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# Subarctic Peatlands in a Changing Climate:

## *Greenhouse gas response to experimentally increased snow cover*

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# SUBARCTIC PEATLANDS IN A CHANGING CLIMATE:
## GREENHOUSE GAS RESPONSE TO EXPERIMENTALLY INCREASED SNOW COVER

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Master's Degree thesis in
Physical Geography and Ecosystem Analysis

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Cover photo:
Storflaket, April 14th 2007

# ABSTRACT

The rate of change of our climate has been amplified since the industrial revolution and is expected to change even further by the end of this century. Global temperature and precipitation are expected to increase considerably over the next century. These increases are expected to be magnified in the Arctic regions. In a high latitude peatland like Storflaket, near Abisko (Northern Sweden), at the fringe of the 0°C isotherm, the environment is quite sensitive to changes in climate. Precipitation here is mainly in the form of snow. Increases in snow cover will most likely affect permafrost and active layer thickness (the layer on top of permafrost that thaws and refreezes annually), since snow insulates the ground from the low winter temperatures, resulting in relatively warm ground temperatures.

With the vast stocks of carbon stored as peat in frozen mires, the thawing of this landscape will possibly make it available for decomposition and subsequent emissions as Greenhouse gases. A snow manipulation experiment that simulates future scenarios of increased winter precipitation initiated in 2005 was further investigated to understand the impacts of increased snow cover on the active layer thickness and the implications of this on carbon dioxide and methane emissions. A 1m high snow fence has been installed on Storflaket perpendicular to the prevailing wind direction every winter since 2005. The snow fences result in about doubled the snow depth on treatment plots compared to control plots.

Active layer thickness has increased significantly on treatment plots after the doubling of snow cover, which has in turn increased the emission of $CO_2$ from treated plots through ecosystem respiration. Also, there has been more carbon uptake on the treatment plots than on the control plots. Thus, the cycling of carbon has simply been enhanced. Significant differences were recorded between control and treatment plots in terms of the $CO_2$ exchange, soil moisture content and the reflected PAR. Surprisingly, $CH_4$ emission was almost inexistent for both sites. This means that Storflaket continues to be a very lucrative carbon sink. This thesis presents these results in detail and discusses the possible reasons for the findings.

# SAMMANFATTNING

Klimatförändringar har amplifierats sedan den industriella revolutionen och modeller pekar på att förändringen kommer forsätta att öka åtminstone till slutet av detta århundrande. Globala temperaturer och nederbörd förväntas öka avsevärt under detta århundrade. Dessa ökningar förväntas bli särskilt markanta i de arktiska områdena. Torvmyrar belägna på höga latituder vid 0°C isothermen, såsom Storflaket nära Abisko, är särskilt känsliga för klimatförändringar. Nederbörden faller huvudsakligen som snö i de här områdena. En ökad snömängd kommer troligtvis påverka permafrost och det aktiva lagret (lagret ovan permafrosten som tinar och fryser årligen), eftersom snö isolerar marken från låga lufttemperaturer och resulterar i relativt varma marktemperaturer.

När landskap som detta börjar tina kommer stora lager av kol som varit lagrat i torven vara tillgängligt för nedbrytning vilket leder till utsläpp av växthusgaser. Ett snömanipulations-experiment som simulerar framtida klimatscenarier med ökad vinternederbörd som initierades 2005, undersöktes ytterligare för att förstå påverkan av ett ökat snödjup på aktiva lagret och dess implikation på koldioxid och metanutsläpp. Ett 1 m högt snöstaket har installerats årligen på Storflaket sedan 2005, vinkelrätt mot den rådande vindriktningen. Snöstaken har resultatet i dubbelt så mycket snö på behandlade ytor jämfört med kontrollytorna.

Aktiva lagret har ökat signifikant på behandlade ytor när snömängden fördubblats, vilket i sin tur har ökat utsläppen av koldioxid genom ökad ekosystem-respiration. Mer kol har tagits upp av marken i behandlade ytor jämfört med kontrollytorna. Således har kolets kretslopp ökat. Signifikanta skillnader uppmättes mellan kontroll och behandlade ytor för koldioxutsläpp, markfuktighet, och reflekterad PAR (Photosynthetically Active Radiation). Förvånansvärt nog var metanutsläppen nästan obefintliga från både behandlade och kontrollytorna. Detta betyder att Storflaket fortsätter att vara en lukrativ kolsänka. Den här uppsatsen presenterar dessa resultat och diskuterar tänkbara anledningar till de uppmätta resultaten.

# TABLE OF CONTENTS

# 1 INTRODUCTION

Global climate models (GCMs) predict increases in mean annual temperature and precipitation in most parts of the globe. In the Arctic region, the expected increases in these parameters are far larger than the global averages. Observations over the past century show temperature increases in the Arctic, twice as high as the global average (IPCC, 2007[1]). Sælthun and Barkved (2003) predict an increase in precipitation between 18 to 27% by 2080 in northern Europe while Christensen et al (2007) project increases in winter precipitation to range between 13 and 36% in the Arctic. In the Abisko area of northernmost Sweden, winter snow depth has shown an increasing trend in the last century of 2-3cm per decade (Kohler et al, 2006). Snow depth is the largest single factor accounting for variations in ground surface temperature during winter (Desrochers and Granberg, 1988). It acts as an insulator and prevents the release of soil heat to the atmosphere. As such, it reduces temperature variability during winter. When snow melts, it most likely increases water content of the soil, thereby increasing the thermal conductivity which is of utmost importance in permafrost landscapes. Thus, it provides water and nutrient for vegetation while inserting significant controls over Carbon dioxide ($CO_2$) and Methane ($CH_4$) fluxes (Johansson et al, submitted). This makes snow cover a key element of the climate system, as such; changes in its depth and duration may initiate a myriad of changes in the ecosystem.

Over the last millennia, peatlands have accumulated vast amounts of carbon in their soils, amounting to approximately 50% of the world's total soil carbon pool (Tarnocai et al, 2009). Concerns have therefore been raised by many authors about the stability and potential release of carbon as $CO_2$ and $CH_4$ into the atmosphere from such ecosystems due to expected changes in climate (Christensen et al, 1999; Jorgenson et al, 2001; Roulet et al, 2007; Åkerman and Johansson, 2008). High latitude peatlands occur within the sporadic (10-50% permafrost coverage) and discontinuous (50-90% permafrost coverage) permafrost zone (Matthews and Fung, 1987). In areas where peatlands and permafrost exist simultaneously, there exist very fragile ecosystems which are most sensitive to climatic changes (Johansson T et al, 2006). This mainly takes place in the subarctic tundra, as the permafrost are likely to first disappear from areas with a mean annual temperature around 0°C (Kneisel, 2010). It is already evident from a cross section of studies that permafrost has started to degrade at northern high latitudes and altitudes.

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[1] Intergovernmental Panel on Climate Change, Fourth Assessment Report (2007)

This is seen with a shift in the southern border of discontinuous permafrost northwards and uphill in Fennoscandia (Sollid and Sørbel, 1998; Christensen et al, 2004; Luoto et al, 2004).

The repercussion of an increased winter precipitation will be increased permafrost thawing, which inevitably leads to an increased active layer thickness. This in turn might initiate changes in vegetation cover, topography and hydrology (Johansson T et al, 2006). Several subarctic mires have been observed to become wetter with corresponding changes in vegetation and carbon flux (Jorgenson et al, 2001; Christensen et al, 2004). Other studies have shown that vegetation changes from 1970 to 2000 have not only changed the micro topography and hydrology, but also increased the landscape $CH_4$ emissions by 22% to 66% (Johansson T et al, 2006). Another study concluded that changes in vegetation composition will further increase emissions of $CH_4$ as the species that are expanding also stimulate the production and transport of $CH_4$ to the atmosphere (Ström and Christensen, 2007). The implications of an increased active layer thickness could therefore range from biogeochemical cycling, biological, geomorphological, hydrological and even on infrastructures which depend on permafrost for foundation and on economies of northern Europe. The active layer plays an important role in cold regions since most ecological, hydrological and biogeochemical activities take place there (Åkerman and Johansson, 2008; Johansson *et al.*, 2008).

# 2 OBJECTIVES AND HYPOTHESES

Permafrost is an integral part of a complex geo-ecological system with both positive and negative feedbacks on the biosphere. Many studies in mires of Northern Europe have looked at the effects of increases in mean air temperature on permafrost stability and active layer thickness e.g. in northern Sweden (Christensen et al, 2004, Johansson et al, 2008; Åkerman and Johansson, 2008), northern Finland (Luoto et al, 2004), southern Norway (Sollid and Sørbel, 1998) and even in boreal peatlands of North America (Camill, 2005). Yet, very few studies have looked at how much it is affected by increases in precipitation (e.g. Johansson et al, submitted). To my knowledge, no study has looked at how these changes in winter precipitation will affect greenhouse gas exchange in subarctic mires.

The main objective of this study is to investigate how predicted increases in winter precipitation would affect a fragile ecosystem like the Storflaket mire in the Abisko area of northernmost Sweden; with principal focus on the direct and indirect effects these changes would have on greenhouse gas exchange.

The main hypotheses were:

- Future increase in winter precipitation will contribute to thicker active layers, thereby indirectly enhancing the emission, exchange and storage of carbon on subarctic mires with discontinuous and sporadic permafrost.

- Increased snow will lead to wetter soil conditions during summer with corresponding increases in methane emission.

To test these hypotheses, measurements of relevant parameters have been carried out, analyzed and tested for statistical significance. From the results, appropriate preliminary conclusions have been drawn.

# 3 BACKGROUND

## 3.1 THE GREENHOUSE EFFECT AND CLIMATE CHANGE

In 1824, French natural philosopher, Joseph Fourier, came up with the idea that the Earth's climate is driven mainly by the delicate balance between the incoming solar radiation and the outgoing thermal radiation (Bolin, 2008).On the whole, about 342Wm$^{-2}$ is received at the top of the atmosphere. Of these, over a third is reflected back into space by the atmosphere. The remainder two-thirds is absorbed by the Earth's surface and the atmosphere and emitted back into space more slowly as long wave radiation. Most of this thermal radiation is absorbed by the atmosphere and emitted in all directions (figure 3.1). This process is enabled by the presence of greenhouse gases in the atmosphere. This is known as the "natural greenhouse effect" and is the major reason for the Earth's current average temperature of 14°C (NOAA[2], 2010) instead of the -15°C it would be without greenhouse gases. This comfortable temperature is the main reason for the existence of life (Ruddiman, 2008). The atmospheric content is a main determinant of the efficacy with which the atmosphere absorbs, traps and re-emit radiation in all directions. Increased carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$) concentrations in the atmosphere help amplify this process (enhanced greenhouse effect).

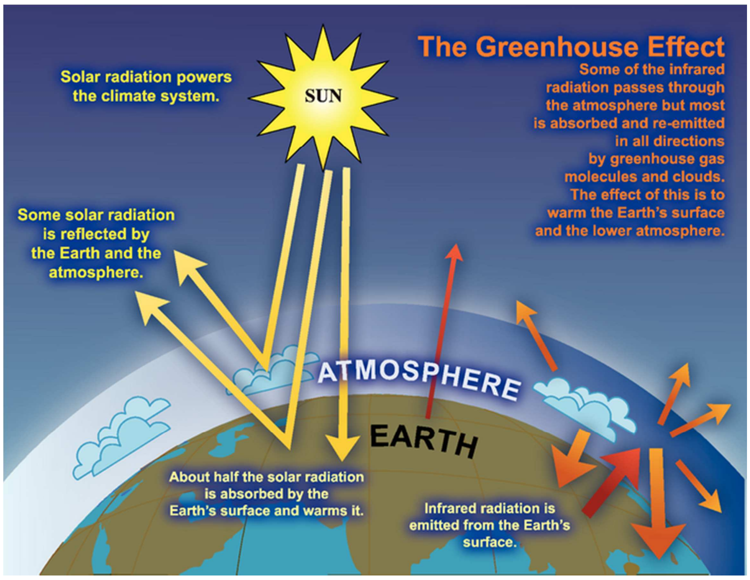

***Fig 3.1: An idealized model of the natural greenhouse effect.*** *(IPCC - AR4, 2007)*

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[2] NOAA: National Oceanic and Atmospheric Administration

Variations in the factors influencing incoming and outgoing radiation would ultimately affect the net radiation balance and thereby lead to either a warming or cooling of the globe. The causes of such variations could either be human induced or natural. Prominent anthropogenic factors include increased fossil fuel combustion and land use changes with accompanying $CO_2$ emission as well as $CH_4$ and $N_2O$ emissions associated with industrial and agricultural developments. Natural causes could be alterations in solar input due to orbital changes in the Earth's revolution around the sun and variations brought about by increasing aerosol in the atmosphere from volcanic eruptions.

Due to feedback mechanisms, the response of the Earth's climate system to the enhanced greenhouse effect is quite complex and nonlinear. A feedback refers to a change in one aspect of the environment whose response would either further amplify (positive) or minimize (negative) the initial effect. A good example of a positive feedback is seen in increased $CO_2$ concentration in the atmosphere which leads to a warming of the globe, thus, increasing decomposition and microbial respiration, which would then increase the concentration of $CO_2$ in the atmosphere.

Observations of past and recent climate show annual increases in mean air temperature of 0.4 to 0.8°C over the last century. The 2000-2009 decade is the warmest decade on record since 1880 with mean air temperature anomaly of 0.54°C over the 20th century mean (NOAA, 2010). This trend is expected to continue as predicted increases in temperature are of 1.8 to 4°C by the end of the century and it is expected to be greatest over the northern latitudes than anywhere else on the globe. Precipitation is also expected to increase in most northern latitude regions with this temperature trend as evapotranspiration will be enhanced and the capacity for the atmosphere to hold more water will be increased (Bridgham et al, 1999; IPCC, 2007).

## 3.2 GREENHOUSE GASES

Population growth and corresponding increases in greenhouse gas emissions has increased the concentration of these gases in the atmosphere. Global greenhouse gas emissions have increased by 70% between 1970 and 2004 (IPCC, 2007). This has led to a positive radiative forcing, warming the globe. Further temperature increases would most likely increase emission especially from natural sources, thereby increasing the global mean temperature further. For the purpose of this study, we will focus on 2 main greenhouse gases ($CO_2$ and $CH_4$) as their fluctuations affect and are affected by wetland conditions.

