not affected by transport or storage.

All gas samples, including the standards, were transported to Winnipeg and stored at room temperature until analyzed. The samples were run on an automated gas chromatograph (Varian 3800, Mississauga, ON) (GC) fitted with an electron capture, flame ionization and thermal conductivity detectors at 300, 250 and 130^{o}C, respectively. The analyses on the GC were quality controlled using multi-point calibration, as well as, high and low standard checks run throughout each analysis of samples to ensure calibration drift does not occur. Using a Combi-PAL autosampler (CTC Analytics, Zwingen, Switzerland) paired to the GC, 2.5 mL of sample was injected from each vial and delivered to the GC in order to obtain CO_2, CH_4 and N_2O concentrations. The GC had two sample loops, one for CO_2 and CH_4 and one for N_2O analysis; both use a volume of 500 μL.

3.3.3. Oxygen Concentration Measurement and Analysis

After the samples were analyzed for CH_4, N_2O and CO_2 on the automated GC, the O_2 concentration within the sample vial was analyzed using a micro gas chromatograph (Varian CP-4900, Mississauga, ON). All samples, except for the samples from the first sampling date of each year, were analyzed for O_2. These samples could not be run for O_2 concentration as the vials were in need of use. The micro GC had two channels, both fitted with thermal conductivity detectors. Channel 1 had a 20 m MS5 column with a 20 ms injection time, 42 ^{o}C temperature and internal pressure of 40 psi, while Channel 2 had a 1 m COX column with a 900 ms injection time, 100 ^{o}C temperature and internal pressure of 30 psi. A 1-mL glass syringe and side port needle (VICI Precision Sampling Gas Tight Series A Syringe and Side Port Needle 2.25"L Point Style 3", Alltech Canada – Mandel Scientific Co. Inc., Guelph, ON) was used to inject samples manually into the GC. The GC was "warmed up" by running three consecutive 1-mL lab air samples and then subsequently 1-mL *Injection Purge* injections to clear residual sample gas in the injector between each sample. Sample analysis was done on 1-mL of sample from the Exetainer vial and injecting the sample consistently slow into the injection port. To calculate the gas concentration, concentrations of O_2 were used, 0% O_2 (helium), 9.96% O_2 (prepared gas mixture from Praxair Distribution Inc.) and 20.87% O_2 (outdoor ambient air) were run on the GC.

3.3.4. Gas Flux Measurement and Analysis

Static-vented dark chambers were used to determine GHG fluxes (respiration, CH_4 and N_2O) from gas collected in the chamber headspace at 0, 10, 20 and 30 minute intervals in 2005 and 2006 at the sampling locations at the Peat and Spruce sites. For more detail on the occurrence of gas flux sampling and gas flux analysis refer to Chapter 2, Sections 2.3.2 and 2.3.3, respectively.

3.3.5. Statistical Analysis

Statistical analyses for all data were done using the Statistical Analysis Software (SAS) package version 9.1 (SAS Institute Inc., Cary, NC). The association between soil gas concentrations as well as CH_4 and N_2O soil gas concentrations to CH_4 and N_2O surface fluxes at both 5 to 9 and 23 to 32 cm depths were determined using Spearman rank correlation analysis at $P<0.05$ significance level. Spearman rank correlation analysis was chosen as it is a non-parametric method which tests both the direction and strength of the relationship between two variables and makes no assumptions about the frequency distribution of the variables.

3.4. Results

3.4.1. Weather Conditions

Daily precipitation and average daily air temperature were relatively similar for the field seasons of 2005 and 2006, in Churchill. Both seasons had wet summers, however the summer of 2006 had more precipitation throughout the field season. With respect to air temperature, both 2005 and 2006 had very similar average air temperatures for the field season months of June, July and August and were slightly higher than the 30 year daily average air.

The field season weather conditions can be found in the results section of Chapter 2, Section 2.4.1.

3.4.2. Environmental Conditions

The soil temperatures at 2.5 ($Temp_{2.5}$) and 15 cm ($Temp_{15}$), volumetric moisture content (VMC), active layer depth and respiration values for both the Peat and Spruce sites for 2005 and 2006 can be found in the results section of Chapter 2, Section 2.4.4.

3.4.3. Soil Gas Concentrations

At the Peat site the concentrations of CH_4 and CO_2 were generally much higher at the deeper depth and tended to be greater in the summer of 2006 than the summer of 2005. The only exception was for the CH_4 concentrations at the Polygon Top habitat where the CH_4 concentration was typically lower at the deeper depth than the shallow depth. Very high concentrations of CH_4 were found in the wettest plant habitats, such as the Upper Sedge, Ice Wedge and Lower Sedge habitats, with values as high as 22,458, 905 and 3,697 μL CH_4 L^{-1}, respectively. Carbon dioxide concentrations followed the same trends as seen for CH_4, with higher CO_2 concentrations in the Upper Sedge, Ice Wedge and Lower Sedge habitats. Values for CO_2 were one if not two magnitudes smaller in the Polygon Top habitat. Nitrous oxide concentrations tended to be lower at the deeper depths compared to the shallow depths, in the Upper Sedge, Ice Wedge and Lower Sedge habitats, while it was generally higher with depth for the Polygon Tops. However, typical N_2O concentrations for these sites were very small, around 0.3 μL N_2O L^{-1}. Oxygen concentrations were greater at the shallow depth in all plant habitats and were greatest in the Polygon Top habitat at both shallow and deeper depths, with values around 20%. The Upper Sedge, Ice Wedge and Lower Sedge habitats had consistently lower O_2 concentrations than the Polygon Top plant habitat in 2005 and 2006, with values as low as 6% for the Upper Sedge at the deep depth (Tables 3.1 and 3.2)

At the Spruce site, CH_4 concentrations were low in all plant habitats at around 2 μL CH_4 L^{-1}, except for the Sedge-Moat habitat which had values as high as 9,295 μL CH_4 L^{-1} in 2006. Similar to the Peat site, CO_2 concentrations were greater at the deeper depth and were typically greatest in the Sedge-Moat habitat. Nitrous oxide concentrations were generally the same for all habitats except for the Sedge-Moat where N_2O concentrations were reduced. Oxygen concentrations for the Upper Lichen and two Moss habitats were very similar over both field seasons. Values were typically around 20% for the shallow depth and between 16 and 20% for the deeper depth. The Sedge-Moat constantly had lower O_2 concentrations with values as low as 5% in 2005 and 2006 (Tables 3.3 and 3.4).

Also, at both sites O_2 concentrations generally decreased over the course of the field season for all habitat types.

General trends were found when comparing the soil gas concentrations from the plant habitats at the Peat and Spruce sites at both the shallow and deep depths. At both depths, decreased O_2 concentrations led to increased CH_4 and decreased N_2O concentrations while lower CO_2 concentrations were related to CH_4 concentrations. Significant negative correlations were found between CH_4 and O_2 concentrations, while significant positive correlations were found between N_2O and O_2 concentrations as well as between CH_4 and CO_2 concentrations. Based on the results, O_2 concentrations were approximately 17% or lower before CH_4 began accumulating in the soil (Figure 3.1).

Table 3.1. Soil gas concentrations for plant habitats at the Peat site in 2005.

Day of the Year	Plant Habitat	Depth (cm)	n	CH_4 (µL CH_4 L^{-1})	N_2O (µL N_2O L^{-1})	CO_2 (µL CO_2 L^{-1})	O_2 (%)
213	Upper Sedge	5-9	4	8.5 ± 2.5	0.34 ± 0.01	2639.2 ± 701.6	-
	Upper Sedge	23-32	2	1295.3 (544.3-2046.1)	0.36 (0.35-0.38)	7210.9 (5435.2-8986.6)	-
	Polygon Top	5-9	5	3.0 ± 0.2	0.37 ± 0.01	711.6 ± 23.3	-
	Polygon Top	23-32	5	3.1 ± 0.2	0.37 ± 0.01	991.1 ± 154.9	-
	Ice Wedge	5-9	3	3.7 ± 0.4	0.34 ± 0.01	1860.5 ± 1059.0	-
	Ice Wedge	23-32	1	22.9	0.39	2870.5	-
	Lower Sedge	5-9	4	3.4 ± 0.1	0.38 ± 0.02	1794.4 ± 583.6	-
221	Upper Sedge	5-9	4	22.1 ± 8.8	0.29 ± 0.01	2634.4 ± 607.0	20.5 ± 0.1
	Upper Sedge	23-32	4	5859.5 ± 2183.3	0.20 ± 0.03	16873.7 ± 5301.9	17.8 ± 1.2
	Polygon Top	5-9	5	6.9 ± 2.9	0.31 ± 0.01	580.2 ± 35.4	20.8 ± 0.1
	Polygon Top	23-32	5	2.3 ± 0.8	0.34 ± 0.02	772.4 ± 84.4	20.0 ± 0.5
	Ice Wedge	5-9	4	5.8 ± 4.0	0.29 ± 0.01	2801.2 ± 2086.7	20.4 ± 0.4
	Ice Wedge	23-32	2	13.0 (6.3-19.6)	0.16 (0.04-0.29)	8435.0 (4702.5-12167.4)	15.6 (10.5-20.6)
	Lower Sedge	5-9	4	2.1 ± 0.5	0.27 ± 0.01	2958.1 ± 1111.8	19.5 ± 1.1
269	Upper Sedge	5-9	4	185.2 ± 143.8	0.29 ± 0.03	5779.2 ± 3589.7	19.0 ± 0.7
	Upper Sedge	23-32	4	11733.2 ± 1492.7	0.12 ± 0.01	32582.6 ± 3928.0	6.4 ± 1.2
	Polygon Top	5-9	5	11.5 ± 8.0	0.36 ± 0.01	482.9 ± 21.4	20.7 ± 0.03
	Polygon Top	23-32	5	1.9 ± 1.0	0.36 ± 0.003	595.8 ± 54.5	20.3 ± 0.6
	Ice Wedge	5-9	4	905.1 ± 899.7	0.30 ± 0.05	4834.8 ± 3549.1	16.7 ± 3.5
	Ice Wedge	23-32	2	365.2 (72.8-657.6)	0.14 (0.11-0.16)	17716.5 (16873.3-18559.8)	11.1 (6.1-16.1)
	Lower Sedge	5-9	4	32.2 ± 13.7	0.28 ± 0.04	4789.3 ± 1791.9	16.1 ± 2.5

Values shown are the mean of n replicate sample positions and ± 1 standard error of the mean, except for where n=2 in which the range of values are shown in parentheses. Dash indicates analysis not available.

Table 3.2. Soil gas concentrations for plant habitats at the Peat site in 2006.

Day of the Year	Plant Habitat	Depth (cm)	n	CH_4 (μL CH_4 L^{-1})	N_2O (μL N_2O L^{-1})	CO_2 (μL CO_2 L^{-1})	O_2 (%)
147	Upper Sedge	5-9	4	166.9 ± 122.2	0.31 ± 0.05	3670.9 ± 1933.8	-
	Upper Sedge	23-32	4	3018.7 ± 232.9	0.21 ± 0.03	21757.0 ± 3023.8	-
	Polygon Top	5-9	5	3.2 ± 1.4	0.42 ± 0.01	534.3 ± 29.3	-
	Polygon Top	23-32	4	1.8 ± 0.1	0.62 ± 0.14	1077.2 ± 391.8	-
	Ice Wedge	5-9	4	2.7 ± 0.7	0.34 ± 0.04	2587.6 ± 1807.4	-
	Ice Wedge	23-32	2	51.6 (1.7-101.5)	2.07 (0.85-3.28)	39521.8 (39484.1-39559.5)	-
	Lower Sedge	5-9	4	31.5 ± 26.5	0.28 ± 0.06	5030.3 ± 2824.0	-
170	Upper Sedge	5-9	4	15.6 ± 5.6	0.35 ± 0.01	1485.7 ± 354.2	20.7 ± 0.04
	Upper Sedge	23-32	4	22458.3 ± 6178.3	0.24 ± 0.02	21394.0 ± 941.6	14.4 ± 0.4
	Polygon Top	5-9	5	5.9 ± 3.9	0.38 ± 0.01	469.5 ± 15.1	20.7 ± 0.03
	Polygon Top	23-32	5	1.9 ± 0.4	0.62 ± 0.13	807.6 ± 182.1	20.7 ± 0.02
	Ice Wedge	5-9	4	2.5 ± 0.1	0.37 ± 0.01	825.3 ± 216.7	20.7 ± 0.1
	Ice Wedge	23-32	2	5.0 (2.6-7.4)	0.59 (0.34-0.84)	7664.0 (3211.2-12116.8)	16.6 (12.6-20.5)
	Lower Sedge	5-9	4	4.4 ± 2.3	0.36 ± 0.01	1918.2 ± 917.1	20.5 ± 0.1
205	Upper Sedge	5-9	4	21.1 ± 6.4	0.33 ± 0.03	3672.2 ± 1108.8	19.7 ± 0.7
	Upper Sedge	23-32	4	7804.2 ± 5608.0	0.12 ± 0.02	23033.5 ± 1562.3	6.1 ± 1.1
	Polygon Top	5-9	5	1.8 ± 0.3	0.37 ± 0.01	547.7 ± 46.7	20.7 ± 0.03
	Polygon Top	23-32	5	1.3 ± 0.2	0.41 ± 0.02	695.1 ± 89.4	20.7 ± 0.01
	Ice Wedge	5-9	4	9.5 ± 7.4	0.32 ± 0.04	7237.4 ± 6584.2	18.9 ± 1.8
	Ice Wedge	23-32	2	46.0 (3.3-88.7)	0.15 (0.12-0.18)	13774.8 (12767.8-14781.9)	13.5 (8.8-18.2)
	Lower Sedge	5-9	4	747.8 ± 744.6	0.29 ± 0.06	5192.9 ± 2883.7	15.9 ± 3.8
233	Upper Sedge	5-9	4	18.2 ± 8.7	0.32 ± 0.02	4640.7 ± 1537.7	20.7 ± 0.2
	Upper Sedge	23-32	4	8491.9 ± 760.3	0.15 ± 0.02	32561.1 ± 3966.1	6.3 ± 0.9
	Polygon Top	5-9	5	1.9 ± 0.2	0.36 ± 0.003	472.4 ± 34.1	20.9 ± 0.02
	Polygon Top	23-32	5	1.8 ± 0.3	0.35 ± 0.003	553.7 ± 55.7	20.9 ± 0.1
	Ice Wedge	5-9	4	825.1 ± 498.1	0.30 ± 0.05	6008.8 ± 4712.5	17.3 ± 3.4
	Ice Wedge	23-32	2	167.5 (27.6-307.3)	0.19 (0.12-0.26)	16842.9 (12899.4-20786.3)	12.3 (5.2-19.3)
	Lower Sedge	5-9	4	3696.6 ± 2973.6	0.17 ± 0.03	13579.0 ± 2424.1	8.23 ± 3.3

Values shown are the mean of n replicate sample positions and ± 1 standard error of the mean, except for where n=2 in which the range of values are shown in parentheses. Dash indicates analysis not available.