## 3.2.1 Carbon dioxide

Global atmospheric $CO_2$ concentration has increased by approximately 39% from a pre-industrial value of about 280ppm to 387ppm in 2008. The annual $CO_2$ concentration growth rate was larger during the last decade (2000-2009 average: 1.9ppm per year) than it has been since the beginning of continuous direct atmospheric measurements (1960-2005 average: 1.4ppm per year), although there is year-to-year variability in growth rates. The main source of $CO_2$ has been from fossil fuel emission and cement production. In 2009, estimated $CO_2$ emission was about 8.4±0.5PgC which is about 37% higher than the 1990 levels (figure 3.2). This is the second highest in human history (highest being 41% in 2008). The mean growth rate of $CO_2$ emissions was 3.2% per year from 2000-2008(GCP[3], 2009).

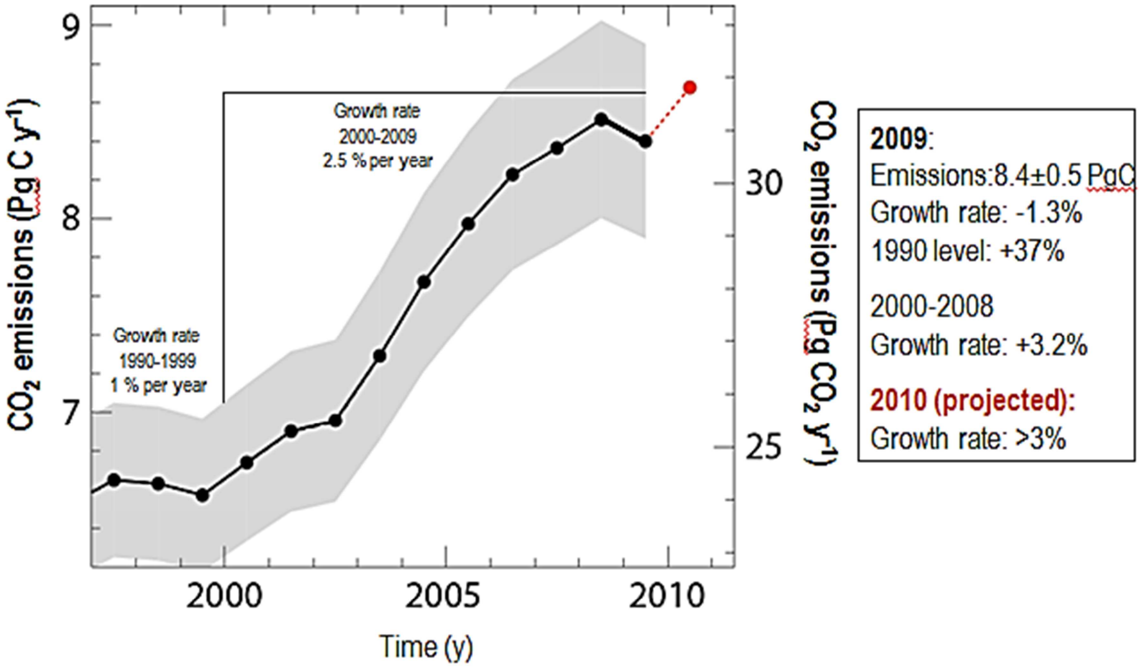

***Fig 3.2: Global $CO_2$ emission in the last 2 decades*** *(Global Carbon Project, 2009).*

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[3] GCP: Global Carbon Project

### 3.2.2 Methane

The global atmospheric concentration of $CH_4$ has increased from about 715ppb in pre-industrial times to 1732ppb in the early 1990s, and was 1774ppb in 2005. Growth rates have declined since the early 1990s, consistent with total emissions (sum of anthropogenic and natural sources) being nearly constant during this period (IPCC 2007). Just like $CO_2$, global atmospheric concentrations of $CH_4$ have increased exponentially since the beginning of the industrial revolution. Even though its current atmospheric concentration of 1.8ppmv is a lot smaller than that of $CO_2$, its global warming potential is about 23 times higher than that of $CO_2$ on a 100 year time horizon (IPCC, 2007). Methane is produced only under anaerobic conditions, thus wetlands account for over 70% of the naturally produced methane. Other natural sources include fresh water sediments, fermentation in the guts of termites and ruminants while fossil fuel extractions, waste management, agriculture (rice paddies, biomass burning and cattle rearing) are important anthropogenic sources. The major sink of $CH_4$ in the atmosphere is in its photochemical reaction with the OH radical in the presence of sunlight, which accounts for over 85% of atmospheric $CH_4$ consumption ($CH_4 + OH^- \rightarrow CH_3 + H_2O$). Other losses occur in its reaction with ozone in the stratosphere and its removal by methanotrophs in soils. This leaves about 10% annual accumulation of $CH_4$ from total anthropogenic flux (Chapin et al, 2002).

Apart from anaerobic soil conditions, other factors have been cited to significantly correlate with $CH_4$ emission. These include air and soil temperature, water table height and supply of organic material. Through permafrost degradation and subsequent increases in active layer thickness, factors such as vegetation composition, density and distribution have been shown to indirectly affect methane emission rates (Johansson et al, submitted).

## 3.3 PERMAFROST DYNAMICS ON A PEAT PLATEAU

Palsas are peat hummocks with permanently frozen peat and mineral soil core that rise to a height of 0.5–10 m above the water-saturated mire surface. Sometimes, they extend laterally from a few hundred meters to several kilometers. This is then referred to as a peat plateau (Luoto et al, 2004). It is estimated that about 1672 Pg of carbon are stored in northern peatlands as soil organic matter (Tarnocai et al, 2009). In a warming world with higher temperature increases in northern high latitudes, it is expected that there will be widespread degradation of permafrost and increases in active layer thickness, most especially in zones with discontinuous and sporadic permafrost (Anisimov, 2007). This could lead to the release of the vast amount of carbon stored in the permafrost and making them available for decomposition. As a consequence, additional greenhouse gases can be released into the atmosphere, thereby amplifying the changes in climate. Largest changes are expected in ecosystems located around the 0°C isotherm (Åkerman and Johansson, 2008). Peatlands exist around this temperature threshold, thus; they are expected to be extremely sensitive to changes in future climatic conditions (Smith and Riseborough, 1983). This makes them good indicators of past and current climatic trends (Parvainen and Luoto, 2007)

Significant changes in permafrost have already been recorded in mires across the world. Of particular interest is the rate at which permafrost disappears in some areas. For example, Åkerman and Johansson (2008) recorded an 81% decrease in permafrost in Katterjokk (northern Sweden) between 1996 and 2006. They also registered increases in average thaw depths on nine mires of 0.7 to 1.3 cm per year between 1978 and 2006. Johansson T. et al (2006) also observed the absence of permafrost under a considerable part of Stordalen in the year 2000 where it existed in the 1970s.

Factors determining the presence and absence of permafrost range from climatic factors (air temperature, precipitation and wind); to changes in surface and ground features. All these boil down to changing the soil temperature which determines permafrost presence and thaw depth. Figure 3.3 illustrates the land surface – atmosphere interactions which affect ground temperatures, active layer thickness and permafrost (after Johansson M. et al, 2006).

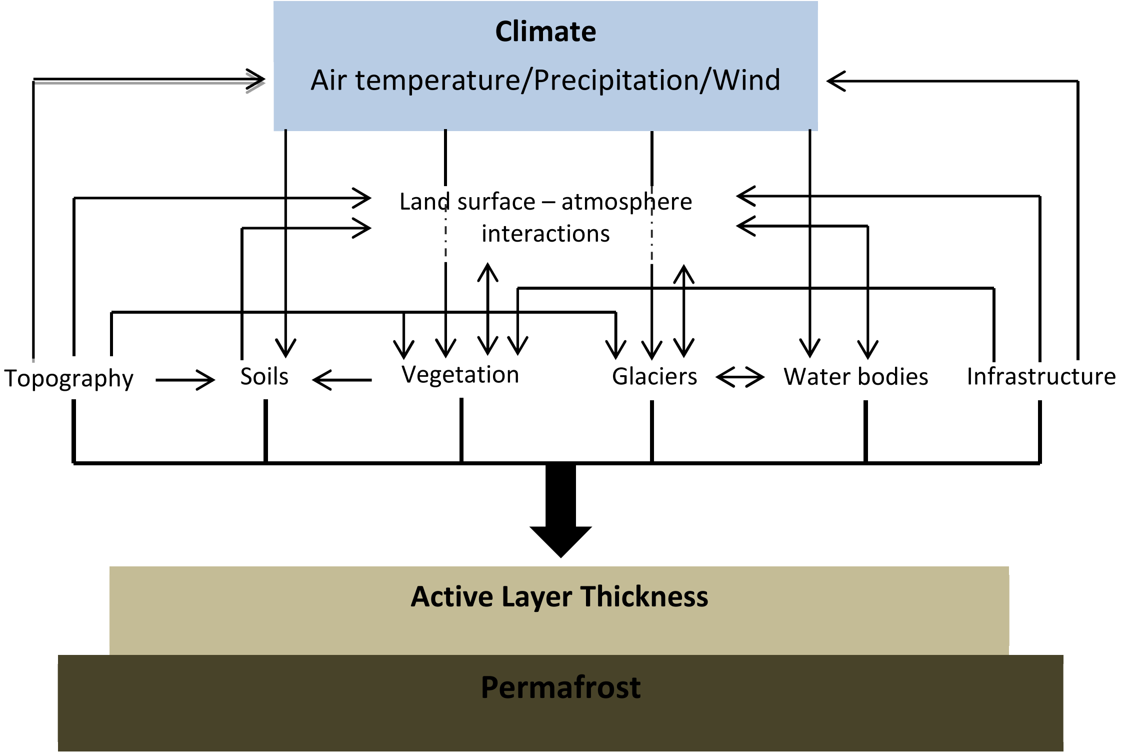


***Fig 3.3: Parameters affecting permafrost stability in subarctic mires*** *(Modified from Johansson M et al, 2006)*

The increased thawing of permafrost and subsequent increases in active layer thickness leads to the introduction of unique geomorphological features in the mire. The most common ones include taliks, thermokarst features and ponds. In favorable environmental conditions, palsa formation and degradation is a natural cyclic process on peat plateaus. Due to the fact that such mires exist at different stages in this process, they form a mosaic of micro-topography, thus offering habitat to a wide range of organisms and breeding spots for many bird species (Luoto et al, 2004). It is this balance between the degradation and formation of palsa that is encroached unto with increasing temperatures and precipitation, thus, changes in hydrology, surface features and vegetation.

## 3.4 BIOGEOCHEMISTRY OF NORTHERN PEATLANDS

Northern latitudes are strong natural sinks of carbon as they accumulate vast amounts of carbon in their forest biomass, peat deposits and wetlands. Peatlands are formed in regions where the net primary productivity exceeds rate of decomposition, thereby leading to a net storage of carbon as dead plant materials. This is enabled by the slow decomposition rates associated with low soil and air temperatures. Due to these low temperatures, precipitation input usually exceeds evapotranspiration, thereby creating anoxic waterlogged conditions, thus, further inhibiting decomposition. This enables peatlands to store carbon for thousands of years. The fixing of atmospheric $CO_2$ by mire plant biomass through photosynthesis is the main source of carbon greenhouse gases ($CO_2$ and $CH_4$) emitted by peatlands. Thus, peatlands are generally net $CO_2$ sinks where prevailing waterlogged, anoxic and cool conditions reduce decomposition rate and enhance accumulation and formation of peat. Yet, these anoxic conditions also favour anaerobic decomposition, thus making wetlands significant methane sources (Ström and Christensen, 2007). Currently, much research is focused on the role of peatlands as potentially large sources and sinks of carbon dioxide and methane (Christensen et al, 2004; Johansson M et al, 2006)

### 3.4.1 Carbon dioxide flux from wetlands

Photosynthesis is the process by which plants fix carbon from the atmosphere for their growth and maintenance. Photosynthesis is therefore the uptake of $CO_2$ by plants by capturing light energy that splits water molecules to produce high energy molecules and energy, after which the reduction of $CO_2$ into carbohydrates occurs (see equation 1).

$$CO_2 + \text{light energy} + H_2O \rightarrow CH_2O + O_2 \qquad (1)$$

Part of the carbon taken up by plants is returned to the atmosphere as $CO_2$ during maintenance and growth respiration of above and below ground biomass of the plants and their heterotrophic microbial communities. The rest is transformed into plant structures and subsequently deposited as peat. In anoxic layers, this is the carbon that is available for methanogenic bacteria, which produces $CH_4$ as end product. While diffusing upwards, this $CH_4$ is then oxidized by methanotrophic bacteria back into $CO_2$ in upper aerobic peat layers (Sundh et al, 1994).

Net primary productivity (NPP) which is the result of gross carbon uptake minus release by plants (autotrophic respiration) explains to a large extent the sink function of $CO_2$ in peatlands since photosynthesis (GPP) usually exceeds plant respiration ($R_{plant}$). Thus, $NPP = GPP - R_{plant}$ is negative. In order to incorporate a better proportion of the ecosystem scale carbon uptake function, it is better to make use of the net ecosystem exchange (NEE) which is the difference between carbon uptake by plants and the total ecosystem carbon loss through plant and soil respiration ($R_{eco}$). Thus, $NEE = GPP - R_{eco}$.

Another factor of relevance to the sink function of carbon in subarctic mires would be the export of particulate and dissolved organic carbon to nearby ecosystems which this study does not take into consideration.

### 3.4.2 Methane flux from wetlands

It is expected that with a degradation of permafrost beneath subarctic mires, there will be a lot more water available in some areas, which would most likely cause the production of $CH_4$. Yet, methane emission rates depend on more than prevailing anaerobic conditions even though they are a precursor to its production. Methane flux from wetlands is a direct function of its production and oxidation in the soil profile and the transport mechanisms in play. Microbial methane production (or methanogenesis) is a prominent process during the anaerobic decomposition of organic matter. Methanogenesis is solely driven by a small group of strictly anaerobic organisms called methanogenic *archaea*, which belong to the kingdom *Euryarchaeota* (Garcia et al. 2000; in Wagner, 2008).The biological oxidation of methane by methane - oxidizing (or methanotrophic) bacteria, which represent very specialized Proteobacteria, is the only sink for methane in permafrost habitats (Trotsenko and Khmelenina 2005 in Wagner, 2008). The balance between the methanogenesis and methanotrophy could explain how much methane is available to be emitted.