Table 3.3. Soil gas concentrations for plant habitats at the Spruce site in 2005.

Day of the Year	Plant Habitat	Depth (cm)	n	CH_4 (µL CH_4 L^{-1})	N_2O (µL N_2O L^{-1})	CO_2 (µL CO_2 L^{-1})	O_2 (%)
213	Upper Lichen	5-9	4	2.2 ± 0.2	0.35 ± 0.01	799.9 ± 53.5	-
	Upper Lichen	23-32	3	2.8 ± 0.9	0.36 ± 0.01	2774.0 ± 932.6	-
	Moss (*Sphagnum*)	5-9	5	2.7 ± 0.1	0.36 ± 0.004	808.9 ± 53.6	-
	Moss (*Sphagnum*)	23-32	3	2.8 ± 0.1	0.38 ± 0.04	884.5 ± 85.3	-
	Moss (*Hylocomium*)	5-9	3	2.5 ± 0.2	0.37 ± 0.01	752.0 ± 105.0	-
	Moss (*Hylocomium*)	23-32	2	2.2 (2.0-2.3)	0.32 (0.29-0.34)	1779.0 (690.3-2867.7)	-
	Sedge-Moat	5-9	-	-	-	-	-
221	Upper Lichen	5-9	4	2.4 ± 0.3	0.29 ± 0.003	645.0 ± 35.6	20.3 ± 0.02
	Upper Lichen	23-32	4	1.8 ± 0.2	0.31 ± 0.02	5153.9 ± 2224.9	17.6 ± 1.6
	Moss (*Sphagnum*)	5-9	5	2.4 ± 0.1	0.29 ± 0.01	621.0 ± 53.9	20.3 ± 0.1
	Moss (*Sphagnum*)	23-32	5	2.0 ± 0.2	0.28 ± 0.01	1918.9 ± 1166.2	18.6 ± 1.6
	Moss (*Hylocomium*)	5-9	3	2.3 ± 0.03	0.30 ± 0.01	579.2 ± 52.5	20.3 ± 0.1
	Moss (*Hylocomium*)	23-32	3	1.9 ± 0.4	0.28 ± 0.01	2467.9 ± 958.8	16.7 ± 1.7
	Sedge-Moat	5-9	2	3552.1 (9.0-7095.1)	0.16 (0.14-0.18)	15997.6 (5840.4-26154.8)	4.7 (3.9-5.5)
276	Upper Lichen	5-9	4	1.7 ± 0.2	0.37 ± 0.003	590.3 ± 101.0	20.1 ± 0.6
	Upper Lichen	23-32	4	1.7 ± 0.3	0.33 ± 0.01	5738.7 ± 1774.7	16.3 ± 0.7
	Moss (*Sphagnum*)	5-9	5	2.1 ± 0.1	0.37 ± 0.003	704.4 ± 238.0	20.1 ± 0.5
	Moss (*Sphagnum*)	23-32	5	2.1 ± 0.1	0.34 ± 0.02	1894.2 ± 1308.3	17.9 ± 2.8
	Moss (*Hylocomium*)	5-9	3	2.0 ± 0.02	0.37 ± 0.001	634.9 ± 179.5	19.7 ± 0.7
	Moss (*Hylocomium*)	23-32	3	8.5 ± 7.2	0.27 ± 0.09	4286.0 ± 3176.3	15.7 ± 3.3
	Sedge-Moat	5-9	2	5441.6 (307.1-10576.0)	0.12 (0.11-0.13)	8905.4 (6068.1-11742.7)	5.0 (3.9-6.1)

Values shown are the mean of n replicate sample positions and ± 1 standard error of the mean, except for where n=2 in which the range of values are shown in parentheses. Dash indicates analysis not available.

Table 3.4. Soil gas concentrations for plant habitats at the Spruce site in 2006.

Day of the Year	Plant Habitat	Depth (cm)	n	CH_4 (µL CH_4 L^{-1})	N_2O (µL N_2O L^{-1})	CO_2 (µL CO_2 L^{-1})	O_2 (%)
147	Upper Lichen	5-9	4	2.4 ± 0.1	0.43 ± 0.04	1558.5 ± 394.6	-
	Upper Lichen	23-32	4	1.3 ± 0.4	0.55 ± 0.15	27540.5 ± 8041.3	-
	Moss (*Sphagnum*)	5-9	5	2.9 ± 0.4	0.38 ± 0.03	6785.3 ± 6235.4	-
	Moss (*Sphagnum*)	23-32	5	2.2 ± 0.1	0.37 ± 0.005	1697.9 ± 862.6	-
	Moss (*Hylocomium*)	5-9	3	2.9 ± 0.9	0.39 ± 0.01	514.9 ± 42.1	-
	Moss (*Hylocomium*)	23-32	3	7.2 ± 4.9	0.74 ± 0.35	7777.4 ± 4587.6	-
	Sedge-Moat	5-9	2	1495.7 (106.9-2884.5)	0.23 (0.09-0.38)	4711.3 (2156.4-7266.3)	-
170	Upper Lichen	5-9	4	2.0 ± 0.1	0.37 ± 0.001	692.1 ± 54.7	20.7 ± 0.02
	Upper Lichen	23-32	4	1.2 ± 0.2	0.43 ± 0.06	16116.2 ± 6867.3	16.8 ± 2.2
	Moss (*Sphagnum*)	5-9	5	3.6 ± 14	0.37 ± 0.005	558.6 ± 14.8	20.8 ± 0.04
	Moss (*Sphagnum*)	23-32	5	2.5 ± 0.2	0.35 ± 0.01	850.0 ± 248.1	20.7 ± 0.02
	Moss (*Hylocomium*)	5-9	3	3.8 ± 1.5	0.37 ± 0.01	559.5 ± 23.2	20.8 ± 0.02
	Moss (*Hylocomium*)	23-32	3	2.3 ± 0.2	0.34 ± 0.01	849.8 ± 84.2	20.8 ± 0.2
	Sedge-Moat	5-9	2	130.5 (7.5-253.6)	0.36 (0.35-0.36)	2806.2 (2184.3-3427.7)	20.0 (19.6-20.3)
205	Upper Lichen	5-9	4	2.5 ± 0.6	0.37 ± 0.01	773.1 ± 83.2	20.7 ± 0.03
	Upper Lichen	23-32	4	1.4 ± 0.4	0.39 ± 0.03	6776.5 ± 1735.2	16.7 ± 1.4
	Moss (*Sphagnum*)	5-9	5	2.0 ± 0.03	0.36 ± 0.002	722.0 ± 53.9	20.7 ± 0.03
	Moss (*Sphagnum*)	23-32	5	1.8 ± 0.2	0.33 ± 0.03	1539.9 ± 786.9	18.9 ± 1.8
	Moss (*Hylocomium*)	5-9	3	2.0 ± 0.04	0.37 ± 0.004	655.7 ± 99.7	20.7 ± 0.1
	Moss (*Hylocomium*)	23-32	3	1.6 ± 0.5	0.32 ± 0.04	4623.6 ± 2260.9	16.6 ± 2.5
	Sedge-Moat	5-9	2	512.2 (1.5-1022.9)	0.27 (0.26-0.28)	8975.9 (6226.9-11724.8)	11.1 (8.7-13.4)
233	Upper Lichen	5-9	4	2.0 ± 0.2	0.35 ± 0.001	629.0 ± 52.8	21.0 ± 0.1
	Upper Lichen	23-32	4	2.5 ± 1.3	0.36 ± 0.02	5210.7 ± 1902.7	19.0 ± 1.2
	Moss (*Sphagnum*)	5-9	5	2.1 ± 0.2	0.36 ± 0.001	658.0 ± 69.6	20.9 ± 0.02
	Moss (*Sphagnum*)	23-32	5	1.7 ± 0.2	0.32 ± 0.03	2708.0 ± 1968.2	18.1 ± 2.8
	Moss (*Hylocomium*)	5-9	3	2.1 ± 0.2	0.36 ± 0.001	656.3 ± 112.5	20.9 ± 0.03
	Moss (*Hylocomium*)	23-32	3	2.0 ± 0.7	0.34 ± 0.03	3623.2 ± 1485.6	17.3 ± 2.5
	Sedge-Moat	5-9	2	9295.3 (7.5-18583.1)	0.17 (0.10-0.24)	24769.9 (8771.1-40768.8)	5.2 (4.2-6.3)

Values shown are the mean of n replicate sample positions and ± 1 standard error of the mean, except for where n=2 in which the range of values are shown in parentheses. Dash indicates analysis not available.

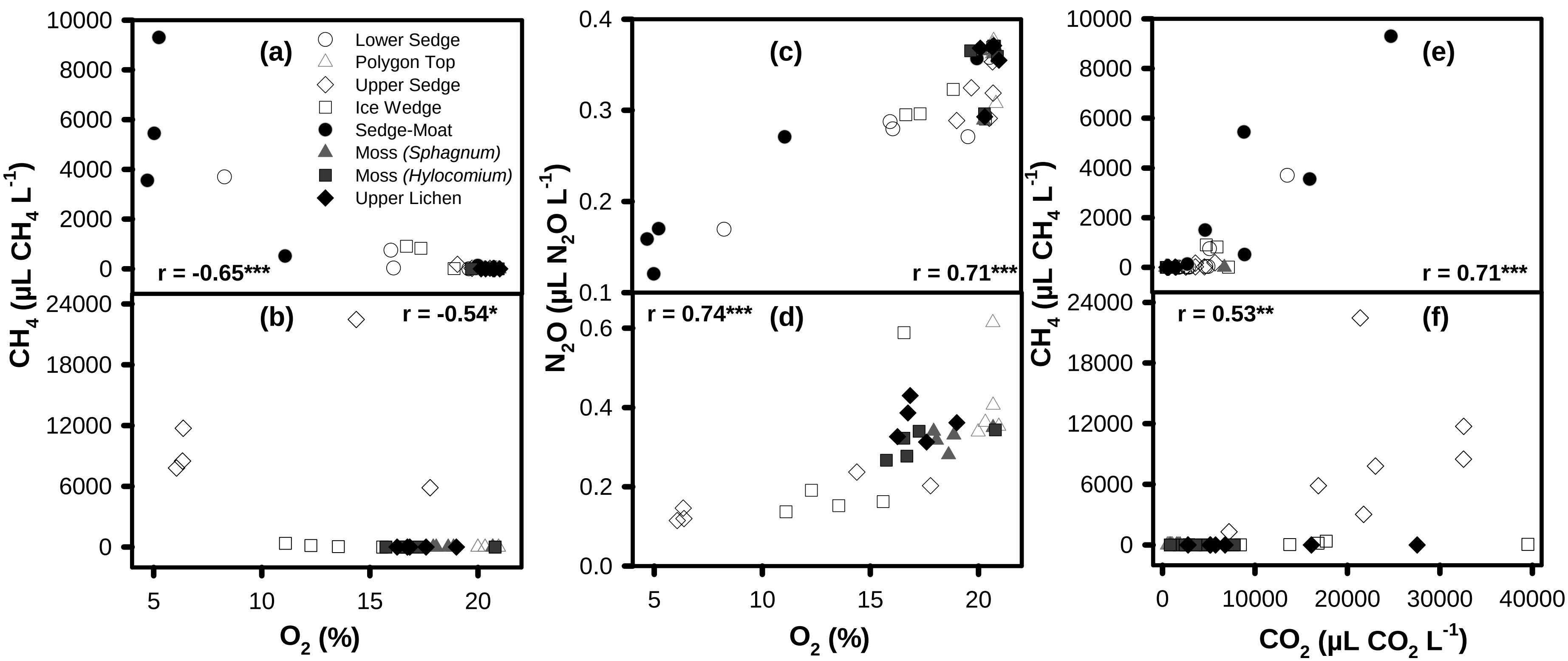

Figure 3.1. Comparison of soil gas concentrations both the shallow (5 to 9 cm) and deep (23 to 32 cm) depths for the plant habitats and the Peat and Spruce sites in 2005 and 2006; (a) shallow depth CH_4 and O_2 concentrations, (b) deep depth CH_4 and O_2 concentrations, (c) shallow depth N_2O and O_2 concentrations, (d) deep depth N_2O and O_2 concentrations, (e) shallow depth CH_4 and CO_2 concentrations, and (f) deep depth CH_4 and CO_2 concentrations (n=5 for Polygon Top and Moss (*Sphagnum*), n=4 for Lower Sedge, Upper Sedge, shallow depth Ice Wedge and Upper Lichen, n=3 for Moss (*Hylocomium*) and n=2 for deep depth Ice Wedge and Sedge-Moat plant habitats). Spearman rank correlation analysis results shown with *, ** and *** indicate the correlation is significant at P<0.01, 0.001 and 0.0001 level of significance, respectively.

3.4.4. Relation of Soil Gas Concentration to Surface Fluxes of CH_4 and N_2O

Generally there was a relationship found between increased soil gas concentrations at both shallow and deep depths and increased surface fluxes of CH_4 and N_2O. Also, soil gas concentrations followed the trends found for the plant habitat surface fluxes. For example, the Sedge-Moat plant habitat at the Spruce site had extremely high shallow depth CH_4 soil concentrations corresponding to very high CH_4 surface fluxes, while the Upper Sedge at the Peat site had high soil CH_4 concentrations at the deep depth which related to high CH_4 surface fluxes. Low soil CH_4 concentrations for the Polygon Top plant habitat at the Peat site also corresponded with negative CH_4 surface fluxes. Soil concentrations and surface fluxes of CH_4 were found to be significantly correlated at both depths when combining all habitat types and both sites (Figure 3.2).

Shallow depth N_2O soil concentrations in the wet plant habitats, such as the Sedge-Moat, Ice Wedge and Upper and Lower Sedge, generally had lower values and related to slightly decreased N_2O surface fluxes. In contrast, at both shallow and deep depth soil N_2O concentrations for the Polygon Top habitat had increased soil concentrations strongly related to slightly increased N_2O surface flux (Figure 3.2).

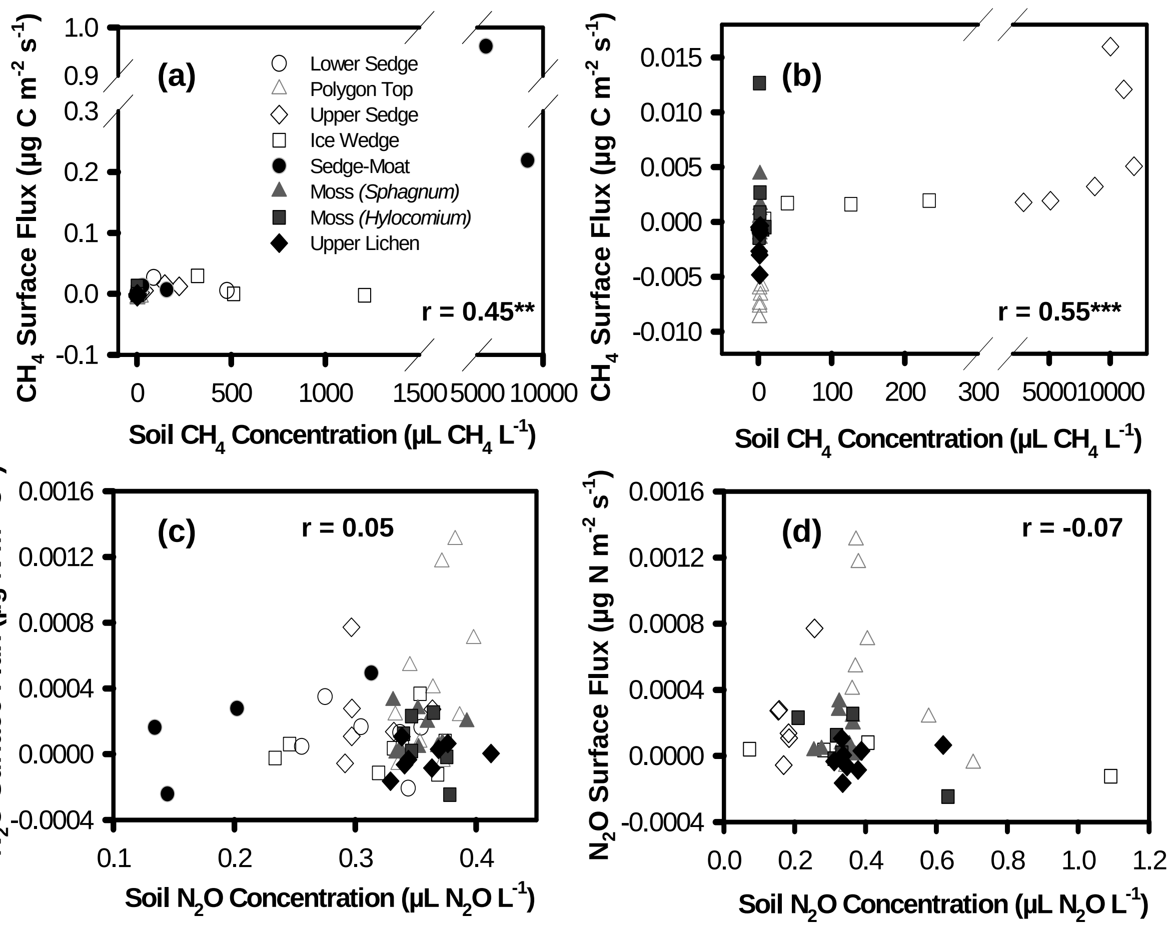

Figure 3.2. Comparison of average CH_4 and N_2O surface flux to average CH_4 and N_2O soil concentrations, respectively for both the shallow (5 to 9 cm) and deep (23 to 32 cm) depths for the plant habitats and the Peat and Spruce sites in 2005 and 2006; (a) CH_4 surface flux and shallow depth soil CH_4 concentration, (b) CH_4 surface flux and deep depth soil CH_4 concentration, (c) N_2O surface flux and shallow depth soil N_2O concentration, and (d) N_2O surface flux and deep depth soil N_2O concentration (mean of n=3 for soil concentrations in 2005, n=4 for soil concentrations in 2006, n=12 for surface fluxes in 2005 and n=14 for surface fluxes in 2006). Spearman rank correlation analysis results shown with *, ** and *** indicate the correlation is significant at P<0.01, 0.001 and 0.0001 level of significance, respectively.

3.5. Discussion

3.5.1. Soil Gas Concentrations Related To Environmental Conditions

At both the Peat and Spruce sites soil gas concentrations were generally much higher at greater depth. At depth, these gases are less likely to escape to the atmosphere than the gases closer to the surface, at depths of only 5 to 9 cm.

Methane (CH_4) and carbon dioxide (CO_2) concentrations were greater in the wetter plant habitats, like the Upper Sedge, Ice Wedge and Lower Sedge at the Peat Site and the Sedge-Moat of the Spruce site. Both CH_4 emissions and microbial and root respiration are controlled by environmental factors such as temperature, soil moisture and water table depth. Moisture was an extremely important environmental factor determining greenhouse gas (GHG) emissions at the sites used in this study. Methane consumption is limited by diffusion into the soil, which is inversely related to moisture content. As soil moisture decreases conditions favor CH_4 oxidizers and CH_4 consumption can occur, however, there is a point at which microbes become moisture stressed (Gulledge and Schimel, 1998). Saturated soil conditions limit aerobic processes and favor CH_4 production (Yavitt et al., 2005). Also, for CH_4 production to occur, low redox conditions created by prolonged saturated conditions and labile carbon are a necessity (Smith et al., 2003). Indication of low redox conditions were found when measuring oxidation-reduction potential (ORP) of soil water from monitoring wells in the different plant habitats (Table A.1 and A.2). Low ORP values were found for the wetter habitats at the Peat and Spruce sites, especially in the Upper Sedge and Sedge-Moat habitats where values were almost always negative and ranged from -166 to 12 and -102 to 100 mV, respectively. Furthermore, microbial respiration is slowed in saturated soil conditions that limit oxygen (O_2) concentrations, as well as in dry soil conditions with limited water content (Gulledge and Schimel, 1998). All gas concentrations tended to be greater in the summer of 2006 than the summer of 2005, due to increased soil moisture, as the summer of 2006 was a wetter season.

There was less nitrous oxide (N_2O) at the Peat site in the wetter areas at the deep depths compared to the shallow depths due to the reduction of N_2O to nitrogen (N_2) during denitrification that likely occurred well below the soil surface in saturated soil (Smith et al., 2003). Soils can act as sinks for N_2O consumption under a wide range of conditions, but generally in soils with increased water filled pore space and limited nitrate (NO_3^-) availability (Chapuis-Lardy et al., 2007). Nitrous oxide concentrations were also less in the saturated Sedge-Moat habitat at the Spruce site. The shallow depths in wet plant habitats and both depths in the drier habitats like the Polygon Tops at the Peat site and the Moss habitats at the Spruce site, the N_2O concentrations found are likely due to nitrification occurring in limited O_2 environments. This will result in the production of nitric oxide (NO) and N_2O emissions (Smith et al., 2003).

Moisture is largely responsible for the O_2 concentrations found at both sites. In contrast to CH_4 concentrations, O_2 concentrations are higher in the drier plant habitats. These results are expected as drier conditions create a more aerobic environment, as more soil pores become air-filled. In wet conditions O_2 diffusion is restricted, leading to decreased soil O_2 concentrations, where O_2 is consumed by heterotrophic respiration (Gulledge and Schimel, 1998). The O_2 concentrations were greater at the shallow depths in all habitat types, as O_2 more readily available in the soil at 5 to 9 cm than 23 to 32 cm since conditions become more anaerobic with depth. The expected trends found for the O_2 concentrations also acted as a check to ensure the gas samplers were working. Also, at both sites O_2 concentrations generally decreased over the course of the field season for all plant habitats, which is likely due to the increased rainfall and subsequent increased soil moisture contents later in the field seasons.

3.5.2. Soil Gas Concentrations Related To Greenhouse Gas Surface Fluxes

There was a relationship found between increased soil gas concentrations at both shallow and deep depths and increased surface fluxes of CH_4 and N_2O, as well as a trend between plant habitat soil gas concentrations and surface fluxes. Soil concentrations and surface fluxes of CH_4 were found to be significantly correlated at both depths when combining all habitat types and both sites. Wet plant habitats such as the Sedge-Moat and Upper Sedge tended to have increased CH_4 concentrations at both the shallow and deep depths compared to drier plant habitats. Increased CH_4 soil concentrations corresponded to high CH_4 surface fluxes from these habitats. Low soil CH_4 concentrations for the dry Polygon Top plant habitat at the Peat site also corresponded with negative CH_4 surface fluxes (Figure 3.2).

Trends with CO_2 concentrations were very similar to CH_4 concentrations. Soil respiration concentrations were greatest in the wet plant habitats especially at deeper depths, and were smallest in the drier habitats. These trends followed surface flux values, as the wetter habitats had increased respiration.

Furthermore, the wet plant habitats, such as the Sedge-Moat, Ice Wedge and Upper and Lower Sedge at shallow depths generally had lower N_2O soil concentrations which related to decreased N_2O surface fluxes. However in the dry Polygon Top habitat, at the Peat site, both shallow and deep depth soil N_2O concentrations had increased soil concentrations strongly related to slight increased N_2O surface flux (Figure 3.2).

However, N_2O concentrations at both sites and all habitat types were very low which corresponds with the negligible N_2O surface flux emissions found in Chapter 2.

3.5.3. Climate Change Altering Soil Gas Production and Consumption

Climate change is expected to increase mean annual temperature and precipitation, with most of the warming and increased rainfall occurring in the winter (Phoenix and Lee, 2004). Changes in temperature and precipitation will ultimately alter other factors, such as hydrology and permafrost extent (Tarnocai, 2006). Hydrology controls the physical, chemical and biological processes that occur within peatlands and therefore changes to hydrologic regimes will affect carbon dynamics in these systems (Weiss et al., 2006). In the Hudson Bay Lowlands (HBL), climate change is expected to result in rising sea levels which will lead to flooding in coastal peatlands, as well as the melting of permafrost, both of which will result in increased saturated soil conditions (Tarnocai, 2006). Soil moisture content is the primary factor influencing organic matter decomposition in peatlands as it greatly alters soil aeration (Trettin et al., 2006). Moisture content and subsequent soil O_2 concentrations primarily affected the zones of soil gas production and consumption at both the Peat and Spruce site. Therefore, changes in hydrology will likely alter GHG emissions as a result. Increased saturated conditions, which are expected in areas underlain by permafrost, along with increased temperatures will lead to anaerobic decomposition and increased CH_4 production (Tarnocai, 2006). Tarnocai's findings are supported by this study as soil CH_4 concentrations at both sites increased when soil conditions became wetter and therefore, increasingly anoxic. In contrast, in areas of the HBL that generally have unfrozen soil, higher temperatures could result in drier conditions, higher evapotranspiration and a longer growing season, which would lead to increased CO_2 concentrations in the soil due to aerobic decomposition, but CH_4 consumption may also occur (Tarnocai, 2006). Previous studies have found there is a large influence of soil temperature, water table position and micro-sites in peatlands, like hummocks versus hollows, on CH_4 emissions, with hollows having greater CH_4 production (Macdonald et al., 1998). The findings in Chapter 2 also support these findings as wet plant habitats had increased CH_4 production while CH_4 consumption occurred in the dry habitats. In plant habitats such as Ice Wedges and Sedge-Moat areas, which are prone to having high water tables, saturated conditions and CH_4 production, increased moisture content in these areas would likely result in higher CH_4 soil concentrations and surface emissions. Whereas habitats such as the Polygon Top, which are currently higher elevation with lower soil moisture contents, may be less affected by the changing hydrology and may even result in increased CH_4 consumption as warming trends occur. Therefore, understanding the processes governing soil gas production and consumption in peatlands is important to predict the potential effect of changes in GHG surface flux emissions as factors such as hydrologic regimes are altered under a changing climate.

3.6. Conclusion

Soil gas concentrations provide important insight about the extent of microbial processes within the soil and how these processes will affect GHG emissions at the soils surface. Arctic and subarctic peatlands are large carbon stores and are among the most sensitive areas to climate change. Changes in temperature, precipitation and hydrology are expected to be very significant in regions such as the HBL and are the factors that will most influence microbial soil processes and subsequently soil gas concentrations. No other studies have taken into account the *in situ* GHG soil gas concentrations and related these to GHG surface fluxes. Results indicate that soil gas concentrations follow the same trends as GHG surface fluxes and can be related to different plant habitats and environmental conditions. Aerobic versus anaerobic conditions caused by soil moisture conditions tended to be the primary influence on soil gas. Wetter and subsequently more anoxic plant habitats, like the Upper Sedge and Sedge-Moat, had increased CH_4 and CO_2 concentrations compared to drier, aerobic habitats, like the Polygon Top. Therefore, understanding what factors drive soil gas concentrations at different depths is critical to discover zones of soil gas production and consumption in numerous habitat types within peatlands. These zones of production and consumption must be further studied in order to determine the potential impact on soil gas concentrations due to changing hydrologic regimes, as a result of climate change, which will ultimately impact GHG surface emissions.

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4. DOES VARIATION IN SOIL CONDITIONS WITHIN A SIMILAR PLANT COMMUNITY AFFECT GREENHOUSE GAS EMISSIONS?

4.1. Abstract

Relating greenhouse gas (GHG) emissions to plant communities and soil conditions creates a means to scale local measurements to regional estimates of GHG emissions in the Hudson Bay Lowlands (HBL). The Lowlands are an important area to the study of greenhouse gases, as it is a main store of organic carbon in the form of peat, and has the potential for methane (CH_4) emissions. This region is expected to experience large increases in temperature and alteration in precipitation, in both amount and patterns, associated with elevated levels of greenhouse gases. The objective of this study was to determine if variations in soil conditions affect GHG emissions within a similar plant community. Four sections of sample positions were established in 2005 on *Cladina stellaris* lichen mats, a dominant circumpolar species common in the HBL. Static-vented dark chambers were deployed to collect GHG samples (respiration, CH_4, N_2O) every week from snow melt to late summer and one sampling in late fall 2005. In 2006, GHG samples were collected every two weeks. Soil pits were dug July 31, 2005 and the site verified to contain catena and therefore a gradient in soil conditions with differences in moisture, active layer, peat accumulation, water table height and depth to permafrost in the downslope direction towards a pond's edge. Based on the results from 2005 and 2006, soil conditions altered respiration emissions but did not exert great influence upon CH_4 and N_2O emissions, at least for emissions from within a similar lichen community. However, the differences in GHG emissions found were not as great as those between plant habitats shown in Chapter 2. Therefore, the results from this study suggest that

plant communities could be extremely useful predictors of GHG emissions, especially CH_4, even in differing soil conditions.