Figure 3.4 illustrates the transport mechanism for $CH_4$ in a wetland. Ebullition is the process by which $CH_4$ is emitted from waterlogged environments as bubbles. During diffusion, methane travels through a pressure gradient from the soil to the atmosphere. $CH_4$ emission is often limited by the presence of methanotrophic bacteria which oxidizes $CH_4$ into $CO_2$. The present plant community is also important as vascular plants have been known to not only aid in the transport of methane to the atmosphere but also in the downwards transportation of $CO_2$ from the atmosphere to the soil thereby increasing oxidation rate. Root exudates also serve as substrates which assist in making the carbon available to methanogenic bacteria.

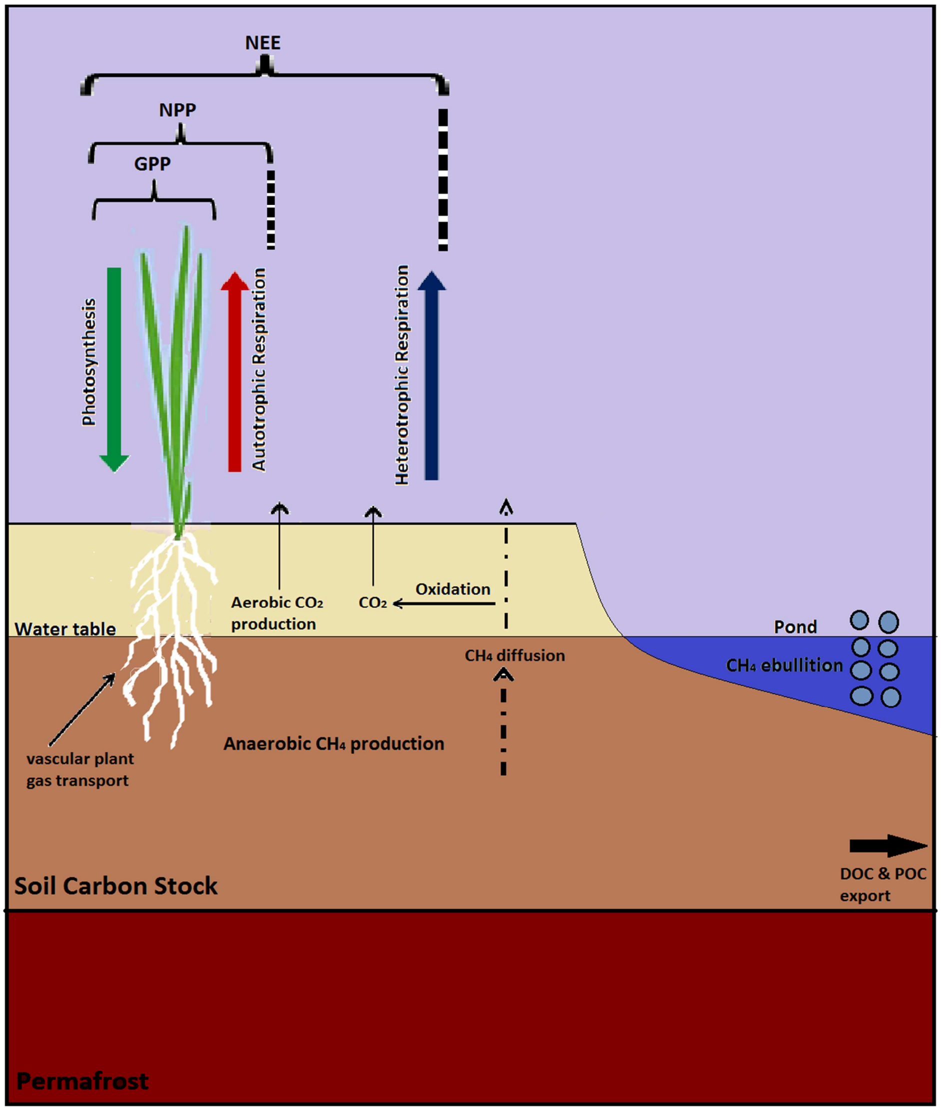


***Fig 3.4: Methanogenesis, Methanotrophy and Methane pathways on subarctic mires.*** *This also shows the general elements of carbon cycling i.e. GPP, NPP, NEE and respiration. (Modified from Christensen et al, 2008)*

# 4 MATERIALS AND METHODS

## 4.1 STUDY SITE

Abisko is located in northern Swedish Lapland (68°19′N, 18°41′E), approximately 250 km north of the Arctic Circle. At the Abisko Scientific Research Station (385 m above sea level) the mean annual temperature is -0.6°C (1913-2006), with July being the warmest month (+11°C) and January being the coldest with -12°C (Johansson et al, 2008). Mean annual air temperatures in regions north of 65°N have increased by about 2 – 3°C since the 1950s, which is almost twice the rate of the rest of the world (Chapman and Walsh, 2003).

Abisko falls into the subarctic climate zone and has a mean annual precipitation from 1961 to 1990 of 304 mm. The mean annual precipitation has increased since then and was 362 mm for 1997-2007. This makes Abisko one of the driest places in Sweden. This low precipitation is a result of a rain shadow effect of the mountains towards the west. Winter snow depth has increased by 2 cm per decade since 1913 (Kohler et al, 2006). The growing season varies in length from less than 2 months at the highest altitudes to around 6 months at low altitudes. (Callaghan et al, 2010)

To simulate the effects of future possible climate scenario, an experiment was set up in a subarctic peat bog called Storflaket (68°20′48”N, 18°58′16”E). The area is located on the southern shore of Lake Torneträsk, 6 km east of Abisko Scientific Research Station (Johansson M et al., submitted). This palsa mire has a mean annual temperature and precipitation of −0.8°C and 304 mm respectively. The Abisko area falls within the sporadic permafrost zone. On high altitudes (above 880 m above sea level), permafrost is likely to exist everywhere, yet in lowlands, it only exists beneath peatlands and wind exposed ridges (Johansson M et al, 2006).

Storflaket mire falls within what is classified as “Ecosystem protected permafrost” which was formed during colder climates and continues to thrive as sporadic patches in a warmer world (protected by vegetation and peat). Such permafrost occurs in areas with mean annual temperature between +2 and -2°C (Shur and Jorgenson, 2007). The thickness of the permafrost here is about 14 m with a mean active layer about 60-70 cm thick (Åkerman and Johansson, 2008). This peat plateau is about 900 m long and 400 m wide, split into a western and eastern part by a depression with standing water. It is bordered to the east and west by a sparse subarctic birch forest (*Betula* *pubescens* spp. *czerepanovii);* to the south by the railroad and to the north by the main road in the area. Dominant vegetation types on drier parts are dwarf shrubs (e.g. *Empetrum nigrum, Andromeda polifolia* and *Betula nana*), mosses (e.g. *Dicranum scoparim, Sphagnum fuscum* and *Sphagnum balticum*) and lichens (e.g. *Cetraria cucullata, Cetraria nivalis* and *Cladonia* spp.) while the wetter parts are dominated by grasses (e.g. *Eriophorium vaginatum)* (Johansson et al, submitted)

## 4.2 SNOW MANIPULATION EXPERIMENTAL DESIGN

The snow manipulation experiment was set up in 2005 on the western part of the Storflaket peat plateau, with the establishment of 12 random plots (figure 4.1). Six of these were randomly chosen, on which every year, snow fences (10m long and 1m high) are installed before the onset of snow fall (mid October) and removed after the snow melt (early June). These snow fences are installed in a north - south direction, perpendicular to the prevailing wind (westerly and easterly wind). These plots are further on referred to as "treatment plots". The other six sites were simply demarcated and left untouched to serve as "control" or reference plots (Johansson et al, submitted). On the eastern part of the plateau, active layer thickness has been monitored since 1978 (Åkerman and Johansson, 2008). Plots 1, 5, C, C2 C3, and C5 are control plots while 2, 3, 4, 6, C4 and C6 are treatment plots.

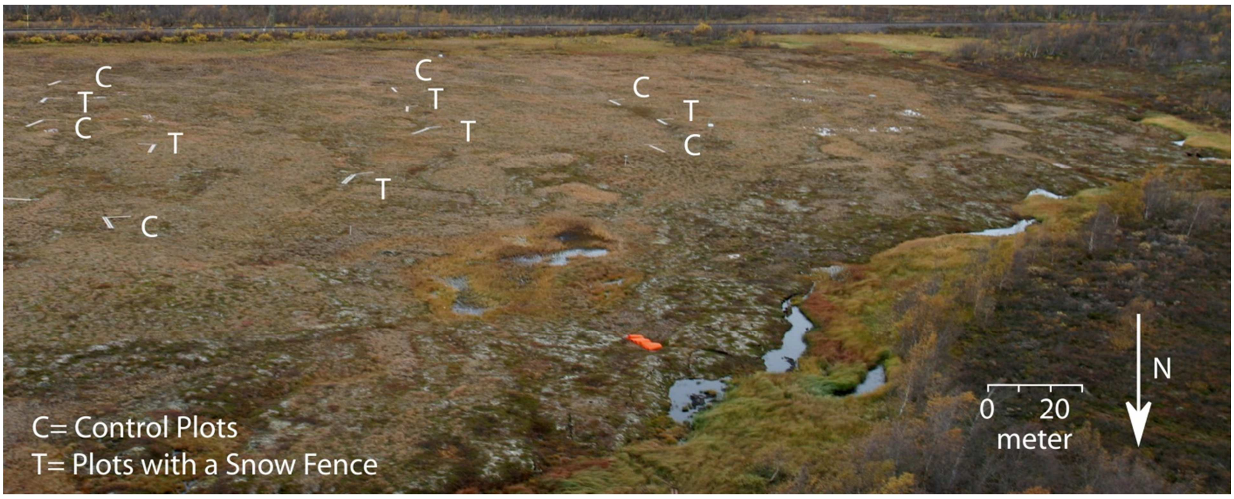


***Fig. 4.1: Control and Treatment plots on Storflaket mire.***

*Twelve plots were randomly chosen, six of which were left as control plots while the rest carried snow fences. (Photo by Jonas Åkerman in Johansson et al, submitted)*

## 4.2.1 Field work

Between July and September 2010, field measurement was carried out on several days on the Storflaket mire. Data used here was recorded four times in July, seven times in August and four times in September. Thus, measurements span from mid summer with relatively high air temperatures to early autumn with colder temperatures. All measurements were carried out between 9 a.m. and 4 p.m.

## 4.2.2 Variables measured on Storflaket

- *Snow cover depth*

Snow cover depth was measured in each of the 12 plots on Storflaket once a month from November 2009 to April 2010 (Johansson et al, submitted). This was averaged for the whole winter per plot to get the mean snow cover depth for each plot.

- *Active layer thickness*

Active layer thickness was measured once in September (when maximum thaw depth was expected). On each of the 12 plots, active layer thickness was measured using graded metal probes on 10 m by 10 m plots at every 1 m with 2.5 m apart transects (fig 4.2). Thus, a total of 55 measurements were taken on each plot and averaged to represent the active layer thickness for the plot.

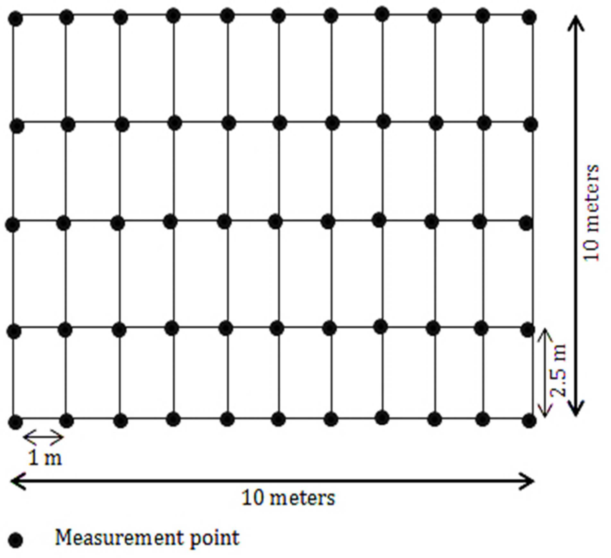


***Fig. 4.2: measurement points for active layer thickness***

- *Soil Temperature and Moisture*

These were measured manually using a soil thermometer and a soil moisture meter (theta kit) on three points on each plot at 5cm depth into the soil, every field day. Points were marked to ensure that measurements were repeated on the same spot each day. The mean of these three measurements represented the daily soil temperature and moisture on each plot. The driest point on each site was selected because $CO_2$ flux measurements were also carried out here, whose instruments are sensitive to moisture. The mean over the study period represented the soil temperatures and moisture for the plot for each field day during the summer of 2010.

- *Reflected Photosynthetically active radiation (PAR)*

An installation of 12 PAR sensors to measure reflected PAR was done on each plot on July 14th 2010 during the field exercise. These measure the reflected PAR from the surface, that is, all available PAR that is not absorbed by the surface vegetation during photosynthesis. To capture this, all sensors were installed facing the ground surface. Installation was set up on the middle of the plot at 50 cm above the ground. This was to ensure that PAR sensors on all sites had the same aerial coverage. The sensors used here was the EMS Brno's Minikin QT which automatically measures PAR and temperature once an hour and stores in its inbuilt data logger. Data was retrieved on September 22, 2010. Assuming that the incoming solar radiation is the same all over the site and the photosynthetic active radiation is a constant proportion of incoming radiation, the larger the value for reflected PAR, the less has been absorbed, indicating a scanty vegetation cover and vice versa.

### 4.2.3 Flux measurements

- *$CO_2$ Chamber measurements*

$CO_2$ fluxes were measured manually using a PP Systems' gas analyzer (EGM-4) attached to an airtight plexiglas chamber. The chamber was equipped with a fan for mixing of the air during measurements. Three measurements were conducted on each plot per day and the mean demonstrated the emissions and exchange of $CO_2$ for the whole plot. These measurements were carried out on 15 days between July and September. The average of this measurement period was used to correlate with other environmental variables. Net Ecosystem Exchange (NEE) was measured as the exchange of $CO_2$ between the soil and the atmosphere with a negative value illustrating uptake by the soil (sink) and a positive value for emissions from the soil (source). Uptake was mainly due to plant $CO_2$ sequestration. NEE was therefore measured in a transparent chamber so the effect of photosynthesis could be quantified. Ecosystem respiration referred to ecosystem emission of $CO_2$ (both autotrophic and heterotrophic respiration), which was measured in the dark by shading transparent chamber with a dark cloth. Photosynthesis (GPP) was calculated as the difference between NEE and ecosystem respiration. These measurements were taken on the driest part of each plot since wetness affects the gas analyzer and gives faulty values.

- *Grab sampling and GC analysis*

$CH_4$ emission was measured as a change in its concentration in steel chambers over time (5 minute intervals). This flux measurement was closed chamber technique at the wettest parts on each of the plots. The aim was to undertake a campaign in which we could get an image of the emission scenario of this very potent Greenhouse gas. Six samples were taken over 30 minutes into 10 ml syringes. Syringes were numbered so they could be identified according to which carried what sample. These were safely transported back to the GC lab at the Abisko Scientific Research Station, where analyses were done using a Shimadzu GC-14A gas chromatograph with a flame ionization detector. Using the ambient $CH_4$ concentration as standard gas, a conversion factor was calculated and used to convert the ionization detected into parts per million volume of $CH_4$. The 'slope' function in Microsoft Excel used to identify the rate of change in $CH_4$ concentration per square meter and time, which was inserted into equation of the ideal gas law (see equation 2), to get the flux in milligrams of methane per square meter per hour ($mgCH_4m^{-2}h^{-1}$). All slopes with an $R^2$ value of less than 0.65 were considered 'not detectable' and set to zero. $CH_4$ measurements were undertaken twice in July and 4 times in late September and the mean for each plot was assumed to be a representation for that plot over the study period.

Using the ideal gas law, *PV=nRT*, where P = pressure, V = volume, n = number of moles, T = temperature and R = 8.31 J (mol.K) is the ideal gas constant, the $CH_4$ flux calculation looked like this:

$$flux = \left(slope * \left({}^{P}/_{R} * 16g/mol\right) * {}^{1}/_{T} * {}^{V_c}/_{A_c} * {}^{1000mg}/_{g} * {}^{60min}/_{h}\right) = gCH_4\, m^{-2} h^{-1} \qquad \textbf{(2)}$$

Where: slope = the change in concentration in chamber over time

P = pressure assumed to be 1013Pa

R = ideal gas constant = 8.31 J (mol.K)

T = temperature in Kelvin

Vc = volume of the specific chamber used

Ac = area of the specific chamber used

## 4.3 DATA PROCESSING AND STATISTICAL ANALYSES

Data analysis was carried out using both Microsoft Excel 2010 and SPSS 17.0 statistical software. This involved averaging values for snow cover depth, active layer thickness, reflected PAR, soil temperature and soil moisture. All sets of data were then tested for normal distribution using histograms and checked for sphericity using the Mauchly's test. Mauchly's test was not significant for all datasets, indicating that the variance of differences in measurements were not significantly different.

Since measurement of $CO_2$ flux from this wetland was done using the PP systems EGM-4 gas analyzer, flux values were already calculated by the machine. Thus, photosynthesis was easily calculated by subtracting ecosystem respiration from NEE (Net Ecosystem Exchange) using equation (3).

$$\text{Photosynthesis (GPP)} = NEE - R_{eco} \qquad (3)$$

Statistical analyses was done using a two-tailed student t test to identify significant differences between the control and treatment plots (with snow fences) in terms of all variables measured on Storflaket. Using a general linear model (repeated pairwise ANOVA); significant differences could be identified among individual plots, thus making it easy to see which plots were significantly different from the other. With the help of linear regression, the dependence of the fluxes measured could be tallied to soil temperature, soil moisture or both, based on their $R^2$ to identify which of these could better explain the fluxes witnessed. Finally, a Pearson correlation was used to identify significant correlations between all variables measured. Only daytime measurements were used in this study.

# 5 RESULTS

## 5.1 EFFECTS OF SNOW MANIPULATION

After installation of the snow fences, treated plots had a mean snow depth during the winter of 2009 of 20.13 ± 2.21cm as opposed to 10.43 ± 1.17cm on control plots (fig 5.2a). This represents a significant difference between the means of the treatment and control plots (*p=0.01).*This increase in snow depth caused a myriad of responses of the landscape to the disturbance introduced. Thawing permafrost caused a thicker active layer in treatment plots (70.26 ± 2.88cm), while control plots had a thinner active layer (60.11 ± 1.29cm). This 16.7% increase in mean active layer thickness is significant *p=0.01* (fig 5.2b). As a result of the increased active layer thickness in treatment plots, we see a slight subsidence of the land, thus increasing the possibility for plots to trap and hold water and in most cases exposing the water table. This explains the significant difference in mean soil moisture between both types of plots (*p=0.05*). See fig 5.2d.

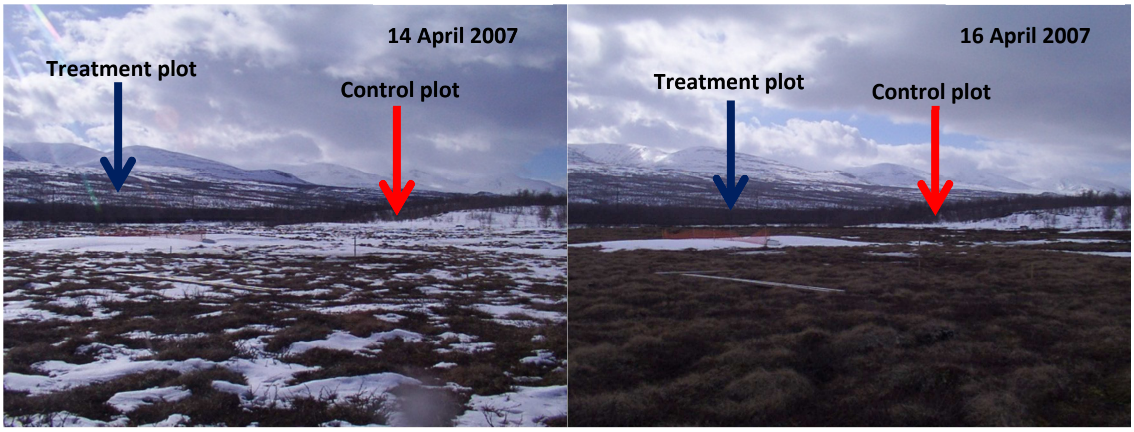
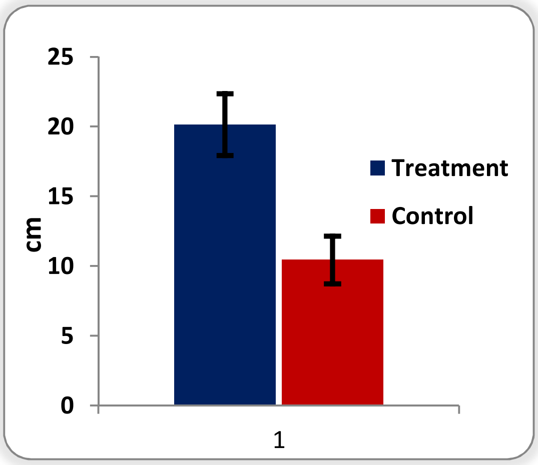
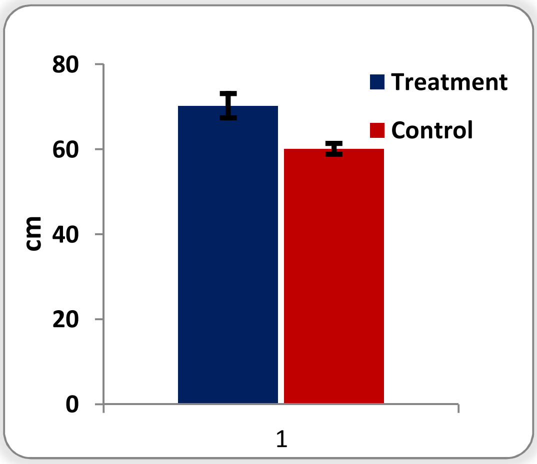


***Fig 5.1: Treatment and Control plot during winter.*** *Treatment plots trap more snow during winter and snow continues to exist here for days after surrounding has melted. (Adapted from Johansson et al, submitted)*

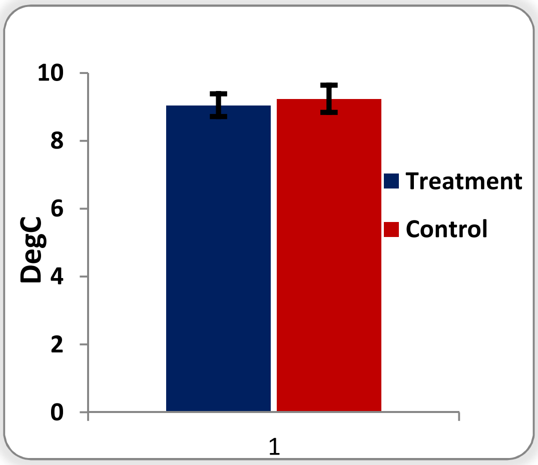
From a visual perspective, treatment plots could be associated with greener and taller vegetation all through summer with mostly tall graminoid species like *Eriophorium vaginatum* while dwarf shrubs like *Empetrum nigrum, Andromeda polifolia* and *Betula nana* thrived on control plots. This could be confirmed by the reflected PAR on both types of plots. Since vegetation absorbs photosynthetically active light and use for the photosynthetic process, areas with greener plant cover absorb more PAR and therefore have a higher carbon uptake and storage as photosynthesis. This explains why we find a significantly higher PAR reflected by the surface of control plots than on treatment plots (fig 5.2e) with 16.32±0.87 µmol $m^{-2}$ $s^{-1}$ and 12.23±0.53 µmol $m^{-2}$ $s^{-1}$ respectively. As a result of this, we see more carbon storage on treatment plots thus making them stronger sinks of carbon than control plots (photosynthesis of -0.51±0.05 and -0.34±0.04 $gCO_2m^{-2}h^{-1}$; for treatment and control plots respectively) and more respiration on treatment plots (fig 5.2f). No significant differences were found in the mean summer soil temperatures (fig 5.2c) and methane emission (fig 5.2i) for treatment and control plots respectively.