4.2. Introduction

Terrestrial subarctic and arctic ecosystems are of vast importance as early warning indicators of the effects of global warming as they are expected to undergo earlier and more drastic climatic changes than lower latitude environments (Joabsson and Christensen, 2001). Of these northern environments, peatlands like the Hudson Bay Lowlands (HBL) are very important with respect to greenhouse house (GHG) emissions. Peatlands occupy about 15% of the boreal and subarctic regions and contain approximately one-third of the world's soil carbon pool (Pastor et al., 2003). Peatlands also play an important role in the global cycling of carbon through the exchange of carbon dioxide (CO_2) with the atmosphere, the emission of methane (CH_4) and production and export of dissolved organic carbon (DOC) (Moore et al., 1998). The HBL is the third largest wetland in the world (Ricketts et al., 1999; ArcticNet, 2007) and contain the second largest contiguous peat accumulation and are an important repository of organic carbon in Canada and the world (Rouse et al., 2002). Many subarctic terrestrial environments, such as the peatland sites at Churchill, are underlain by permafrost. Churchill is in a transition zone between having continuous and discontinuous permafrost (Camill, 2005). Permafrost provides major variations in physical soil formation, which affects surface micro-topography and influences plant community structure. Permafrost also determines the hydrological and nutritional status of soil conditions, which is important for vegetation distribution, ecosystem carbon balance and the emissions of greenhouse gases (Christensen et al., 2004). Also, discontinuous permafrost has recently been shown to be melting across western Canada creating new vegetation communities (Turetsky et al., 2002). Therefore, studying in areas like Churchill, which is part of the HBL, allows the opportunity to collect information on the present rates of GHG emissions under specific plant communities and apply these findings to similar locations within the HBL.

Being able to predict GHG emissions from specific environments is important in order to easily create models depicting emissions from these areas and upscale the results to a regional, national or global scale. Regional patterns in subarctic and arctic environments are extremely complex with respect to plant communities and soils. Plant communities differ in species, growth form, biomass and productivity, while soils differ in factors such as organic matter content, nutrient levels, and depth of active layer and water table (Williams and Rastetter, 1999). One of the simplest ways to predict GHG emissions is by using vegetation communities. Compared to environmental variables such as water table depth and soil temperature, remote sensing techniques can be more easily applied to plant communities (Bubier et al., 1995). Therefore, if vegetation can be used as a predictor of GHG emissions, even in varying soil conditions, it would allow a relatively quick and simple way to scale emissions to regional estimates of GHG emissions.

Vegetation is particularly important in determining CH_4 fluxes. Plant properties such as density, life form and species composition affect CH_4 production, consumption and transport, especially in wetland environments (Hirota et al., 2004). Plants can be predictors for future CH_4 emissions and the environmental conditions like temperature and moisture, and the soil conditions present (Bubier et al., 1995). This is further supported by the findings from Chapter 2 in which GHG emissions were found to vary considerably with plant habitat type at three study sites located in different environments containing a large range of environmental and plant community gradients. Plant habitats such as riparian and sedge areas and submerged peat ledges in ponds, continually showed high CH_4 production, due to the increased moisture content and the presence of dominate sedges like *Carex spp*. Whereas CH_4 consumption was related to low moisture content in areas with lichen dominated plant biomass, such as polygon tops. Conversely, areas of high moisture and plant productivity were sinks for nitrous oxide (N_2O) and low moisture and plant productivity areas were a source of N_2O, albeit at very low rates.

This study was carried out to investigate how GHG emissions are affected by varying soil conditions under a similar plant community type. The study site was located approximately two km southwest of the Churchill Northern Studies Centre (CNSC), Churchill, Manitoba. It consisted of a ridge grading down in elevation to the edge of Orange Pond. The entire site was vegetated with the lichen species *Cladina stellaris*, which is a dominant circumpolar plant species that is present all throughout the HBL. The lichen surface was underlain by peat and the thickness of peat, depth to water table and permafrost varied from the ridge to the pond's edge. This site was ideal to examine if plant community or soil type was a better predictor of GHG emissions from a subarctic environment.

4.3. Materials and Methods

4.3.1. Site Location and Field Layout

A study site was established in 2005 in the vicinity of the town of Churchill, Manitoba. The site was a Peat Plateau (58.73^{o}N: 093.84 ^{o}W) and was situated approximately two km along Twin Lakes Road, which runs south of the CNSC beginning about 23 km east of the town of Churchill, Manitoba. The study area was oriented southwest to northeast from a gravel ridge downslope towards the edge of Orange Pond.

The study area consisted of 32 sample positions on *Cladina stellaris* lichen mats. On June 9, 2005, the area was divided into four sections with eight sample positions in each section (Figure 4.1). Elevation above sea level (m) for all positions was obtained using a total station (TPS700, Leica Geosystems, Heerbrugg, Switzerland). At each position, a section of PVC pipe was inserted into the underlying peat material to serve as a collar or base of a static-vented chamber for gas sampling. All sample positions had over 90% *Cladina stellaris* vegetation cover as determined by percent cover estimates.

Details regarding static-vented chamber installation and construction can be found in Chapter 2, Section 2.3.1.

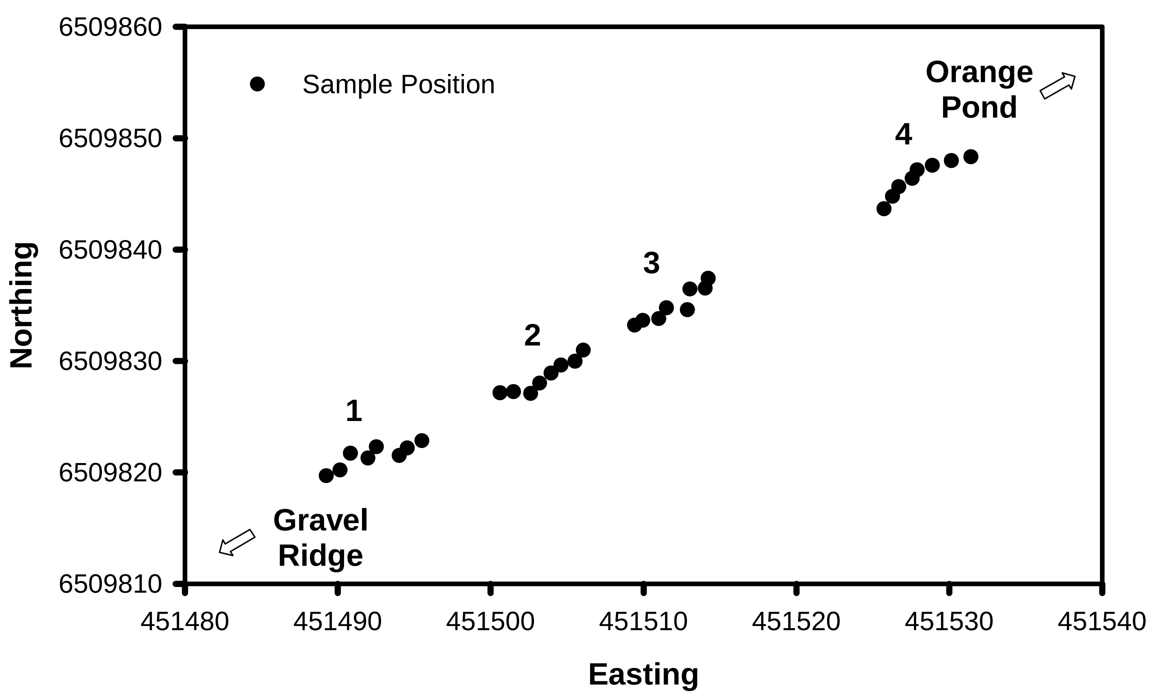

Figure 4.1. Layout of the sample positions at the study area in 2005 and 2006.

4.3.2. Occurrence of Gas Flux Sampling and Analysis

Static-vented dark chambers were used to determine GHG emissions (respiration, CH_4 and N_2O) from gas collected in the chamber headspace at 0, 10, 20 and 30 minute intervals. In 2005, sampling occurred every week from approximately snow melt (June 10) until late summer (August 8) with one sampling on September 22. In 2006, the site was sampled every 2 weeks from May 30 to August 23.

The procedures for gas collection, analysis and emissions estimates can be found in Chapter 2, Section 2.3.2.

4.3.3. Environmental Conditions

Environmental conditions (soil temperature at 2.5 cm depth [$Temp_{2.5}$], soil temperature at 15 cm depth [$Temp_{15}$], air temperature [$Temp_{air}$], volumetric moisture content [VMC], and active layer depth) potentially controlling gas emissions were determined during the course of and following gas sampling for flux emissions. The environmental parameters were determined as detailed in Chapter 2, Section 2.3.3.

4.3.4. Soil Characterization

Four soil pits of 0.25 m^2 were dug on July 31, 2005. One pit per section was dug in order to determine differences in soil conditions in sections grading from the gravel ridge to the edge of the pond. The pits were chosen adjacent to sample positions, mid-way in each section. Surface features were noted before the pits were dug and the vegetation cover of each pit was predominantly *Cladina stellaris* lichen mats. Within each pit, different soil horizons and their depths, as well as the depth to the water table and/or frost were determined. Soils were classified according to the Canadian Soil System of

Classification (Soil Classification Working Group, 1998). Soil bulk density rings were used to collect soil samples from the organic horizons of the pits and loose samples were taken from the mineral horizons. The samples were frozen and later thawed for analyses. Degree of decomposition was determined for the organic samples using the Von Post decomposition scale, with 1 being the least decomposed and 10 being the most decomposed (Parent and Caron, 1993). The samples were then weighed and dried at 70^{o}C for 48 hours. After drying, samples were weighed again in order to calculate gravimetric moisture content (GMC) and bulk density (BD). Where samples were mineral, texture was determined by shaking 50 g of the samples through a stack of brass sieves of various mesh sizes (1, 0.5, 0.25, 0.1 and 0.05 mm diameter). The organic samples were ground using an electric coffee grinder and the mineral samples were ground using a ball grinder (SamplePrep 8000 Mixer/Mill, SPEX CertiPrep Group, Metuchen, NJ).

Soil extractions were also completed on all samples and were analyzed for pH and EC as described in Chapter 2, Section 2.3.4.

4.3.5. Statistical Analysis

Statistical analyses for all data were done using Statistical Analysis Software (SAS) package version 9.1 (SAS Institute Inc., Cary, NC). A generalized linear model (GLM) analysis of variance (ANOVA) was run on the average CH_4, N_2O and respiration for the transect sections for each field season, separately. A $P<0.05$ level of significance was used for the GLM ANOVA tests. Shapiro-Wilk and Levene tests were used to test normality and homogeneity of variance of the data sets, respectively. Any average flux data that were not normal or homogenous were transformed using log (base 10) or power-transformed, to improve both normality and homogeneity. In the cases where negative fluxes occurred, a common coefficient was added before the data transformation. Scheffe's test was used to compare fluxes between transect sections at a significance level of $P<0.05$.

4.4. Results

4.4.1. Weather Conditions

Daily precipitation and average daily air temperature were relatively similar for the field seasons of 2005 and 2006, in Churchill. Both seasons had wet summers, however the summer of 2006 had more precipitation throughout the field season. With respect to air temperature, both 2005 and 2006 had very similar average air temperatures for the field season months of June, July and August and were slightly higher than the 30 year daily average air.

The field season weather conditions can be found in the results section of Chapter 2, Section 2.4.1.

4.4.2. Temporal Variation in Greenhouse Gas Emissions

Some slight CH_4 and N_2O positive fluxes occurred for specific dates and sections which corresponded with increased VMC values, in both 2005 and 2006, with values as high as 0.007 $\mu g\ C\ m^{-2}\ s^{-1}$. Slight negative CH_4 fluxes also occurred throughout the field seasons for specific dates and all sections which were related to lower VMC values. In both years, Section 1 showed the highest negative CH_4 fluxes of the sections, with the largest values occurring in 2006 at -0.006 $\mu g\ C\ m^{-2}\ s^{-1}$. Slight negative N_2O fluxes were also found for the study sections for specific dates. However, N_2O emissions were negligible for all sections, with the majority of values falling within the range of flux values considered to be the same as zero (Figure 4.2).

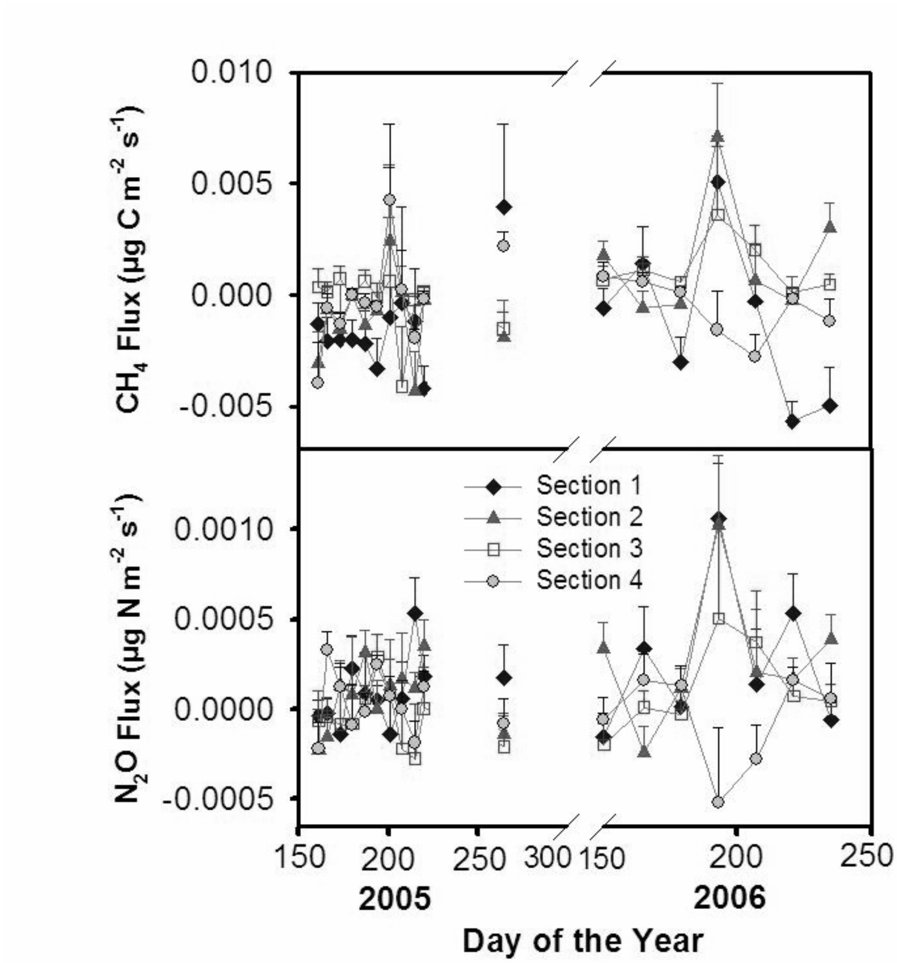

Figure 4.2. CH_4 and N_2O flux for study sections in 2005 and 2006 (mean of n=8, +1 SE shown). Note: Flux values not significantly different from zero ranged from -0.00089 and 0.0011 µg C m^{-2} s^{-1} for CH_4 and -0.00034 and 0.00026 µg N m^{-2} s^{-1} for N_2O.