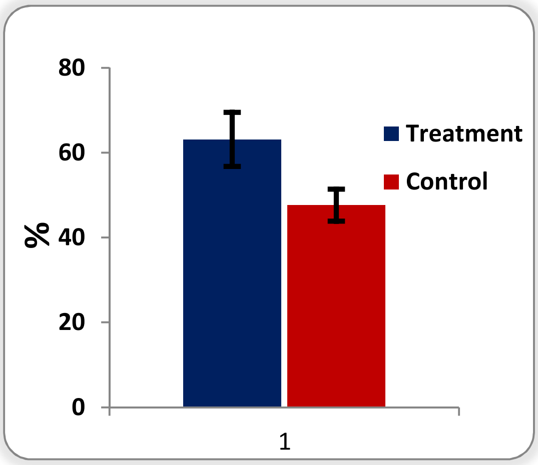
*(a) Mean Snow Depth (**)*



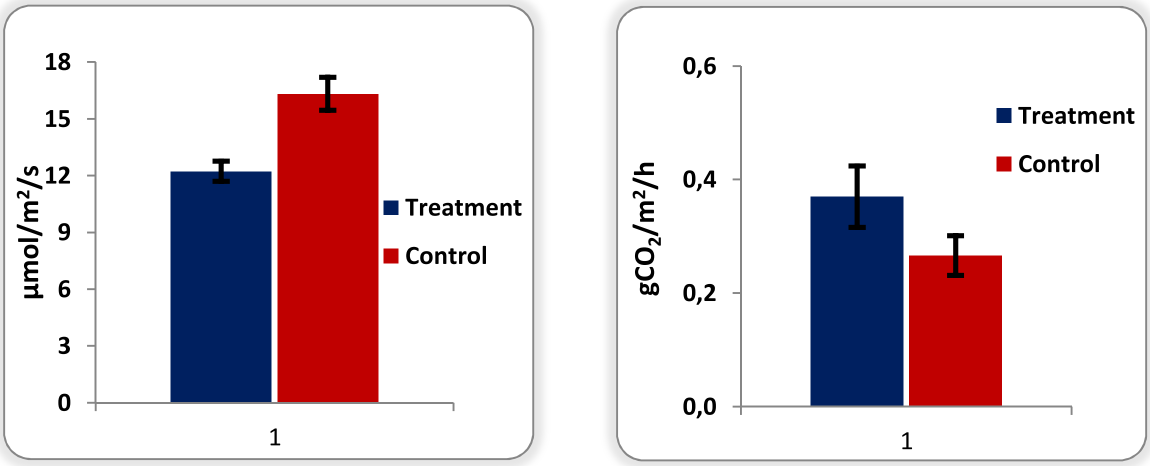
*(b) Mean Active Layer Thickness (**)*



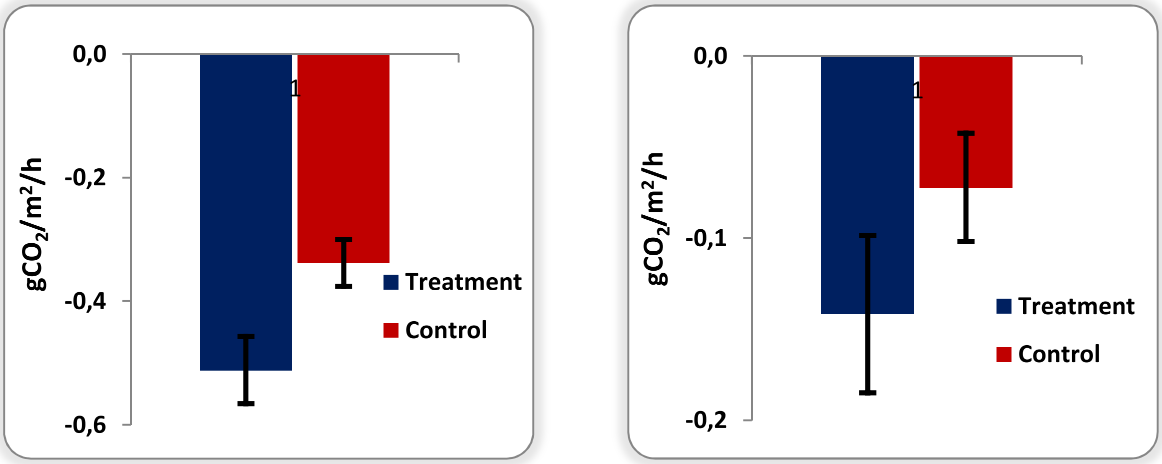
*(c) Mean Soil Temperature*



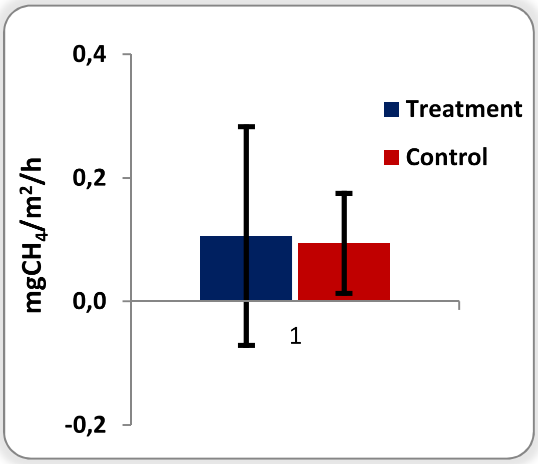
*(d) Mean Soil Moisture (*)*



***(e) Mean Reflected PAR (**)*** ***(f) Mean CO2 Respiration (*)***



***(g) Mean Photosynthesis (**)*** ***(h) Mean NEE (*)***



***(i) Mean Methane Flux***

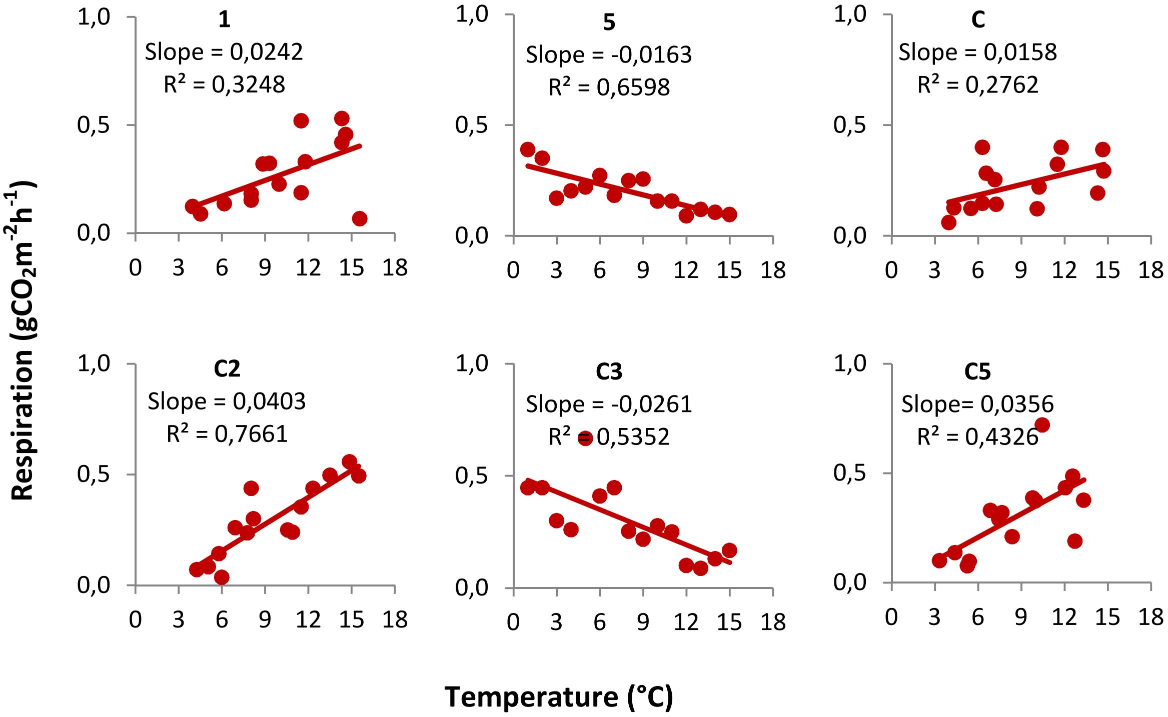
***Fig 5.2 a-i Difference between treatment and control plots on Storflaket.***

*(*) refers to those variables with significant difference at p=0.05; (**) refers to those variables with significant difference at p=0.01. Fig 5.2 c and i illustrate mean soil temperature and mean* $CH_4$ *emission which show no significant difference between control and treatment plots at both levels of significance. Test of significance was done using a two-tailed student t test.*

## 5.2 GAS FLUXES AND DEPENDENCES ON ENVIRONMENTAL VARIABLES

Correlation between $CO_2$ emission and Net ecosystem exchange against soil temperature and moisture show that gas fluxes tallied more with soil temperature than with soil moisture. Yet both environmental variables show an even stronger relationship with $CO_2$. The dependences of gas fluxes on environmental variables were illustrated by the soil respiration (otherwise, $CO_2$ production). Due to the fact that this site failed to emit any considerable amount of methane, its relationship with other variables has been ignored.

Figure 5.3 shows a linear regression between soil temperature and respiration on control plots. The dependence of respiration on soil temperature is not unidirectional, that is, both positive (1, C, C2, C5) and negative correlations (5 and C3) can be found here. Treatment plots have very strong and clear positive correlations to temperature with $r^2$ values as high as 0.85 (plot 4). In control plots, a majority of the respiration rates are below $0.6 gCO_2m^{-2}h^{-1}$ while on treatment plots, emissions are as high as $0.9 gCO_2m^{-2}h^{-1}$. This confirms that treatment plots emit more $CO_2$ than control plots.



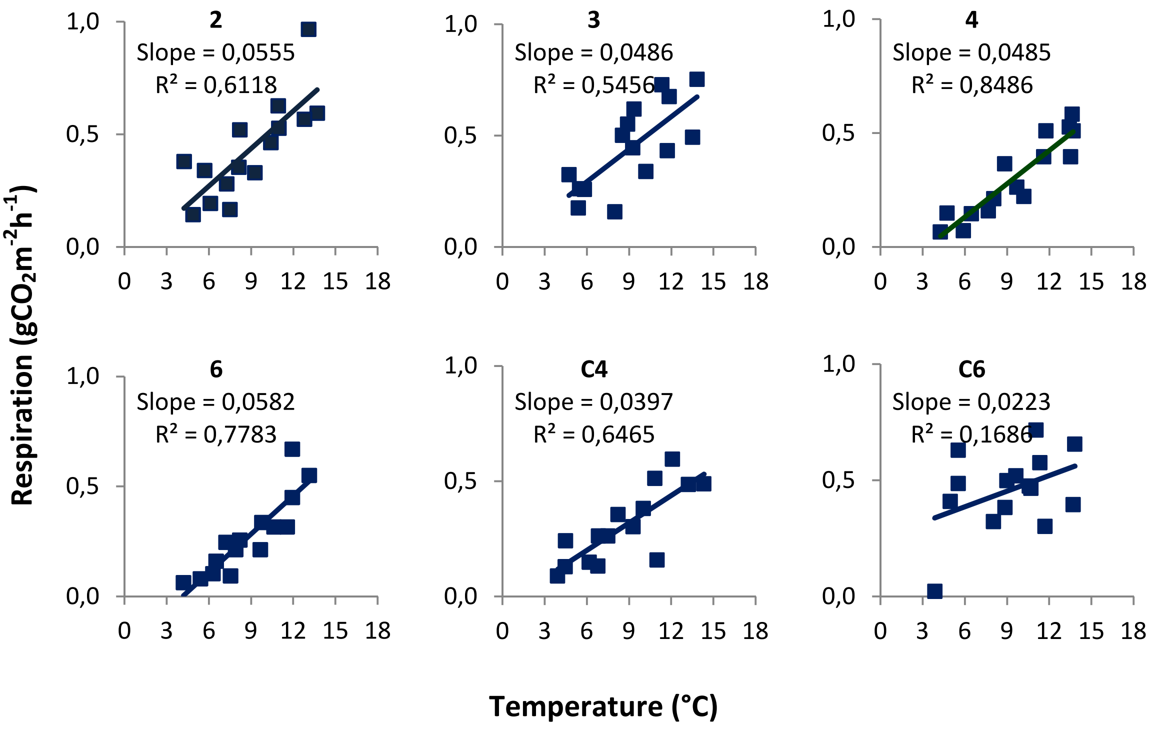
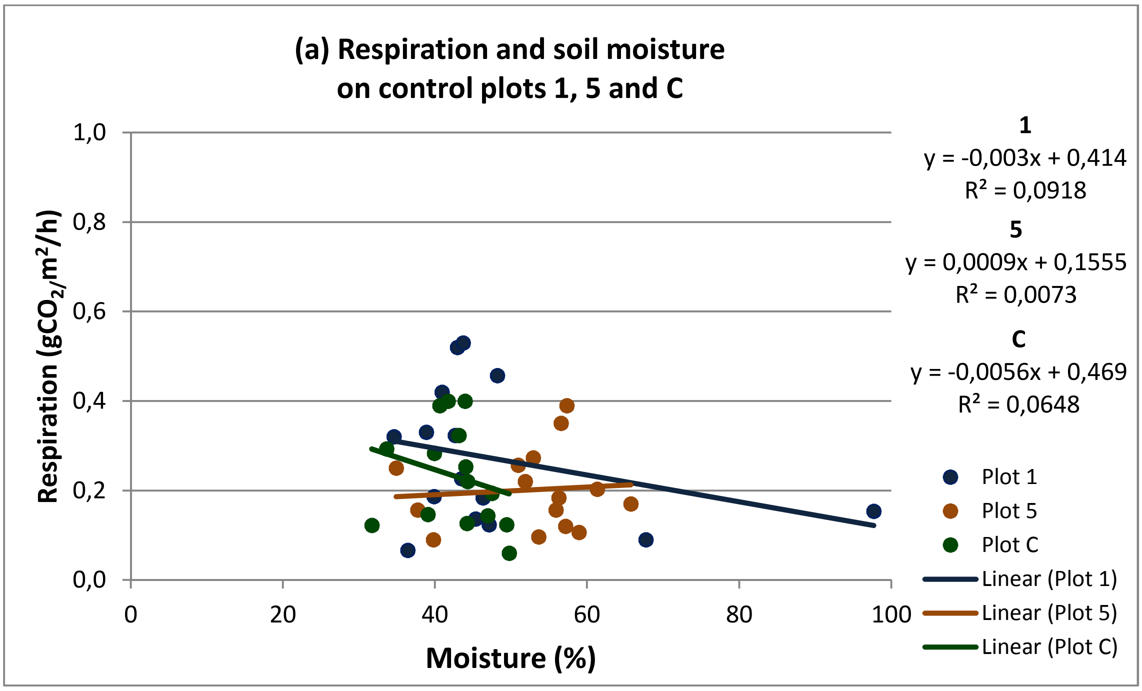
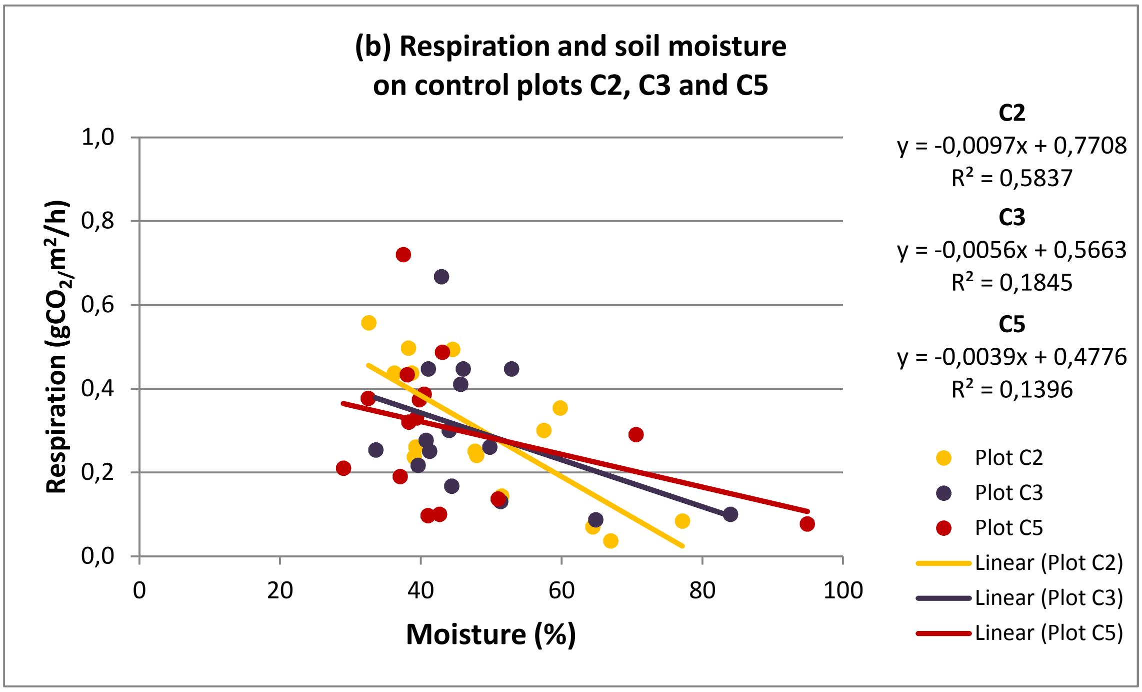


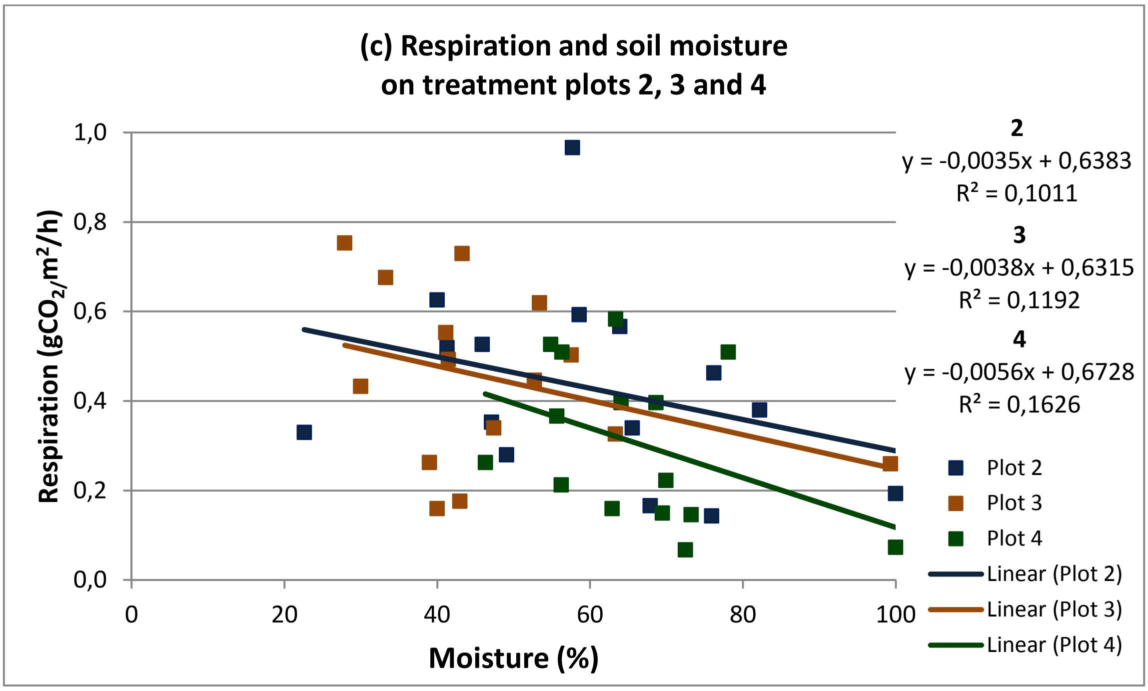
***Fig 5.3: Dependence of $CO_2$ production (respiration) on soil temperature.***

*Red cases: relationship between respiration and soil temperature is not unidirectional on control plots. Blue cases: Relationship between respiration and soil temperature show strong positive correlations on treatment plots with $r^2$ as high as 0.85.*

A negative relationship is found between respiration and soil moisture in 10 out of 12 sites on Storflaket. Also $r^2$ values show the weak dependence of respiration on soil moisture. In control plots (fig 5.4a and b), soil moisture content is mainly restricted to a range between 30 and 70% while in treatment plots, soil moisture spans across a wider range (fig 5.4c and d).


(a) Respiration and soil moisture on control plots 1, 5 and C
Respiration (gCO$_2$/m²/h)
1,0
0,8
0,6
0,4
0,2
0,0
0
20
40
60
80
100
Moisture (%)
1
y = -0,003x + 0,414
R² = 0,0918
5
y = 0,0009x + 0,1555
R² = 0,0073
C
y = -0,0056x + 0,469
R² = 0,0648
Plot 1
Plot 5
Plot C
Linear (Plot 1)
Linear (Plot 5)
Linear (Plot C)


(b) Respiration and soil moisture on control plots C2, C3 and C5
Respiration (gCO$_2$/m²/h)
1,0
0,8
0,6
0,4
0,2
0,0
0
20
40
60
80
100
Moisture (%)
C2
y = -0,0097x + 0,7708
R² = 0,5837
C3
y = -0,0056x + 0,5663
R² = 0,1845
C5
y = -0,0039x + 0,4776
R² = 0,1396
Plot C2
Plot C3
Plot C5
Linear (Plot C2)
Linear (Plot C3)
Linear (Plot C5)



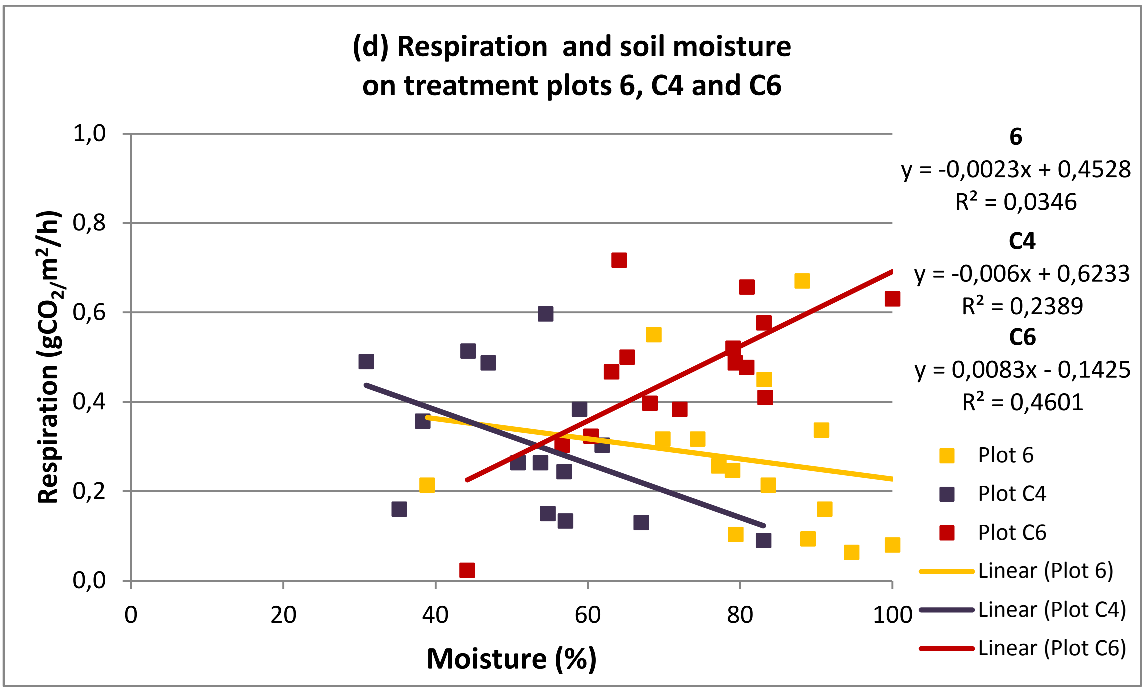


***Fig 5.4: Dependence of $CO_2$ production (respiration) on soil moisture.***

*a and b: Soil moisture on control plots range mainly between 30 and 70%. Respiration shows weaker dependence on soil moisture as compared to soil temperature. c and d: Soil moisture on treatment plots spans across a wider range with moisture contents as high as 100% on some days. Respiration on treatment plots is higher than on control plots.*

## 5.3 DIFFERENCES WITHIN CONTROL AND TREATMENT PLOTS

There is a great difference between individual control and treatment plots (shaded area in table 5.1). Except for between plot 3 and C5, no significant difference in the soil temperatures of the plots was found. Control plots are quite similar to one another except for a few differences in soil temperature and moisture. Yet, treatment plots show large differences between one another. This shows that the snow manipulation experiment introduced a disturbance onto the mire which responds in different ways. The essence of this is to illustrate the variance in the variables measured on Storflaket.

| | | **Treatment** | | | | | | **Control** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **2** | **3** | **4** | **6** | **C4** | **C6** | **1** | **5** | **C** | **C2** | **C3** | **C5** |
| **Treatment** | **2** | | | a d | | | | | a | | | a | |
| | **3** | | | a d | a d | d | a | a | a | A | a | a | c |
| | **4** | | a d | | d | | | b d | | D | d | d | d |
| | **6** | a d | a d | d | | d | | d | d | D | d | d | d |
| | **C4** | | a | | d | | d | b | | | | | |
| | **C6** | | d | | | d | | d | a d | a d | d | d | |
| **Control** | **1** | | a | b d | d | b | d | | | | | | |
| | **5** | a | a | | d | | a d | | | D | | | c |
| | **C** | | a | d | d | | a d | | d | | c | | |
| | **C2** | | a | d | d | | d | | c | | | | |
| | **C3** | a | a | d | d | | d | | | | | | c |
| | **C5** | | c | d | d | | | c | | | | c | |

***Table 5.1: Significant difference between plots (p=0.05).***

*a – Respiration; b – NEE; c – soil temperature; d – soil moisture. Shaded area shows difference between individual control and treatment plots. Control plots are more similar to one another while treatment plots respond differently to snow manipulation. Blank grids refer to plots with no significant difference.*

## 5.4 SEASONAL FLUX OF CARBON DIOXIDE

There is a stronger exchange of carbon between the ecosystem and the atmosphere in July when vegetation is greener. More $CO_2$ emission and uptake can be seen in July compared to September. As the ecosystems get colder with autumn approaching, $CO_2$ production decreases and at the same time its uptake and the sink function of the mire weakens. There is a significant difference between the control and treatment plots in terms of $CO_2$ production, exchange and storage (see fig 5.5a and b). Thus, with the snow manipulation experiment, there is an intensification of the exchange of $CO_2$ on Storflaket.

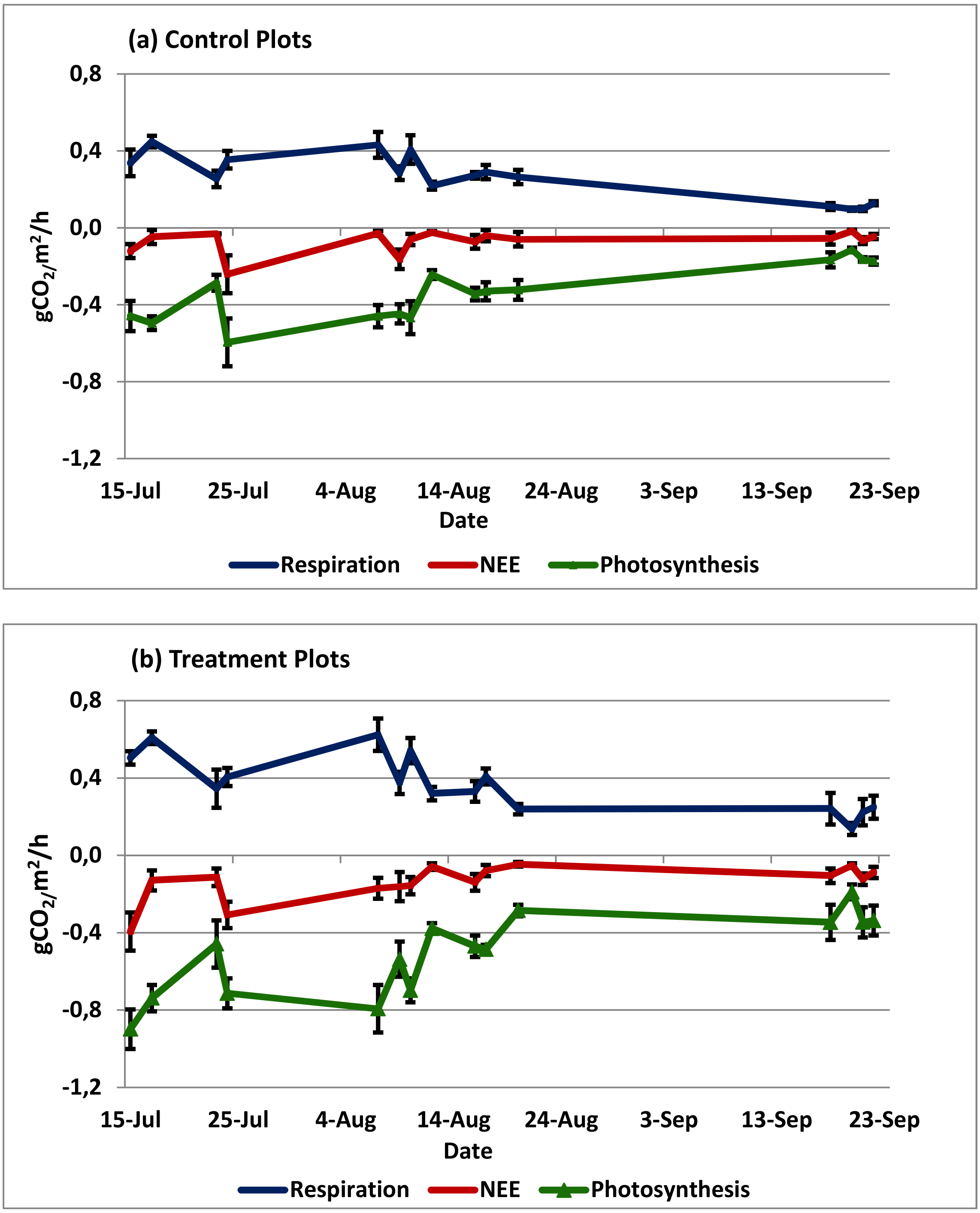


***Fig. 5.5:*** ***$CO_2$ production (Respiration), exchange (NEE) and carbon storage (Photosynthesis) in control (a) and treatment plots (b) on Storflaket.*** *Treatment plots illustrate stronger carbon exchange than control plots. Both treatment and control plots experience a reduction in carbon uptake, release and total exchange during Autumn.*

## 5.5 RELATIONSHIP BETWEEN ENVIRONMENTAL VARIABLES

A strong positive correlation between active layer thickness and respiration was found on Storflaket at p=0.01 (n=12). This means that as the active layer becomes thicker, the respiration increase. This is most likely due to the fact that as active layer thickens, more oxygen is accessible to the soil. At p=0.05 (n=12), NEE showed an inverse relationship to soil moisture and snow cover depth, and a positive correlation to reflected PAR on plots on Storflaket. Soil moisture on its part correlated negatively to reflected PAR and positively to active layer thickness. All other variables showed no significant correlation with one another at 0.05 level of significance.

Figure 5.6 show the relationship between active layer thickness and soil moisture on Storflaket. Sorting all plots according to the active layer thickness, we find that thicker active layers are associated with higher soil moisture which is mostly the case for treatment plots except for plots C3 which had the thickest active layer thickness of the control plots. However, plot C3, was among the wettest plots on Storflaket before the introduction of the snow manipulation experiment. The five plots with least active layer thickness were control plots.