4.4.3. Average Growing Season Greenhouse Gas Emissions

In 2005, all study sections had negative CH_4 fluxes and were not significantly different from each other. The highest rates occurred in Sections 1 and 2, with average flux values of -0.001 µg C m^{-2} s^{-1}. Similar trends occurred for CH_4 emissions for Sections 1 and 4 in 2006. However, in 2006 Sections 2 and 3 were found to on average to have net CH_4 flux values of 0.002 and 0.001 μg C m^{-2} s^{-1} , respectively, and be statistically similar.

Average N_2O emissions for both years were very small ranging from -0.00005 to 0.0003 μg N m^{-2} s^{-1} and no significant difference was found between the different transect sections. However, very slight negative N_2O fluxes were found in wet sections in both 2005 and 2006, while the driest section, Section 1 consistently had the highest N_2O emissions.

In 2005 and 2006, the greatest respiration values were found in Section 4, with values of 3.8 and 4.1 μg C m^{-2} s^{-1}, respectively. Sections 2 and 3, were found to be statistically similar with intermediate respiration levels. The lowest average respiration emissions were 2.3 μg C m^{-2} s^{-1}, found in Section 1 (Table 4.1).

Trends for all GHG fluxes tended to follow the trends seen for soil moisture. Generally the wetter conditions found in Sections 2, 3 and 4 related to increased CH_4 and respiration emissions and decreased N_2O fluxes. In contrast, the dry Section 1 had lower CH_4 and respiration values and higher N_2O emissions.

Average CH_4 and N_2O flux variability for each study section was high compared to that of average respiration. Section 4 had the greatest variation with coefficient of variations (CV) as large as 775% for CH_4 emissions and 469% for N_2O flux.

Cumulative GHG emissions for each section in both field seasons followed the same trends as found for average GHG emissions (Table A.6).

Table 4.1. Average CH_4, N_2O and respiration (CO_2) flux for study sections in 2005 (day 161 to 265) and in 2006 (day 150 to 235).

		CH_4 Flux ($\mu g\ C\ m^{-2}\ s^{-1}$)			N_2O Flux ($\mu g\ N\ m^{-2}\ s^{-1}$)			Respiration ($\mu g\ CO_2\text{-}C\ m^{-2}\ s^{-1}$)		
Period	**Section**	**Mean**	**SD**	**%CV**	**Mean**	**SD**	**%CV**	**Mean**	**SD**	**%CV**
2005:	1	-0.0014 a	0.0033	229	0.00009 a	0.00013	142	2.3 b	1.1	50
104 days	2	-0.0011 a	0.0017	163	0.00009 a	0.00016	174	3.4 ba	0.7	21
	3	-0.0003 a	0.0011	375	-0.00004 a	0.00010	227	2.8 ba	0.5	19
	4	-0.0002 a	0.0015	775	0.00003 a	0.00009	318	3.8 a	0.8	20
2006:	1	-0.0011 b	0.0023	199	0.00027 a	0.00025	93	2.3 b	0.9	40
85 days	2	0.0016 ba	0.0014	89	0.00029 a	0.00026	92	2.8 ba	0.6	20
	3	0.0012 ba	0.0016	128	0.00011 a	0.00022	202	3.1 ba	0.7	23
	4	-0.0006 a	0.0013	216	-0.00005 a	0.00024	469	4.1 a	1.0	24

Values shown are the mean of 8 replicate sample positions, 11 sample days with total sample data of n=88 in 2005 and the mean of 8 replicate sample positions, 7 sample days with total sample data of n=56 in 2005, ± 1 standard deviation (SD) of the mean and the percent coefficient of variation (CV). Mean values followed by the same letter (within column and year) are not significantly different using Scheffe's test ($P<0.05$).

4.4.4. Environmental Conditions

Respiration occurred in all study sections and was used to assess general microbial activity and autotrophic plant respiration. In both field seasons, respiration values were lowest in Section 1 while Section 4 had the highest respiration at 7.1 μg C m^{-2} s^{-1} in 2005. Sections 2 and 3 had intermediate respiration levels. Respiration generally followed soil temperature trends at both 2.5 and 15 cm and all sections had similar soil temperatures at 2.5 cm in 2005 and 2006 (Figure 4.3).

Soil volumetric moisture content (VMC) was greatest in Sections 2, 3 and 4, respectively, in both 2005 and 2006. The lowest VMC was found in Section 1 with values ranging from 45 to 63% in 2005 and 41 to 74% in 2006 (Figure 4.3).

Active layer depths increased for all study sections over the course of the field seasons with Section 1 increasing at a greater rate than the other three sections in 2005 and Section 4 increasing at a greater rate in 2006. The active layer depths for Sections 2, 3 and 4 were very similar in 2005 with values reaching a maximum of approximately 35 cm. Section 1 in 2005 had the deepest active layer at a maximum of 81 cm. However, in 2005, active layer depths were only established until soil pits were dug on July 31, 2005 as locations to measure active layer depth near the sampling locations could not be found without hitting the cobble layer found within the soil profile. In 2006, areas near the sample location were found in which the cobble layer did not interfere with active layer depth measurements. Section 4 had the deepest active layer at a maximum of 83 cm at the end of August while Sections 1, 2 and 3 had similar active layer depths in 2006 with maximum levels of 31, 39 and 50 cm, respectively, in late August 2006 (Figure 4.3).

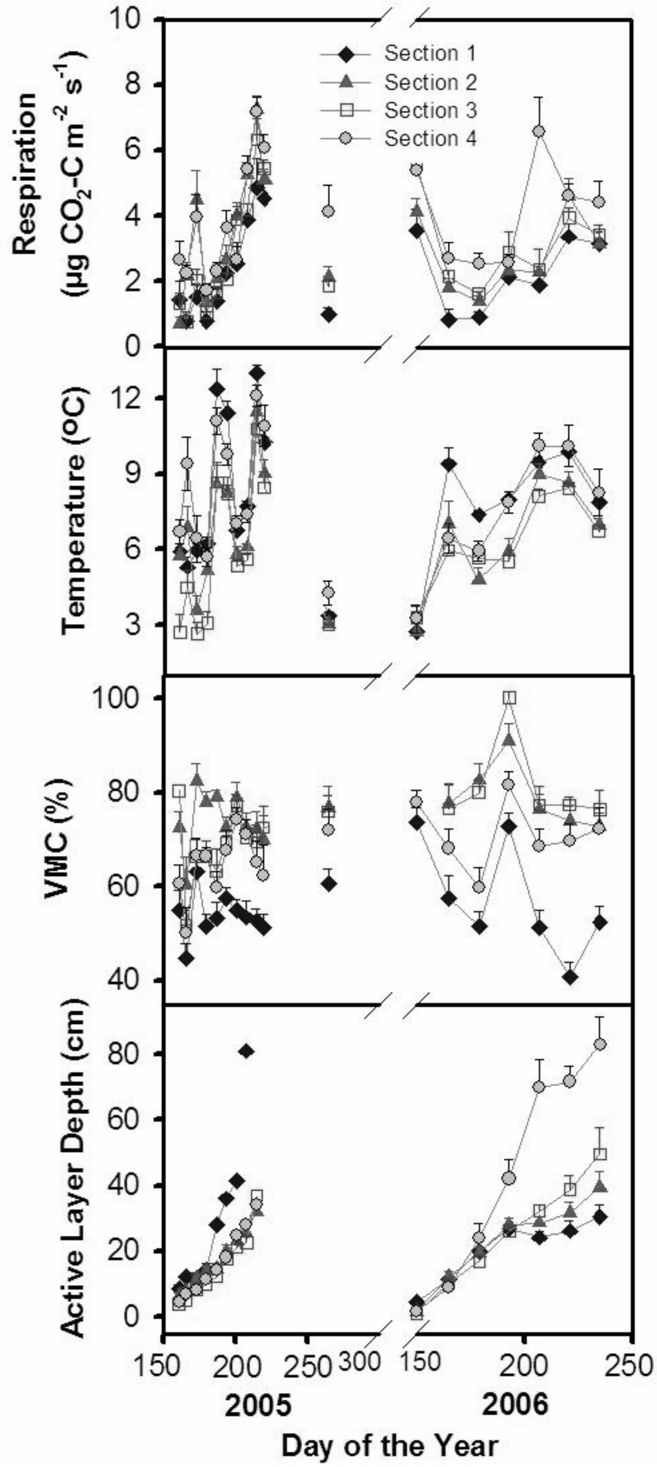

Figure 4.3. Respiration (CO_2) flux, soil temperature at 2.5 cm, soil volumetric moisture content (VMC) and active layer depth, for transect sections in 2005 and 2006 (mean of n=8; +1 SE shown). Note: Flux values not significantly different from zero ranged from 0 and 1.83 µg C m^{-2} s^{-1} for CO_2.

4.4.5. Soil Characteristics

The study site started on a gravel ridge and progressed downslope towards the edge of Orange Pond, which resulted in the formation of a catena and therefore a gradient in soil conditions for the study sections. One soil pit (0.25 m^2) was observed for each section. All the soil pits had an organic layer at the surface, followed by a cobble layer with a cherty gravelly and coarse cherty gravelly texture, and finally a base sand layer. In 2005, Section 1 had the thinnest peat layer, thickest cobble layer, deepest active layer and greatest distance to the water table at 81 cm. The soil was classified as a Brunisolic Eutric Static Cryosol. The pits characterized for Sections 2 and 3 were very similar with thicker peat layers of 26 and 23 cm and higher water tables at 32 and 37 cm, respectively, than that of Section 1. Section 4 was also similar to the pits in Sections 2 and 3, with an organic layer of similar thickness, but had frost present at 34 cm. The soil in Sections 2, 3 and 4 were classified as Histic Eutric Static Cryosols (Figure 4.4).

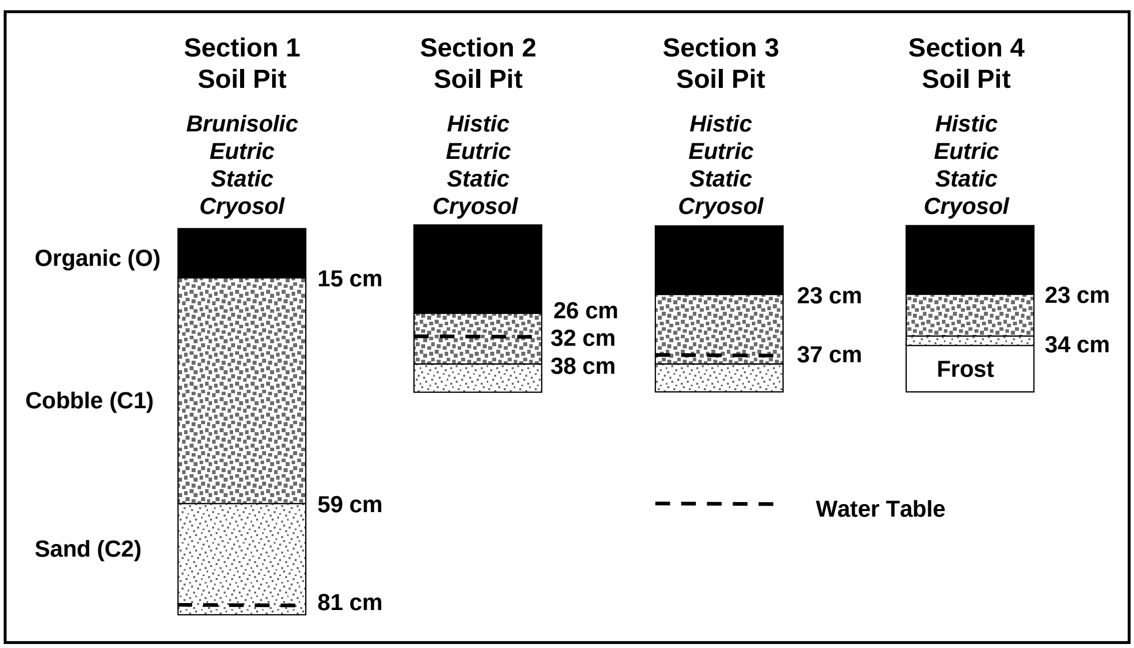

Figure 4.4. Depiction of the soil characteristics based on soil pit analysis at the study site on July 31, 2005. One soil pit (0.25 m^2) was observed for each section.

Soil samples were taken from each soil pit the day they were initially dug (July 31, 2005). The organic horizon of the soil was more decomposed in the soil of Sections 3 and 4 than Sections 1 and 2. Section 1 had the driest organic layer, with moisture contents of approximately 360 g H_2O/g soil, as well as the lowest electrical conductivity (EC) and pH values of ranging from 5.6 to 6.1. Section 3 had the wettest organic horizon, the lowest bulk density (BD) and the highest EC and pH readings. The organic horizons of Sections 2, 3 and 4 were generally of a neutral pH. The mineral sand layer of the pits were relatively similar, as they all had basic pH values of 9.2, and electrical conductivities ranging from 109 to 130 μS cm^{-1}. However, Section 1 had the driest mineral layer of all the sections at only 4.5 g H_2O/g soil, compared to values of 13.7 and 12.4 g H_2O/g soil for Sections 2 and 3, respectively. The top of the C2 sand horizon in the soil pit of Section 1 was dominated by very coarse (34%) to coarse (34%) sand while the bottom of the C2 horizon was dominated mainly by fine sand (58%). Section 2 had a sand layer C2 horizon dominated by medium (34%) and fine (28%) sand textures (Table 4.2).

Table 4.2. Soil characteristics of the soil pits analyzed for each study section sampled July 31, 2005.