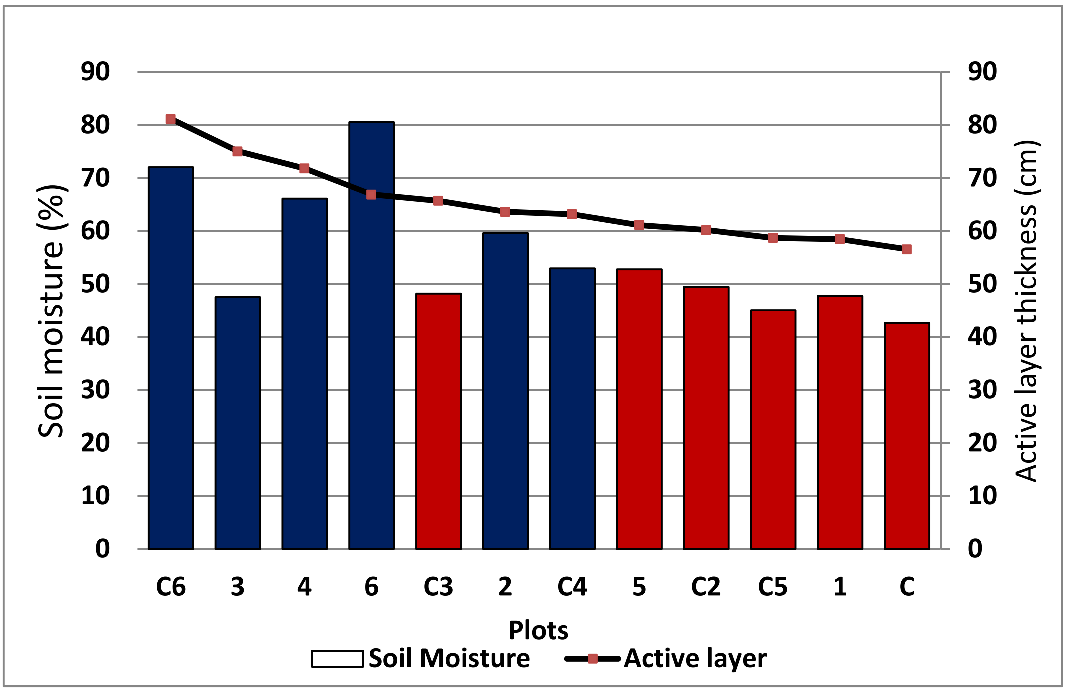


***Fig 5.6: Relationship between active layer thickness and soil moisture.*** *Blue bars represent treatment plots while red ones denote the control plots. The higher soil moisture on treatment plots mostly coincides with thicker active layers while control plots have the lowest soil moistures and thinnest active layers.*

# 6 DISCUSSION

Permafrost degradation and the subsequent changes in the exchange of greenhouse gases from Storflaket and the surrounding mires, is ongoing (Johansson T et al, 2006; Åkerman and Johansson, 2008). For different sites the processes and ecosystem properties that determine and affect the production and release of $CH_4$ and $CO_2$ may vary but generally, such properties as the composition of plant species, dissolved $CH_4$ in the pore water, substrate availability for methane producing bacteria, water table depth, active layer thickness and temperature have been cited as primary drivers (Ström and Christensen, 2007). Therefore, meteorological factors such as ambient temperature and precipitation have a significant effect on the overall emission rate on any given day and time. Transport of heat from the surface to the permafrost beneath depends in large on the active layer thickness, soil moisture and texture.

## 6.1 CLIMATE CHANGE AND PERMAFROST DEGRADATION

### *6.1.1 Climate Change*

In a warming world, the rate of the processes affecting permafrost stability will invariably increase. Winter precipitation and subsequent snow cover depth has increased during the last two decades (Kohler et al, 2006). Projected increases in autumn/winter precipitation are expected to be twice that of summer precipitation (Saelthun and Barkved, 2003). In this study, a thickening of the active layer has been found to be significantly correlated with snow cover depth. Yet previous studies refer to mean summer air temperature and thawing degree days as stronger forcings to active layer thickness. It is expected that the combined effect of these three factors would be far reaching (Åkerman and Johansson, 2008). Permafrost temperatures are dependent on snow cover depth as much as on changes in near surface air temperature (Johansson T. et al 2006). Thus, if the predicted increases in precipitation cause an increase in snow cover depth, it may cause the degradation of the permafrost beneath and an increase in the active layer thickness.

### *6.1.2 Permafrost degradation and Active layer thickness*

Palsa mires in subarctic Scandinavia are thawing faster and more frequently than new ones are formed (Sollid and Sørbel, 1998). The response of the landscape to permafrost thawing is varied. In peatlands and low-lying environments, ecosystems tend to shift towards wetter conditions (Christensen et al, 2004; Malmer et al, 2005) whereas well drained soils and boreal uplands have been known to become drier with thawing permafrost (Oechel et al, 1993). Differences have been found in terms of land subsidence between the control and treatment plots as the latter has been noted to respond to the manipulation experiment by becoming wetter and subsiding. In the future, it is possible that these depressions will trap even more snow which would amplify the insulation of the underlying permafrost, thereby increasing the active layer as it inhibits the propagation of the low winter temperatures downwards (Johansson T et al, 2006). In this study and many others in boreal peatlands and subarctic mires around Europe and North America, permafrost degradation has been associated with wetter sites and land collapse thus forming thermokarst ponds. In contrast, studies on tussocks and wet sedges in Alaska and upland boreal forest indicate no change in hydrology associated with increased active layer thickness (Oechel et al, 1993). In the most extreme of cases, permafrost has been recorded to completely disappear in over 81% of Katterjokk, ca 40 kilometers from the study site between 1996 and 2006. Active layer has become thicker in all nine mires studied in the area (Åkerman and Johansson, 2008).

### *6.1.3 Soil Temperature*

At 5cm depth, there is no statistically significant difference in soil temperatures between the treatment and control plots in summer. This is in conformity with previous findings from the same site by Johansson et al (submitted), which they explained by the fact that snow disappeared quite early in the season thereby contrasting with Seppälä (2003) in which control plots had higher temperatures in the beginning of the summer as opposed to treatment plots due to the existence of snow on treatment plots weeks to months after surrounding snow cover had melted. Records of winter temperature on Storflaket show significant increase in soil temperature with increased depth as a result of snow manipulations of 0.5 – 1 °C at 15cm (Johansson et al, submitted) which can be compared to 0.2 – 3.6 °C at 20cm depth (Seppälä, 2003) and 6 – 14 °C at 50cm (Hinkel and Hurd, 2006) in northern Sweden, Finland and Alaska respectively.

### *6.1.4 Soil Moisture*

The increase in soil moisture thus recorded in treatment plots could be explained by both increased snow trapped by the snow fences and by trapping of water during summer precipitation. Soil moisture is of utmost importance in peatlands since it determines the conductivity of peat. In control plots where peat is relatively dry, it insulates the permafrost beneath from summer temperatures whereas wet treatment plots conduct heat more efficiently and expedites the transfer of heat to the permafrost layer. This results in thicker active layer. However, Johansson et al (submitted) found at the study site that, treatment plots were associated with lower soil moisture at the beginning of summer and increased towards the end of summer. This was assumed to be as a result of sublimation at the end of winter instead of melting. They also explained this by the possible presence of icy layers beneath the snow which would prevent melting snow from penetrating directly into the ground.

## 6.2 CHANGES IN CARBON FLUX

Peat formation depends on the ability of the ecosystem to accumulate carbon. Atmospheric carbon is the primary source of carbon fixed by plants and re-emitted as $CO_2$ and $CH_4$. For subarctic peatlands, the NPP is usually a negative value illustrating the carbon sink function of this ecosystem. Measurements of $CO_2$ exchange on Storflaket involved measuring the Net ecosystem exchange (NEE) of the land. NEE quantifies the carbon flux in and out of an ecosystem, where a positive value denotes a net source to the atmosphere and a negative value denotes a net sink from the atmosphere to the terrestrial system (Roulet et al, 2007). Another factor of importance here is the decay losses by plants in the acrotelm[4] (oxic layer) before they reach the catotelm (anoxic layer) where they are stored and begin to form peat.

Vegetation affects carbon balance in two ways, that is, through NPP and changing the litter resistance to decay in the acrotelm (Malmer et al, 2005). The occurrence of tall graminoid species in treatment plot as opposed to dwarf shrubs and carpet plants in control plots could explain the enhancement of

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[4] Acrotelm: The upper layer of a peat bog, in which organic matter decomposes aerobically and much more rapidly than in the underlying, anaerobic catotelm. Source: Michael Allaby (ed) "acrotelm." A Dictionary of Ecology. 2004. *Encyclopedia.com.* (December 12, 2010). http://www.encyclopedia.com/doc/1O14-acrotelm.html

the carbon sink function. However, studies on the Stordalen mire revealed that from a radiative forcing perspective, a shift of the vegetation cover from dwarf shrubs to tall grass species could compensate for the carbon sink through the emission of carbon to the atmosphere in the form of methane (Johansson T. et al, 2006). On the current study site, methane emission was negligible. This could mean that the site could be exerting a negative radiative forcing (cooling) on the climate.

The presence and quantity of soil microbial organism is also of importance when considering the exchange of carbon in such an ecosystem. Soil microbes are not only an important part of ecosystem respiration but are also vital in the production and oxidation of the very potent greenhouse gas $CH_4$. Thus, with more microbial biomass, there is a good chance for the weakening of the carbon sink function of this ecosystem. Arctic microbial communities are yet to be studied in detail especially their importance in controlling the functioning, stability, and the carbon dynamics of Arctic ecosystems. It is also important to study and understand the reaction of these microorganisms to the expected changes in environmental conditions at high latitudes (Wagner, 2008).

Another factor of importance which this study fails to address is the transfer of carbon as particulate or dissolved organic carbon (DOC) to nearby ecosystems. With a shift from an ombrotrophic[5] to minerotrophic mire conditions with soil moisture increases; carbon is transported as water drains from the mire into nearby depressions. This can be an efficient means through which this ecosystem loses carbon. Thus, it does not necessarily mean that what we have as NEE is the total amount of carbon stored in the peat since a major part of the carbon exchange budget is missing (Roulet et al, 2007).

With predicted increase in precipitation, the study site could be converted into wetter and more fragmented mire. Moreover, with increasing wetness of the soil, one would expect more ecosystem respiration as plants adapted to wet conditions would be introduced which are most often, in such an ecosystem, tall graminoid species with faster turnover of carbon. Thus, with the predicted increase in precipitation in the form of snow, this mire is expected to turn into a carbon sink. Yet, it is quite possible that in the future, this mire might also be a source of the very potent greenhouse gas methane especially with the increases in soil moisture recorded on treatment plots.

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[5] Ombrotrophic: a mire system that is fed by rain water. Source: Michael Allaby (ed). "ombrotrophic." A Dictionary of Ecology. 2004. *Encyclopedia.com.* (December 12, 2010). http://www.encyclopedia.com/doc/1O14-ombrotrophic.html

On Storflaket, the increased vegetation cover associated with treatment plots shows a higher sequestration of carbon as NEE of -0.142±0.03 $gCO_2m^{-2}h^{-1}$ which is about twice carbon stored by control plots of -0.07±0.02 $gCO_2m^{-2}h^{-1}$ (Table 6.1). At the same time, this has been accompanied by a higher ecosystem respiration of 0.37±0.05 $gCO_2m^{-2}h^{-1}$ on treatment plots as compared to 0.27±0.04 $gCO_2m^{-2}h^{-1}$ on control plots. All measurements were carried out during the day. It is possible that this difference could be minimized if measurements were carried out over 24 hours since during the night, there is the complete shutdown of photosynthesis (which requires sunlight) while the ecosystem continues to respire.

Even though the data used herein is scanty, this study captures the expected seasonal variations in $CO_2$ flux on subarctic mires. With higher photosynthesis and respiration in the heart of summer and less activity as it gets cooler. This cannot be taken to represent exactly what happens every year since the interannual variability of fluxes responds strongly with natural interannual variabilities of seasons (e.g. snow thaw date, snow onset, length of seasons etc.). Christensen et al (2008), show that even after 2-3 years of studies, it remains difficult to ascertain the annual carbon budget of Arctic tundra ecosystems.

## 6.3 METHANE FLUX

This study had two main findings on $CH_4$ fluxes. Firstly, $CH_4$ production and emission from this study site was almost negligible. This fails to agree with a plethora of $CH_4$ studies in similar sites where peatlands tend to be large $CH_4$ sources especially with degrading permafrost. Secondly, there was no significant difference in the flux of $CH_4$ between the control and treatment plots. From the literature, one could find the following possible explanations as to this unusual trend:

- The microbial biomass is of utmost importance when considering wetlands as potential $CH_4$ sources. According to Wagner (2008) high microbial cell numbers can be associated with high microbial biomass. Boreal Swedish peatlands are known to contain very low microbial cell numbers (0.2 – 7.0 nmol $g^{-1}$ wet peat, Sundh et al., 1997) as opposed to significantly higher cell numbers in arable soils (35.2 – 59.4 nmol $g^{-1}$, Gattinger et al., 2002,), rice paddies (44.7 – 90.9 nmol $g^{-1}$dw, Bai et al., 2000). It is therefore possible that the absence of methane production could be as a result of the relatively small presence of methanogenic bacteria.

- Secondly, the delicate balance between methanogenesis and methanotrophy could explain why there is no methane emission from this peatland. Should methane oxidation exceed production, it is quite possible that all what is produced is oxidized in the oxic acrotelm before it reaches the atmosphere. Wagner (2007) realised that the calculated balance of the $CH_4$ production and oxidation for the Lena delta showed that the microbial $CH_4$ oxidation capacity (66 mg $m^{-2}$ $d^{-1}$) was about two times higher than the $CH_4$ production (29 mg $m^{-2}$ $d^{-1}$). He also noticed a seasonal pattern to $CH_4$ emission during which $CH_4$ production from the upper soil layer decreased by 4.5 nmol $CH_4$ $h^{-1}$ $g^{-1}$ between July and August while its oxidation increased to between 4 and 7 nmol $CH_4$ $h^{-1}$ $g^{-1}$ over the same period.