Section	Horizon	Depth (cm)	von Post Decomposition Scale	Moisture (g H_2O/g soil)	BD (mg/m^3)	EC (µS cm^{-1})	pH	Soil Texture (%)
1	Top of O	0-10	3	354.5	0.19	91	5.55	-
	Bottom of O	10-15	4	362.3	0.19	91	6.12	-
	C1	15-59	Mineral Soil					CG/CCG
	Top of C2	59-70	Mineral Soil	4.5	-	130	9.16	33.6 (VCS)
			-	-	-	-	-	33.6 (CS)
			-	-	-	-	-	18.7 (MS)
			-	-	-	-	-	10.7 (FS)
			-	-	-	-	-	3.4 (<0.05 mm)
	Bottom of C2	70-81+	Mineral Soil	13.7	-	109	9.16	7.6 (VCS)
			-	-	-	-	-	9.0 (CS)
			-	-	-	-	-	17.4 (MS)
			-	-	-	-	-	57.5 (FS)
			-	-	-	-	-	8.5 (<0.05 mm)
2	Top of O	0-10	3	452.7	0.14	177	6.97	-
	Bottom of O	10-26	4	447.9	0.17	150	6.84	-
	C1	26-38	Mineral Soil					CG/CCG
	C2	38+	Mineral Soil	12.4	-	125	9.15	14.7 (VCS)
			-	-	-	-	-	17.1 (CS)
			-	-	-	-	-	33.6 (MS)
			-	-	-	-	-	27.6 (FS)
			-	-	-	-	-	6.9 (<0.05 mm)
3	Top of O	0-10	4	497.5	0.12	203	7.30	-
	Bottom of O	10-23	5	442.5	0.18	152	7.20	-
	C1	23-37	Mineral Soil					CG/CCG
	C2	37+	Mineral Soil					-
4	Top of O	0-10	5	423.2	0.18	118	6.70	-
	Bottom of O	10-23	6	324.5	0.22	140	7.35	-
	C1	23-34	Mineral Soil	-	-	-	-	CG/CCG
	C2	34+	Mineral Soil	-	-	-	-	-

Dash indicates no analysis available. Note: CG = cherty gravelly, CCG = coarse cherty gravelly, VCS = very coarse sand, CS = coarse sand, MS = medium sand, FS = fine sand.

4.5. Discussion

Northern terrestrial ecosystems are of vast importance as early warning indicators of the effects of global warming as they are expected to undergo earlier and more drastic climatic changes than lower latitude environments (Joabsson and Christensen, 2001). Furthermore, the ability to predict greenhouse gas (GHG) emissions from specific environments is important in order to easily create models depicting emissions from these areas and upscale the results to a regional, national or global scale. Regional patterns in subarctic and arctic environments are extremely complex with respect to plant communities, which differ in species, growth from, biomass and productivity, and soils which differ in factors such as organic matter content, nutrient levels, and depth of active layer and water table (Williams and Rastetter, 1999). One of the simplest ways to predict GHG emissions is by using vegetation communities. Compared to environmental variables such as water table depth and soil temperature, aerial photography or remote sensing techniques can be more easily applied to plant communities (Bubier et al., 1995). Therefore, if vegetation can be used as a predictor of GHG emissions, even in varying soil conditions, it would allow a relatively quick and simple way to scale emissions to regional estimates of GHG emissions.

This study was designed to investigate how a similar plant community type with varying soil conditions affects GHG emissions and determine if plant community or soil type was a better predictor of GHG emissions from a subarctic peatland environment.

4.5.1. Greenhouse Gas Emissions Related to Soil Conditions

In both 2005 and 2006 there were slight differences in GHG emissions found along the study sections. In 2005, all sections were found to consume methane (CH_4) with the highest rates occurring in Sections 1 and 2. Trends for CH_4 emissions were similar in 2006 expect for Sections 2 and 3 switched to slight CH_4 production (Table 4.1). Sections 2 and 3 were the wettest study sections in both years, and as the summer of 2006 was wetter than that of 2005, these sections likely switched from slight CH_4 consumption to slight CH_4 production. Section 1 had the lowest soil moisture content, in both the organic and mineral horizons, and the greatest distance to the water table of all the sections, which in organic soils, leads to reduced CH_4 emissions (Trettin et al., 2006). The drier conditions create a more aerobic environment, which result in CH_4 being oxidized by methanotrophs, leading to CH_4 consumption (Smith et al., 2003). The drier conditions and low water table in Section 1 were due to the, thin organic horizon, thick cobble layer, very coarse to coarse texture at the top of the C2 horizon and higher elevation position in the landscape. These soil conditions would allow water to drain readily through the soil profile. Section 2 was a much wetter section as it had a thicker organic layer and a C2 horizon dominated by medium and fine sand textures, which would be more able to hold moisture within soil pores (Figure 4.4 and Table 4.2). Soils with increased organic matter have been found to have a greater water-filled-pore-space and water holding capacity (Gulledge and Schimel, 1998). Saturated conditions, with a water table near the surface limit aerobic processes and create anaerobic conditions necessary for the microbial breakdown of organic compounds and ultimately CH_4 production (Yavitt et al., 2005). Prolonged waterlogged conditions did not occur at the study site due to the soil type present, as well as the depth to the water table. On July 31, 2005, based on the soil pits dug, the depth to water table was 81, 32 and 37 cm, respectively, for Sections 1, 2 and 3. In northern peatlands, a water table depth of 10 to 20 cm below the peat surface has been found to be the limit for CH_4 emissions, and if the water table was below these depths surface CH_4 fluxes were reduced to near zero levels (Trettin et al., 2006).

Respiration occurred at all study sections and was used to assess general microbial activity and autotrophic plant respiration. Respiration generally followed soil temperature trends at both 2.5 and 15 cm and all sections had similar soil temperatures at 2.5 cm in 2005 and 2006. Elevated soil temperatures can lead to increased heterotrophic and autotrophic respiration (Smith et al., 2003). Respiration was more responsive than CH_4 emissions to changes in soil conditions. In both field seasons respiration was lowest in Section 1, which relates to decreased soil moisture content. As soil dries, there is a point at which microbial activity becomes inhibited and subsequently respiration decreases (Smith et al., 2003). Sections 2, 3 and 4 had higher respiration values likely due to the increased soil moisture. Decreased microbial activity and ultimately reduced decomposition rates could also affect respiration. The organic horizon in Section 1 had an acidic pH, while the other soils in the other sections had pH values near neutral. Acidic peat soil is one of many unfavorable conditions for decomposer microorganisms (Yavitt et al, 2005). Also, Sections 2, 3 and 4 had organic matter layers of 26, 23 and 23 cm, respectively, which were thicker than the organic horizon of Section 1. The thicker organic horizons would allow microbes greater access to organic compounds and therefore, increased microbial activity (Yavitt et al., 2005). Furthermore, respiration was affected by lichen mat depth as Section 1 had the thinnest average lichen mat depth, at 6.0 cm, while Section 4 had the thickest, at 9.1 cm. Therefore, the increased respiration found in Section 4 was likely due to the increased autotrophic respiration occurring in the thicker lichen mats. The differences found in autotrophic and heterotrophic respiration emissions between the sections could have implications with respect to net ecosystem exchange (NEE) if increases in plant growth and changes in community structure occur with changing climatic conditions.

Nitrous oxide (N_2O) emissions were negligible, with an average flux values ranging from only -0.00005 to 0.0003 μg N m^{-2} s^{-1}, for all study sections in 2005 and 2006 (Table 4.1). In many peatland environments, N_2O flux has been found to be insignificant (Maljanen et al., 2004). However, very slight negative N_2O fluxes were found in wet sections in both 2005 and 2006, while the driest section, Section 1 consistently had the highest N_2O emissions.

Overall, the slight differences in GHG emissions between sections were due to the differing soil and environmental conditions found in each study section. The site contained a slight change in elevation as it began on a gravel ridge and progressed downslope toward a pond's edge. The site was therefore determined to be a catena, as the soil types found within the pits were derived from similar parent materials, but differed in topography and more specifically, slope and drainage conditions (Jenny, 1994). All sections had an organic layer, followed by a cobble layer and sand layer but due to the differences in slope and drainage, each section had differences in organic layer thickness, soil moisture and distance to water table, which slightly altered the GHG emissions.

4.5.2. Plant Communities as Indicators of GHG Emissions

Recent studies have found vegetation to be a major factor influencing the variability of CH_4 emissions (Joabsson et al., 1999; Joabsson and Christensen, 2001; Hirota et al., 2004). Limited CH_4 production, respiration and CH_4 consumption was partly due to the presence of the macrolichen, *Cladina stellaris*, at all sample locations. Macrolichens are abundant in subarctic and arctic environments and can contribute to nutrient cycling and biomass to the arctic carbon sink (Cornelissen et al., 2001). Macrolichens are low productivity plants compared to other vegetation types such as vascular plants. Findings in this study and previously in Chapter 2 support plant community composition being used as an indicator of GHG emissions in an ecosystem. When compared to the large variation in soil and environmental conditions and plant community composition between the plant habitats found in Chapter 2, the soil, environmental and vegetation conditions of the sections in this study were very uniform. For both field seasons, in this study, GHG emissions were comparable to the emissions found in Chapter 2 for similar plant communities, even though they occurred at different sites. Also, in both this study and Chapter 2, the plant communities present were indicative of the environmental conditions present, which ultimately drive GHG emissions. The plant communities themselves also have the ability to directly drive GHG emissions, particularly through the addition of carbon to the soil. For example, studies have found that sites dominated by sedges, generally *Carex*, like many of the plant habitats found in Chapter 2, were usually saturated and produced high CH_4 emissions as sedges play an active role in increasing CH_4 emissions as they have the ability to transport CH_4 through their plant structures, avoiding the oxidation zone in the peat (Bubier et al., 1995). Much of the CH_4 emissions from peatlands have been found to come from organic matter deposited by sedges in anoxic peat layers (Trettin et al., 2006). These findings lead into the idea that plant communities are associated under particular soil and environmental conditions and subsequently can be used as indicators of GHG emissions, with the potential to model emissions based on vegetation.

4.5.3. Implications to Scaling Greenhouse Gas Emissions

Differing soil and environmental conditions did exert an influence on GHG emissions within a similar plant community, especially for respiration emissions, however, compared to the plant habitats studied in Chapter 2, with a wide range of soil, environmental and vegetation conditions, the differences in GHG emissions were very minimal and conditions were uniform. Therefore, this suggests the ability to use plant communities as predictors of GHG emissions, especially CH_4, and can be important in assessing the variability in a landscape, in order to scale from chamber based measurements to the entire landscape. Vegetation cover could be a very useful factor when modeling these ecosystems (Bubier et al., 1995) and is indicative of the environmental and soil conditions present in an ecosystem. Some vegetation mapping has already occurred in Waspusk National Park and much of the Cape Churchill Wildlife Management Area, which make up a large portion of the Hudson Bay Lowlands (HBL) (Brook and Kenkel, 2002). Vegetation mapping and upscaling of current GHG emissions in subarctic ecosystems is particularly important as these areas are very sensitive to predicted changes in climate. Vegetation shifts are expected in many northern habitats due to the changing environmental conditions associated with climate change. For example, in a subarctic region in Sweden, the vegetation has been found to shift from elevated dry-shrub dominated to wet-graminoid dominated in areas with increased active layers and soil moisture contents due to melting permafrost (Christensen et al., 2004). Also, a study by Cornelissen et al. (2001) found that experiments simulating warming and increased nutrient availability, which are expected results of global warming, resulted in macrolichen abundance and biomass decreasing as vascular plants abundance and biomass increased in subarctic environments. Therefore, climate change appears to induce changes in vegetation distribution that may be used as indicators of significant and rapid GHG emissions (Christensen et al., 2004). The results from this study support the idea that vegetation mapping of peatlands, like the HBL, would be useful indicators of GHG emissions from different landscapes and allow the opportunity to predict potential emissions from different habitats and future plant communities that may arise due to vegetation shifts.

4.6. Conclusion

Being able to predict GHG emissions from specific environments in northern environments is important in order to easily create models depicting emissions from these areas and upscale the results to a regional, national or global scale. Regional patterns in subarctic and arctic environments are extremely complex with respect to plant communities and soils. Therefore, using vegetation cover instead of environmental factors could be a very useful factor when modeling these ecosystems as vegetation is indicative of the soil and environmental conditions present. Based on the results, soil conditions did not exert great influence upon GHG emissions, at least for emissions within a similar lichen community. However, there were differences respiration emissions for the study sections that were likely related to soil characteristics, but these were not nearly as great as the differences found when comparing different plant habitats with a wide range of soil and environmental conditions and plant community composition, in Chapter 2. The results from this study suggest that plant communities could be extremely useful predictors of current and future GHG emissions, especially CH_4, even in slightly differing soil conditions.

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5. OVERALL SYNTHESIS

Global warming, associated with elevated levels of greenhouse gases, is expected to alter hydrologic regimes, permafrost extent and vegetation composition in the Hudson Bay Lowlands (HBL). Determining the current state of surface fluxes and relating these to major environmental conditions such as temperature, moisture, and plant habitats is important to predict the effect of future conditions on greenhouse gas (GHG) emissions and carbon storage in northern environments.

There was considerable spatial variation in GHG emissions and soil concentrations between and within sites due to large gradients in environmental and plant community composition. Most previous studies in the HBL have not considered the influence of the highly variable landscape types or plant habitats on GHG emissions. Without first breaking up the ecosystems into different habitats, and analyzing each separately, we will have no real idea of how the components of an ecosystem function, with respect to GHG emissions. There was also variation within plant habitats depending on the conditions present. "Hot-spots" of intense methane (CH_4) emissions were found in the sedge-dominated habitats such as riparian areas, submerged peat ledges in ponds, sedge-moats and sedge-lawns, which had high moisture content and plant productivity. Conversely, CH_4 consumption was related to low moisture content in areas with lichen dominated plant biomass, such as polygon tops. Of all the sites, the Fen had the largest CH_4 emissions, in all the plant habitats, due to the constantly saturated soil and high water table, creating the anaerobic conditions necessary for methanogenesis (Trettin et al., 2006). These findings indicate the importance of considering plant habitats within sites, but also between sites, in order to obtain accurate estimates of GHG emissions which could be scaled up over long periods of time, as well as over large areas.

Studies have found vegetation to be a major factor influencing the variability of CH_4 emissions (Joabsson et al., 1999; Joabsson and Christensen, 2001; Hirota et al., 2004). Therefore, spatial integration of plant habitats becomes increasingly important as plant community composition can be used as an indicator of GHG emissions in an ecosystem. Large variations in soil and environmental conditions and plant community composition between the plant habitats and sites found in Chapter 2 created the conditions necessary for considerable variations in GHG emissions. Whereas more uniform soil, environmental and vegetation conditions, such as found in Chapter 4, led to minimal variation in emissions. The plant communities present in the habitats were indicative of the environmental conditions present, which ultimately drive GHG emissions. The plant communities themselves also were able to directly drive GHG emissions, particularly through the addition of carbon to the soil. Therefore since plant communities are associated under particular soil and environmental conditions they can be used as indicators of GHG emissions, with the potential to model emissions based on vegetation. Also, vegetation cover could be very useful as it is easier to map using remote sensing techniques compared to environmental factors (Bubier et al., 1995). Overall, vegetation mapping and upscaling of current GHG emissions in subarctic ecosystems, such as peatlands, are particularly important to predict the affects that changing climatic conditions may have on GHG emissions in the future.