- Moreover, the quality of organic matter could be quite important in determining how much methanogenesis could occur. Although there might be high organic carbon accumulated in permafrost soils, a substrate limitation was found by studying potential methane production rates. Further analyses revealed a decrease of bioavailable organic matter with increasing soil depth. This trend shows that there is actually a high quantity of organic matter especially in the wet center that is carbon not available for the microorganisms (Wagner, 2008).

- Since methane production depends strongly on anaerobic decomposition and this snow manipulation experiment is fairly recent (2005), it is possible that the absence of methane in this mire could be as a result of the fact that there just has not been enough time for the carbon to decompose adequately to produce methane. This could be corroborated by the fact that a plot like C3 (control plot) which was already wet before the ignition of this experiment, had a slightly higher emission of methane though still very close to zero.

- The similarity of methane flux between control and treatment plots could be attributed to the insignificant difference in temperature between the control and treatment plots. Microbial organisms depend to a large extent on high temperatures for the growth. With similar mean summer temperatures, it is therefore possible that both sites experience similar microbial growth and response. For different sites the processes and ecosystem properties that determine and affect the release of $CH_4$ may vary but generally, such properties as the composition of plant species, dissolved $CH_4$ in the pore water, substrate availability for methane producing bacteria, water table depth, and active layer thickness and temperature have been cited as primary drivers (Ström and Christensen, 2007).

- The large uncertainty range involved in methane flux could be attributed to the likelihood that measurements may not have been carried out on exactly the same spot on each field day. This could be curbed in further measurements by marking the measurement point to ensure consistency in flux measurements.

Since most methane flux studies on similar environments are carried out over considerably short periods of less than a month in a year (Christensen et al, 2000), long term studies of methane are required to refine methane flux estimates from this wetland (Matthews and Fung, 1987). It is therefore necessary to quantify the methanogens and methanotrophs on treatment plots and compare to control plots. Thus, it is recommended that laboratory and incubation experiments should be carried out in which the microbial cell community should be counted.

# 7 CONCLUSION

Subarctic peatlands underlain by permafrost are very vulnerable and fragile landscape. Changes in one aspect of the climate should be expected to be accompanied by a cross section of corresponding changes on the landscape. With a doubling of the snow cover depth, this research had the following major findings:

- Active layer has become thicker during summer, thus, increasing the amount of soil carbon available for cycling.
- Treatment plots have become wetter with landscape subsidence on most plots.
- Sites have greener vegetation after treatment and vegetation has shifted to mainly vascular plants.
- Carbon turnover has been enhanced with increased $CO_2$ uptake (sink) and release (source).
- Surprisingly, methane produced and emitted from this site was almost negligible both before and after the manipulation experiment.

It is imperative therefore, that long term and continuous measurements of $CO_2$ exchange be carried out on Storflaket. Also, $CH_4$ measurements and microbial analyses should be carried out on a regular basis to investigate the reasons for this unusual trend.

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# APPENDIX

| | **Respiration** | | | | | | | **NEE** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Plots** | 2 | 3 | 4 | 6 | C4 | C6 | Treatment | 1 | 5 | C | C2 | C3 | C5 | Control |
| **Soil Temperature** | 0,61 | 0,55 | 0,85 | 0,78 | 0,65 | 0,17 | 0,82 | 0,32 | 0,65 | 0,28 | 0,77 | 0,70 | 0,43 | 0,80 |
| **Soil Moisture** | 0,10 | 0,12 | 0,16 | 0,03 | 0,24 | 0,46 | 0,10 | 0,09 | 0,01 | 0,06 | 0,58 | 0,18 | 0,14 | 0,38 |
| **Both** | 0,77 | 0,73 | 0,89 | 0,88 | 0,87 | 0,83 | 0,88 | 0,79 | 0,82 | 0,89 | 0,85 | 0,82 | 0,76 | 0,90 |

| | **NEE** | | | | | | | **NEE** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Plots** | 2 | 3 | 4 | 6 | C4 | C6 | Treatment | 1 | 5 | C | C2 | C3 | C5 | Control |
| **Soil Temperature** | 0,16 | 0,00 | 0,30 | 0,29 | 0,41 | 0,00 | 0,24 | 0,07 | 0,23 | 0,18 | 0,03 | 0,02 | 0,00 | 0,08 |
| **Soil Moisture** | 0,07 | 0,22 | 0,03 | 0,00 | 0,02 | 0,08 | 0,01 | 0,05 | 0,06 | 0,06 | 0,01 | 0,03 | 0,02 | 0,00 |
| **Both** | 0,08 | 0,73 | 0,89 | 0,88 | 0,87 | 0,84 | 0,88 | 0,79 | 0,82 | 0,89 | 0,85 | 0,82 | 0,76 | 0,90 |

**Appendix 1: $R^2$ values used to identify dependence of $CO_2$ flux on environmental variables.**

Respiration depends strongly on soil temperature than on moisture. Same holds for NEE in 9 out of 12 plots on Storflaket, yet, both show strong even better dependence of soil temperature and moisture together.

| **Flux ($gCO_2/m^2/h$)** | **Definition** |
|---|---|
| **Photosynthesis (GPP)** | Total carbon uptake by plants during photosynthesis (otherwise known as Gross Primary Production, GPP and defined as NEE- $R_{eco}$) |
| | |
| **Autotrophic Respiration ($R_{plant}$)** | Loss of carbon by plants during respiration |
| | |
| **Heterotrophic Respiration ($R_{soil}$)** | Loss of carbon by soil microbial organisms during respiration |
| | |
| **Total Respiration ($R_{eco}$)** | Carbon loss through autotrophic and heterotrophic respiration. (defined as $R_{eco} = R_{plant} + R_{soil}$) |
| | |
| **Net Primary Production (NPP)** | Photosynthesis (GPP) minus plant respiration (defined as GPP – $R_{plant}$) |
| | |
| **Net Ecosystem Exchange (NEE)** | Total carbon accumulation within the ecosystem; In this case, excludes C loss by DOC export and fire (defined as GPP – $R_{eco}$) |

**Appendix 2: Definition of the general elements of carbon cycling.**

Carbon exchange in this study fails to consider carbon loss through export of dissolved and particulate organic carbon (DOC/POC) and fire.

| | | Respiratn | NEE | $CH_4$ | Soil Temp | Soil Moist | Reflected PAR | SnowDepth | ActiveLayer |
|---|---|---|---|---|---|---|---|---|---|
| Respiration | Pearson Corr. | 1 | -.175 | .049 | .039 | .252 | -.373 | .275 | **.729****  |
| | Sig. (2-tailed) | | .587 | .879 | .904 | .429 | .233 | .386 | **.007** |
| | N | 12 | 12 | 12 | 12 | 12 | 12 | 12 | **12** |
| NEE | Pearson Corr. | -.175 | 1 | -.300 | .484 | **-.651*** | **.686*** | **-.591*** | -.212 |
| | Sig. (2-tailed) | .587 | | .343 | .111 | **.022** | **.014** | **.043** | .508 |
| | N | 12 | 12 | 12 | 12 | **12** | **12** | **12** | 12 |
| $CH_4$ | Pearson Corr. | .049 | -.300 | 1 | .234 | .136 | .058 | -.209 | .130 |
| | Sig. (2-tailed) | .879 | .343 | | .464 | .672 | .857 | .514 | .687 |
| | N | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| Soil Temp. | Pearson Corr. | .039 | .484 | .234 | 1 | -.150 | .191 | -.316 | .105 |
| | Sig. (2-tailed) | .904 | .111 | .464 | | .642 | .553 | .316 | .745 |
| | N | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| Soil Moisture | Pearson Corr. | .252 | **-.651*** | .136 | -.150 | 1 | **-.642*** | .450 | **.585*** |
| | Sig. (2-tailed) | .429 | **.022** | .672 | .642 | | **.024** | .142 | **.046** |
| | N | 12 | **12** | 12 | 12 | 12 | **12** | 12 | **12** |
| Reflected PAR | Pearson Corr. | -.373 | **.686*** | .058 | .191 | **-.642*** | 1 | -.707* | -.361 |
| | Sig. (2-tailed) | .233 | **.014** | .857 | .553 | **.024** | | .010 | .250 |
| | N | 12 | **12** | 12 | 12 | **12** | 12 | 12 | 12 |
| Snow Depth | Pearson Corr. | .275 | **-.591*** | -.209 | -.316 | .450 | **-.707*** | 1 | .225 |
| | Sig. (2-tailed) | .386 | **.043** | .514 | .316 | .142 | **.010** | | .482 |
| | N | 12 | **12** | 12 | 12 | 12 | **12** | 12 | 12 |
| Active Layer | Pearson Corr. | **.729**** | -.212 | .130 | .105 | **.585*** | -.361 | .225 | 1 |
| | Sig. (2-tailed) | **.007** | .508 | .687 | .745 | **.046** | .250 | .482 | |
| | N | **12** | 12 | 12 | 12 | **12** | 12 | 12 | 12 |

****.** Correlation is significant at the 0.01 level (2-tailed).

***.** Correlation is significant at the 0.05 level (2-tailed).

## Appendix 3: Pearson Correlation between variables on Storflaket

Shaded grids show variables with significant correlation between one another. Positive correlations could be found between Respiration and active layer thickness; NEE and reflected PAR;soil moisture and active layer thickness while negative correlations exist between NEE and soil moisture; NEE and snow depth; and soil moisture and reflected PAR.

| | Control Plots | | | | | | | Treatment Plots | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Variables** | **1** | **5** | **C** | **C2** | **C3** | **C5** | **Mean** | **2** | **3** | **4** | **6** | **C4** | **C6** | **Mean** |
| Snow Depth (cm) | 11.80 ±3.51 | 8.60 ± 4.42 | 7.00 ± 4.17 | 7.40 ± 4.04 | 9.60 ± 4.95 | 18.20 ± 6.03 | **10.43 ± 1.71** | 22.20 ± 7.36 | 18.00 ± 6.07 | 24.00 ± 6.20 | 23.20 ± 7.66 | 23.40 ± 7.35 | 10.00 ± 4.39 | **20.13 ± 2.21** |
| Active Layer Thickness(cm) | 58.45 ± 0.57 | 61.11 ± 0.98 | 56.55 ± 0.35 | 60.16 ± 1.49 | 65.69 ± 0.58 | 58.69 ± 0.55 | **60.11 ± 1.29** | 63.60 ± 0.80 | 75.02 ± 2.15 | 71.78 ± 1.39 | 66.87 ± 0.81 | 63.16 ± 0.97 | 81.13 ± 2.49 | **70.26 ± 2.88** |
| Reflected PAR (µmol/$m^2$/s) | 14.61 ± 0.44 | 16.56 ± 0.50 | 17.14 ± 0.51 | 13.42 ± 0.39 | 19.61 ± 0.58 | 16.59 ± 0.50 | **16.32 ± 0.87** | 11.48 ± 0.34 | 13.23 ± 0.38 | 10.82 ± 0.39 | 10.98 ± 0.33 | 12.88 ± 0.38 | 13.98 ± 0.40 | **12.23 ± 0.53** |
| Soil Temp. (°C) | 10.17 ± 0.94 | 8.61 ± 0.87 | 8.98 ± 0.97 | 9.42 ± 0.93 | 10.02 ± 0.97 | 8.65 ± 0.83 | **9.31 ± 0.88** | 8.88 ± 0.78 | 9.20 ± 0.76 | 9.57 ± 0.86 | 8.80 ± 0.69 | 8.62 ± 0.84 | 9.22 ± 0.80 | **9.05 ± 0.75** |
| Soil Moisture(%) | 47.73 ± 4.07 | 52.75 ± 2.26 | 42.68 ± 1.33 | 49.44 ± 3.39 | 48.15 ± 3.17 | 45.02 ± 4.32 | **47.63 ± 2.16** | 59.59 ± 5.05 | 47.51 ± 4.49 | 66.10 ± 3.28 | 80.52 ± 3.77 | 52.95 ± 3.37 | 72.02 ± 3.55 | **63.12 ± 3.13** |
| NEE ($gCO_2m^{-2}h^{-1}$) | -0.03 ± 0.01 | -0.05 ± 0.01 | -0.12 ± 0.03 | -0.11 ± 0.02 | -0.04 ± 0.02 | -0.09 ± 0.05 | **-0.07 ± 0.02** | -0.14 ± 0.04 | -0.12 ± 0.03 | -0.12 ± 0.02 | -0.25 ± 0.06 | -0.13 ± 0.02 | -0.10 ± 0.02 | **-0.14 ± 0.03** |
| $CO_2$ emissions ($gCO_2m^{-2}h^{-1}$) | 0.27 ± 0.04 | 0.20 ± 0.02 | 0.23 ± 0.03 | 0.29 ± 0.04 | 0.30 ± 0.04 | 0.30 ± 0.05 | **0.27 ± 0.04** | 0.43 ± 0.06 | 0.45 ± 0.05 | 0.31 ± 0.05 | 0.27 ± 0.05 | 0.30 ± 0.04 | 0.46 ± 0.04 | **0.37 ± 0.05** |
| Photosynthesis ($gCO_2m^{-2}h^{-1}$) | -0.30 ± 0.05 | -0.25 ± 0.03 | -0.35 ± 0.04 | -0.41 ± 0.05 | -0.34 ± 0.04 | -0.4 ± 0.07 | **-0.34 ± 0.04** | -0.57 ± 0.08 | -0.57 ± 0.06 | -0.42 ± 0.06 | -0.52 ± 0.09 | -0.43 ± 0.06 | -0.56 ± 0.06 | **-0.51 ± 0.05** |
| $CH_4$ emissions ($mgCH_4m^{-2}h^{-1}$) | -0.01 ± 0.05 | -0.01 ± 0.05 | 0.03 ± 0.04 | 0.0 | 0.75 ± 0.41 | -0.13 ± 0.06 | **0.1 ± 0.18** | -0.04 ± 0.03 | 0.13 ± 0.2 | 0.23 ± 0.14 | 0.36 ± 0.17 | 0.05 ± 0.04 | -0.07 ± 0.06 | **0.09 ± 0.08** |

**Appendix 4: Summary of variables measured on Storflaket**

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