Although CH_4 emissions are of great concern in northern environments due to their impact of net carbon and GHG exchanges, other GHG emissions, such as nitrous oxide (N_2O) must not be overlooked. Very slight N_2O emissions were found at all sites and plant habitats in 2005 and 2006. Although the values were very small, slight trends for production and consumption were found when obtaining both surface fluxes and soil gas concentrations. Slight N_2O production was found in the dry plant habitats while slight N_2O consumption was found in the wet habitats. Due to the high warming potential of N_2O and the large area that peatlands encompass globally, N_2O emissions could become very significant GHG in subarctic and arctic ecosytems. Nitrous oxide emissions are also important due to the lack of knowledge surrounding them in northern environments. No previous studies have found N_2O consumption in northern peatland soils and often, N_2O consumption has been neglected in literature, with many of the values being considered error and subsequently discarded from further calculations of net emissions. Furthermore, N_2O consumption in soil depends on the ease of diffusion of N_2O through the soil (Chapuis-Lardy et al., 2007). If concentrations of N_2O in the atmosphere continue to increase, there will be potential for a greater N_2O consumption gradient resulting in N_2O more readily diffusing into the soil.

Due to the changes in climate expected in arctic and subarctic ecosystems a great concern exists in northern peatland environments for the potential of a climate change feedback mechanism to occur. The results found from this study indicate that the potential exists for environmental conditions and plant community compositions to change and subsequently alter GHG emissions under different climatic conditions. For example, if discontinuous permafrost continues to melt, increased active layer depth and soil moisture will result (Camill, 2005). As the results from Chapters 2, 3 and 4 have shown, plant communities are indicators of environmental conditions as well as GHG emissions. Therefore, if conditions shift to a predominantly wetter state, the vegetation will also be expected to change, probably to a water tolerant vegetation cover such as sedges, and as a result the GHG emissions will be greatly affected. Also, as permafrost melts, the release of methyl hydrates in and below the permafrost could substantially increase CH_4 emissions. In general, climatic changes which alter the plant community composition in northern environments will ultimately lead to changes in GHG emissions and if these changes favor melting permafrost and increased soil moisture a significant loss of carbon in the form of CH_4 from these peatland carbon stores can be expected.

In order to better understand the processes occurring in subarctic peatlands many future research studies are needed. For example this was the first study completed in subarctic peatlands to have *in situ* soil gas concentration measurements. Knowing soil gas concentrations is vital to gain knowledge about the extent of microbial processes and zones of GHG production or consumption within the soil. It is also critical to understand and relate surface emissions and soil gas concentrations in numerous plant habitats within peatlands, to determine sensitive zones that will potentially be influenced the most by changing hydrologic regimes and greatly impact GHG emissions released to the atmosphere. Future research must also occur on N_2O emissions from northern peatlands and other subarctic environments. Slight trends were found with respect to N_2O production and consumption occurring in different plant habitats. Even though N_2O emissions compared to CH_4 emissions were small, N_2O emissions may actually be a significant factor in northern environments when considered over the large area these ecosystems encompass. Therefore, N_2O production and consumption trends need to be explored further and a more precise estimate for the contribution of N_2O emissions from peatlands must be developed. Also, future efforts should be aimed at altering environmental conditions in sensitive ecosystems, like the HBL, to determine the actual implications of climate change in these regions. For example, heating the soil to melt permafrost in the same sites and plant habitats used in this study, would allow a comparison between the present GHG emissions found and future emissions under a changing climate. Lastly, a large scale effort to map the vegetation in the HBL and other subarctic and arctic environments must occur in order to effectively use plant communities as predictors of GHG emissions using remote sensing techniques. Vegetation mapping would allow upscaling of current GHG emissions and create the possibility for more accurate regional and global estimates of GHG emissions. Since northern ecosystems are amongst the most sensitive to a changing climate, it would also allow a quick and easy method to determine the future effect of changing environmental conditions and plant community compositions on GHG emissions.

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6. APPENDICES

6.1. Soil Water Chemistry for the Peat and Spruce Sites

Table A.1. Soil water chemistry determined from monitoring wells in plant habitats at the Peat site in 2006.

Day of the Year	Habitat Type	n	Water Depth (cm)	Temp (^oC)	SpCond (mS cm^{-1})	[DO] (mg L^{-1})	pH	ORP (mV)
161	Upper Sedge	3	17.6 ± 3.6	7.3 ± 1.3	0.25 ± 0.03	4.07 ± 1.35	6.76 ± 0.16	12 ± 36
	Ice Wedge	2	10.4 (9.2-11.5)	5.1 (4.8-5.4)	0.10 (0.08-0.11)	4.34 (3.80-4.88)	4.88 (4.68-5.07)	75 (74-75)
	Lower Sedge	4	11.4 ± 3.4	4.3 ± 0.8	0.11 ± 0.02	6.78 ± 1.58	5.79 ± 0.35	120 ± 31
167	Upper Sedge	2	14.2 (6.8-21.5)	6.1 (5.6-6.5)	0.31 (0.30-0.32)	6.72 (6.69-6.74)	6.52 (6.43-6.61)	-68 (-70-(-66))
	Ice Wedge	2	6.3 (5.5-7.0)	4.2 (4.2-4.3)	0.09 (0.06-0.11)	7.87 (6.39-9.35)	5.47 (5.38-5.56)	31 (30-32)
	Lower Sedge	2	9.2 (5.5-12.8)	3.5 (3.0-4.1)	0.14 (0.08-0.20)	8.63 (7.08-10.18)	6.19 (5.76-6.62)	59 (-30-148)
171	Upper Sedge	1	17.5	3.8	0.34	7.02	6.64	-25
	Lower Sedge	1	8.0	1.8	0.02	18.13	5.93	91
178	Upper Sedge	1	13.5	3.6	-0.01	11.30	6.60	-24
185	Upper Sedge	1	9.5	6.6	0.39	5.68	6.71	-166
199	Upper Sedge	3	19.9 ± 4.4	12.8 ± 1.6	0.27 ± 0.04	5.08 ± 1.64	6.85 ± 0.06	-27 ± 38
	Ice Wedge	2	10.7 (8.9-12.4)	8.9 (8.7-9.2)	0.11 (0.09-0.13)	6.24 (5.76-6.72)	5.00 (4.64-5.35)	80 (78-81)
	Lower Sedge	3	14.7 ± 2.7	7.8 ± 1.4	0.12 ± 0.07	5.91 ± 0.72	5.31 ± 0.64	64 ± 35
206	Upper Sedge	3	18.5 ± 6.3	11.1 ± 1.8	0.29 ± 0.01	7.55 ± 2.74	6.99 ± 0.067	-11 ± 46
	Ice Wedge	2	7.9 (5.2-10.5)	7.5 (6.5-8.6)	0.12 (0.08-0.17)	9.56 (9.12-10.00)	5.14 (4.69-5.59)	60 (45-74)
	Lower Sedge	2	17.3 (15.5-19.1)	6.2 (4.8-7.6)	0.19 (0.11-0.27)	6.91 (5.15-8.67)	5.66 (4.85-6.47)	59 (-30-148)
213	Upper Sedge	4	19.5 ± 3.8	7.1 ± 0.6	0.33 ± 0.06	7.88 ± 0.42	6.62 ± 0.07	6 ± 24
	Ice Wedge	4	11.3 ± 2.1	5.3 ± 0.5	0.11 ± 0.03	7.21 ± 1.55	5.04 ± 0.25	105 ± 18
	Lower Sedge	3	14.2 ± 2.6	4.8 ± 0.8	0.15 ± 0.07	8.07 ± 1.16	5.44 ± 0.49	93 ± 53
220	Upper Sedge	3	17.8 ± 6.3	11.3 ± 1.0	0.30 ± 0.11	3.69 ± 0.82	6.31 ± 0.58	-30 ± 34
	Ice Wedge	2	11.8 (10.1-13.5)	8.0 (7.2-8.9)	0.06 (0.01-0.11)	11.96 (4.51-19.41)	6.18 (5.37-6.98)	23 (16-30)
	Lower Sedge	2	18.3 (17.5-19.0)	6.4 (5.8-7.1)	0.17 (0.02-0.32)	3.85 (2.66-5.04)	5.76 (4.95-6.56)	43 (-48-134)

Table A.1 cont'd

227	Upper Sedge	4	17.6 ± 4.8	9.8 ± 0.9	0.31 ± 0.07	4.14 ± 0.87	6.89 ± 0.09	-4 ± 28
	Ice Wedge	3	12.7 ± 3.9	6.6 ± 0.4	0.19 ± 0.13	6.21 ± 2.83	5.14 ± 0.29	64 ± 15
	Lower Sedge	2	15.3 (10.8-19.8)	6.2 (3.9-8.4)	0.21 (0.09-0.33)	4.81 (3.94-5.68)	5.61 (4.73-6.49)	40 (-35-114)
234	Upper Sedge	3	17.6 ± 6.8	7.8 ± 0.9	0.37 ± 0.08	7.56 ± 1.20	7.12 ± 0.01	9 ± 25
	Ice Wedge	2	12.6 (9.4-15.7)	5.3 (4.8-5.7)	0.09 (0.09-0.10)	6.29 (5.61-6.97)	5.12 (4.63-5.60)	54 (36-72)
	Lower Sedge	2	17.1 (15.0-19.2)	3.9 (4.8-4.1)	0.21 (0.10-0.32)	8.66 (5.84-11.48)	5.72 (4.82-6.61)	56 (-20-131)

Values shown are the mean of n replicate sample positions and ± 1 standard error of the mean, except for where n=2 in which the range of values are shown in parentheses. Note: SpCond = specific conductivity, [DO] = dissolved oxygen concentration and ORP = oxidation reduction potential.

Table A.2. Soil water chemistry determined from monitoring wells in plant habitats at the Spruce site in 2006.

Day of the Year	Habitat Type	n	Water Depth (cm)	Temp (°C)	SpCond (mS cm^{-1})	[DO] (mg L^{-1})	pH	ORP (mV)
159	Upper Lichen	2	-	1.1 (0.8-1.4)	0.258 (0.001-0.515)	8.8 (7.6-10.0)	3.01 (2.59-3.42)	349 (267-421)
	Moss (*Hylocomium*)	3	-	2.6 ± 0.9	0.119 ± 0.021	7.9 ± 1.8	5.77 ± 0.75	194 ± 83
	Sedge-Moat	4	-	1.5 ± 0.3	0.190 ± 0.048	7.0 ± 1.4	6.18 ± 0.15	100 ± 39
166	Upper Lichen	1	6.1	5.3	0.000	14.0	3.58	258
	Moss (*Hylocomium*)	1	4.3	4.4	0.003	12.1	5.06	212
	Sedge-Moat	4	22.4 ± 9.3	5.0 ± 1.5	0.201 ± 0.047	5.5 ± 1.1	6.46 ± 0.06	28 ± 26
173	Sedge-Moat	3	18.3 ± 2.7	3.0 ± 1.4	0.259 ± 0.050	7.5 ± 2.0	6.93 ± 0.12	-9 ± 6
180	Sedge-Moat	3	15.8 ± 3.9	4.5 ± 1.3	0.254 ± 0.123	5.1 ± 1.5	7.05 ± 0.18	-78 ± 7
187	Sedge-Moat	3	15.0 ± 3.8	5.0 ± 1.3	0.315 ± 0.062	4.5 ± 1.9	7.29 ± 0.20	-102 ± 10
194	Upper Lichen	2	7.9 (7.8-8.0)	4.4 (4.3-4.5)	0.052 (-0.003-0.106)	15.9 (15.0-16.9)	3.42 (3.09-3.74)	236 (219-253)
	Moss (*Hylocomium*)	3	7.0 ± 1.4	4.9 ± 0.8	0.143 ± 0.046	12.7 ± 2.0	6.36 ± 0.27	171 ± 13
	Sedge-Moat	4	27.3 ± 8.6	4.6 ± 1.2	0.190 ± 0.048	6.2 ± 1.5	6.41 ± 0.16	-16 ± 29
201	Moss (*Hylocomium*)	3	10.4 ± 1.2	9.6 ± 0.5	0.179 ± 0.005	7.0 ± 0.4	6.51 ± 0.10	101 ± 2
	Sedge-Moat	4	22.8 ± 4.7	6.6 ± 1.1	0.186 ± 0.012	4.6 ± 0.4	6.52 ± 0.16	-62 ± 6
208	Moss (*Hylocomium*)	3	20.5 ± 2.2	8.8 ± 0.8	0.232 ± 0.014	7.5 ± 0.8	6.69 ± 0.13	117 ± 5
	Sedge-Moat	4	32.6 ± 2.4	7.0 ± 1.0	0.189 ± 0.015	5.1 ± 0.4	6.62 ± 0.18	-24 ± 11
215	Moss (*Hylocomium*)	3	18.7 ± 1.6	7.7 ± 0.9	0.252 ± 0.012	6.9 ± 0.7	6.61 ± 0.18	40 ± 6
	Sedge-Moat	4	26.9 ± 3.3	5.2 ± 1.2	0.216 ± 0.011	3.2 ± 0.5	6.76 ± 0.19	-56 ± 16
222	Moss (*Hylocomium*)	3	9.0 ± 1.9	9.7 ± 1.0	0.200 ± 0.023	7.9 ± 1.0	6.77 ± 0.16	27 ± 41
	Sedge-Moat	4	26.7 ± 3.8	7.2 ± 1.4	0.244 ± 0.021	2.6 ± 0.5	6.73 ± 0.11	-69 ± 7
229	Moss (*Hylocomium*)	3	17.1 ± 1.5	10.4 ± 1.4	0.213 ± 0.033	5.9 ± 0.5	6.77 ± 0.16	47 ± 7
	Sedge-Moat	4	26.9 ± 2.9	6.8 ± 1.6	0.258 ± 0.016	2.4 ± 0.1	6.70 ± 0.18	-60 ± 10

Values shown are the mean of n replicate sample positions and ± 1 standard error of the mean, except for where n=2 in which the range of values are shown in parentheses. Note: SpCond = specific conductivity, [DO] = dissolved oxygen concentration and ORP = oxidation reduction potential. Dash indicates analysis not available.

6.2. Cumulative Greenhouse Gas Emissions for the Study Sites

Cumulative flux (mg gas-element m^{-2}) for both 2005 and 2006 were determined for each sampling position by the sum of the daily flux values for a chamber over the entire field season. The flux values for days when no gas sampling occurred were calculated by linear interpolation of the flux values prior to, and after the days with no data collected (Equation A.1).

$$\text{Cumulative Flux} = \Sigma \frac{(F_2 + F_1)}{2} \times (D_2 - D_1) \quad \text{(A.1)}$$

Where:

F_2 = gas flux rate per sample day
F_1 = gas flux rate per previous sample day
D_2 = day of year sampling day
D_1 = day of year previous sampling day

Table A.3. Cumulative CH_4, N_2O and respiration (CO_2) flux for plant habitats at the Peat site in 2005 (day 159 to 267) and in 2006 (day 145 to 234).

Period	Habitat Type	CH_4-C (mg C m^{-2})	N_2O-N (mg N m^{-2})	CO_2-C (mg C m^{-2})
2005: 108 days	Upper Sedge	42.7 ± 13.4 a	2.8 ± 1.0 a	49591.9 ± 4112.6 a
	Polygon Top	-58.4 ± 13.8 b	2.8 ± 1.2 a	31229.1 ± 5287.1 a
	Ice Wedge	36.1 ± 29.7 a	1.4 ± 1.0 a	67226.8 ± 10544.9 a
	Lower Sedge	7.4 ± 7.9 a	1.5 ± 0.5 a	47195.5 ± 12027.0 a
2006: 89 days	Upper Sedge	29.8 ± 14.9 a	1.4 ± 0.7 ab	36781.9 ± 3159.4 a
	Polygon Top	-37.0 ± 9.3 b	4.1 ± 1.2 a	27192.9 ± 5672.6 a
	Ice Wedge	29.6 ± 25.5 a	0.9 ± 0.5 ab	49033.1 ± 6426.4 a
	Lower Sedge	54.7 ± 29.6 a	0.1 ± 0.4 b	58435.1 ± 15196.2 a
	Riparian	2155.2 ± 1460.6	21.6 ± 22.6	51018.4 ± 13567.7
	Pond Edge	14572.1 ± 8223.6	1.4 ± 0.2	9754.2 ± 2998.8

Values shown are the mean of 8 replicate sample positions except for the Riparian and Pond Edge values which are mean of 2 replicates and ± 1 standard error of the mean. Mean values followed by the same letter (within column and year) are not significantly different using Scheffe's test ($P<0.05$). Note: CH_4 flux data for 2005 data was not normal. Riparian and Pond Edge not included in Scheffe's test due to limited replicates.

Table A.4. Cumulative CH_4, N_2O and respiration (CO_2) flux for plant habitats at the Spruce site in 2005 (day 161 to 266) and in 2006 (day 144 to 236).

Period	**Habitat Type**	**CH_4-C (mg C m^{-2})**	**N_2O-N (mg N m^{-2})**	**CO_2-C (mg C m^{-2})**
2005:	Upper Lichen	-20.0 ± 10.7 b	-1.7 ± 0.9 b	43107.7 ± 3809.0 b
105 days	Moss (*Sphagnum*)	8.8 ± 6.4 ba	1.5 ± 0.8 ba	46948.3 ± 6678.8 b
	Moss (*Hylocomium*)	3.4 ± 4.3 ba	2.7 ± 0.8 a	86731.4 ± 15070.1 ba
	Sedge-Moat	715.0 ± 398.0 a	1.9 ± 0.8 a	104530.3 ± 398.0 a
2006:	Upper Lichen	-6.7 ± 2.8 b	0.2 ± 0.6 a	28825.1 ± 2890.5 b
92 days	Moss (*Sphagnum*)	1.7 ± 2.5 b	0.5 ± 0.2 a	46850.6 ± 7431.5 b
	Moss (*Hylocomium*)	27.7 ± 16.8 b	0.9 ± 0.7 a	55310.1 ± 7568.8 b
	Sedge-Moat	2322.7 ± 1022.0 a	0.3 ± 0.7 a	108979.5 ± 15809.3 a

Values shown are the mean of 8 replicate sample positions except for the Sedge-Moat values for 2006 which are mean of 12 replicates and ± 1 standard error of the mean. Mean values followed by the same letter (within column and year) are not significantly different using Scheffe's test ($P<0.05$). Note: CH_4 flux data for 2005 and 2006 data was not normal.

Table A.5. Cumulative CH_4, N_2O and respiration (CO_2) flux for plant habitats at the Fen site in 2006 (day 146 to 237).

Period	Habitat Type	CH_4-C (mg C m^{-2})	N_2O-N (mg N m^{-2})	CO_2-C (mg C m^{-2})
2006:	Hummock	1679.0 ± 1497.2 b	3.7 ± 0.2 a	67125.1 ± 3220.3 a
91 days	Pool	7388.8 ± 3164.4 b	2.4 ± 1.0 a	6452.1 ± 296.3 b
	Sedge-Lawn	40706.6 ± 2351.7 a	2.0 ± 2.1 a	65999.9 ± 13180.8 a

Values shown are the mean of 3 replicate sample positions and ± 1 standard error of the mean. Mean values followed by the same letter (within column) are not significantly different using Scheffe's test ($P<0.05$).

Table A.6. Cumulative CH_4, N_2O and respiration (CO_2) flux for study sections at the peat plateau site in 2005 (day 161 to 265) and 2006 (day 150 to 235).

Period	Section	CH_4-C (mg C m^{-2})	N_2O-N (mg N m^{-2})	CO_2-C (mg C m^{-2})
2005:	1	-9.9 ± 9.2 a	1.1 ± 0.3 a	22399.3 ± 3792.0 b
104 days	2	-7.9 ± 4.9 a	1.0 ± 0.3 a	31606.6 ± 2179.1 ba
	3	-3.9 ± 2.5 a	-0.5 ± 0.6 a	28340.8 ± 1589.32 ba
	4	3.2 ± 2.8 a	0.3 ± 0.3 a	38439.8 ± 2576.6 a
2006:	1	-6.3 ± 5.9 a	2.4 ± 0.7 a	15253.9 ± 2260.7 b
85 days	2	10.8 ± 4.1 a	2.0 ± 0.8 a	19688.5 ± 1189.8 ba
	3	9.8 ± 4.4 a	1.0 ± 0.7 a	21394.3 ± 1836.1 ba
	4	-4.7 ± 3.4 a	-0.4 ± 0.6 a	29207.7 ± 2520.7 a

Values shown are the mean of 8 replicate sample positions and ± 1 standard error of the mean. Mean values followed by the same letter (within column and year) are not significantly different using Scheffe's test ($P<0.05$). Note: CH_4 flux data for 2005 data was not normal.

6.3. Transect Data Set for the Peat Site

Table A.7. Entire 92 chamber transect plant habitat data for daily greenhouse gas emissions and environmental parameters in 2005.

Day of the Year	Habitat Type	CH_4 Flux (ng C m^{-2} s^{-1})	N_2O Flux (ng N m^{-2} s^{-1})	CO_2 Flux (ng C m^{-2} s^{-1})	Temperature at 2.5 cm (°C)	VMC (%)	Active Layer Depth (cm)
168	Upper Sedge	3.3 ± 2.2	0.0242 ± 0.1188	2755.8 ± 689.0	13.1 ± 1.0	65 ± 3	17 ± 1
	Polygon Top	0.2 ± 1.1	0.0009 ± 0.1237	1550.0 ± 380.6	13.5 ± 0.8	33 ± 2	11 ± 1
	Ice Wedge	0.2 ± 0.4	-0.1371 ± 0.2495	4283.4 ± 1571.9	14.6 ± 1.2	43 ± 5	13 ± 2
	Moss (*Dicranum*)	-0.4 ± 0.4	-0.2546 ± 0.1861	4028.0 ± 897.5	18.2 ± 1.1	35 ± 3	16 ± 1
	Lower Sedge	-0.4 ± 0.8	-0.2819 ± 0.2529	3849.6 ± 904.5	14.3 ± 0.9	60 ± 5	15 ± 2
	Riparian	10.9	-0.5240	2882.1	14.7	91	20
197	Upper Sedge	6.5 ± 2.0	1.2798 ± 0.5802	2347.1 ± 400.0	8.6 ± 0.3	73 ± 4	28 ± 1
	Polygon Top	-2.3 ± 2.8	0.3720 ± 0.1780	2402.1 ± 270.5	9.6 ± 0.2	41 ± 2	25 ± 1
	Ice Wedge	1.6 ± 4.5	0.5067 ± 0.3339	2310.6 ± 622.5	9.0 ± 0.3	57 ± 6	25 ± 2
	Moss (*Dicranum*)	-4.4 ± 3.3	-0.2483 ± 0.2910	1654.6 ± 496.1	10.3± 0.3	39 ± 4	30 ± 1
	Lower Sedge	-2.7 ± 3.3	0.1712 ± 0.3254	3237.0 ± 713.6	9.4 ± 0.3	74 ± 4	27 ± 2
	Riparian	24.2 ± 25.8	-0.4500 ± 0.2170	5641.6 ± 1530.6	11.8 ± 0.6	83 ± 5	45 ± 3
	Pond Edge	1782.0 ± 1769.2	-0.3852 ± 0.7950	3476.2 ± 3274.4	12.1 ± 0.0	96 ± 0	45 ± 2
217	Upper Sedge	6.6 ± 4.5	2.3841 ± 0.3874	2214.4 ± 294.8	9.3 ± 0.5	76 ± 4	33 ± 1
	Polygon Top	-2.3 ± 1.1	1.2403 ± 0.1784	2076.6 ± 199.2	10.0 ± 0.2	38 ± 2	30 ± 1
	Ice Wedge	3.0 ± 2.1	1.0675 ± 0.4981	4151.7 ± 1001.4	10.1 ± 0.5	62 ± 6	30 ± 2
	Moss (*Dicranum*)	0.1 ± 0.9	0.7730 ± 0.1948	3248.2 ± 741.8	11.8 ± 0.7	47 ± 4	37 ± 2
	Lower Sedge	1.3± 0.6	0.9934 ± 0.1645	4657.4 ± 827.3	11.2 ± 0.7	71 ± 4	33 ± 2
	Riparian	137.5 ± 78.8	0.5056 ± 0.3182	8122.1 ± 1359.3	13.1 ± 2.5	90 ± 5	45 ± 5
	Pond Edge	160.6 ± 147.9	1.7570 ± 0.9117	928.2 ± 330.4	15.5 ± 0.0	96 ± 0	44 ± 3

Values shown are the mean of 9 replicate sampling positions for Upper Sedge, 31 replicate sampling positions for Polygon Top, 14 replicate sampling positions for Ice Wedge, 11 replicate sampling positions for Moss (*Dicranum*), 20 replicate sampling positions for Lower Sedge, 4 replicate sampling positions for Riparian except for day 168 where n=1 and 3 replicate sampling positions for Pond Edge and ± 1 standard error of the mean. Note: VMC = soil volumetric moisture content.

Table A.8. Entire 92 chamber transect plant habitat data for daily greenhouse gas emissions and environmental parameters in 2006.

Day of the Year	Habitat Type	CH_4 Flux (ng C m^{-2} s^{-1})	N_2O Flux (ng N m^{-2} s^{-1})	CO_2 Flux (ng C m^{-2} s^{-1})	Temperature at 2.5 cm (°C)	VMC (%)	Active Layer Depth (cm)
163	Upper Sedge	3.9 ± 0.9	-0.23 ± 0.11	5330.4 ± 932.5	6.3 ± 0.6	90 ± 4	17 ± 1
	Polygon Top	-2.9 ± 0.9	0.18 ± 0.16	1740.4 ± 204.1	6.9 ± 0.4	41 ± 3	12 ± 1
	Ice Wedge	-1.9 ± 0.9	-0.45 ± 0.12	4218.9 ± 904.0	6.6 ± 0.6	71 ± 8	15 ± 1
	Moss (*Dicranum*)	-1.1 ± 0.4	0.22 ± 0.20	4195.2 ± 1275.4	10.8 ± 0.9	62 ± 6	22 ± 2
	Lower Sedge	-0.9 ± 0.5	0.28 ± 0.22	5941.0 ± 1315.1	9.6 ± 0.8	76 ± 6	18 ± 3
	Riparian	37.2 ± 18.2	0.18 ± 0.15	6451.7 ± 445.3	9.7 ± 1.3	-	28 ± 3
	Pond Edge	34.3 ± 11.2	0.68 ± 0.48	93.3 ± 65.7	13.8 ± 0.2	-	28 ± 2
198	Upper Sedge	2.0 ± 1.7	0.76 ± 0.22	8204.9 ± 865.8	11.0 ± 0.7	92 ± 2	37 ± 2
	Polygon Top	-3.9 ± 0.9	0.34 ± 0.11	4373.3 ± 426.2	12.3 ± 0.5	45 ± 4	29 ± 1
	Ice Wedge	-1.4 ± 0.4	0.31 ± 0.12	8530.9 ± 1641.8	12.5 ± 0.7	75 ± 7	32 ± 2
	Moss (*Dicranum*)	-0.3 ± 0.4	0.08 ± 0.14	7126.0 ± 1368.4	17.5 ± 0.8	58 ± 7	41 ± 2
	Lower Sedge	1.8 ± 0.7	0.22 ± 0.12	7091.0 ± 1519.7	14.1 ± 0.9	81 ± 5	47 ± 3
	Riparian	33.4 ± 23.6	0.24 ± 0.15	3295.5 ± 1661.9	19.8 ± 0.5	-	55 ± 5
	Pond Edge	636.5 ± 521.0	0.57 ± 0.13	1684.5 ± 1319.5	18.7 ± 0.1	-	57 ± 4
226	Upper Sedge	2.1 ± 2.2	0.14 ± 0.13	2928.5 ± 605.7	10.4 ± 0.3	94 ± 2	52 ± 3
	Polygon Top	-2.1 ± 1.2	0.15 ± 0.07	3328.5 ± 450.5	11.2 ± 0.2	45 ± 4	41 ± 1
	Ice Wedge	18.6 ± 7.4	0.08 ± 0.19	4665.1 ± 851.2	11.4 ± 0.5	78 ± 7	41 ± 2
	Moss (*Dicranum*)	7.7 ± 4.0	-0.16 ± 0.14	3852.9 ± 1318.3	12.7 ± 0.3	56 ± 7	53 ± 3
	Lower Sedge	1.6 ± 2.1	-0.22 ± 0.19	3462.6 ± 691.3	11.5 ± 0.4	82 ± 6	70 ± 4
	Riparian	156.0 ± 79.4	-0.69 ± 0.39	7296.0 ± 4011.4	13.3 ± 0.6	-	87 ± 3
	Pond Edge	10621.9 ± 6785.3	-0.09 ± 0.28	1044.4 ± 268.7	12.7 ± 1.3E-15	-	87 ± 3

Values shown are the mean of 9 replicate sampling positions for Upper Sedge, 31 replicate sampling positions for Polygon Top, 14 replicate sampling positions for Ice Wedge, 11 replicate sampling positions for Moss (*Dicranum*), 20 replicate sampling positions for Lower Sedge, 4 replicate sampling positions for Riparian and 3 replicate sampling positions for Pond Edge and ± 1 standard error of the mean. Note: VMC = soil volumetric moisture content and no VMC data for Riparian and Pond Edge habitats due to standing water. Dash indicates analysis not available.