Student thesis series INES nr 372

The impact of permafrost degradation on methane fluxes
- a field study in Abisko

Andreas Dahlbom

2016
Department of
Physical Geography and Ecosystem Science
Lund University
Sölvegatan 12
S-223 62 Lund
Sweden

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Andreas Dahlbom (2016).

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Master degree thesis, 30 credits in *Physical Geography and Ecosystem Analysis*

Department of Physical Geography and Ecosystem Science, Lund University

Level: Master of Science (MSc)

Course duration: *August* 2015 until *January* 2016

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The impact of permafrost degradation on methane fluxes
- a field study in Abisko

Andreas Dahlbom

Master thesis, 30 credits, in
Physical Geography and Ecosystem Analysis

Torben Christensen
Dept. of Physical Geography and Ecosystems Science

Marcin Jackowicz-Korczynski
Dept. of Physical Geography and Ecosystems Science

Mikhail Mastepanov
Dept. of Physical Geography and Ecosystems Science

Exam committee:
Thomas Holst
Dept. of Physical Geography and Ecosystems Science

Lena Ström
Dept. of Physical Geography and Ecosystems Science

Abstract

A snow manipulation project was established on a sub-arctic mire close to Abisko, northern Sweden, to study the effect of artificially thicker snow cover on vegetation and permafrost. Several years of increasing winter snow accumulation, clearly led to intensified permafrost degradation and vegetation change. The question arose how much these changes affected emissions of greenhouse gases. This study examines the methane fluxes in the area of the snow manipulation project during summer. Fluxes were studied by the closed chamber technique, in both manipulated and control plots. The results show a clear difference between fluxes at control and manipulated plots, with average values of 0.15 and 0.66 mg CH_4 m^{-2} h^{-1}, respectively. If the trend of the global warming is continuing it will lead to even more thawing of permafrost. Then even more organic material will be available for decomposition and even more methane will be produced, adding to the global warming.

Acknowledgements

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Introduction

Methane

Methane (CH_4) is a greenhouse gas that is produced when biomass is decomposed under anaerobic conditions (without oxygen) (AMAP 2012). The amount of methane in the atmosphere in comparison to carbon dioxide (CO_2) is small. Even though the emissions of CH_4 are smaller than CO_2, it is one of the most important contributor to the global warming (Jackowicz-Korczyński et al. 2010; AMAP 2012). This is because CH_4 is over 25 times more potent as a greenhouse gas than CO_2 over a 100 year time span (IPCC 2014). In 2014 the global average concentrations of CH_4 in the atmosphere was 1833±1 ppb (parts per billion) and for CO_2 it was 397.7±0.1ppm (parts per million)(WMO 2015). Since the start of the industrial revolution, the amount of CH_4 has more than doubled. During the same time the amount of CO_2 has risen around only 30% (Norina 2007). CH_4 is not as long lived in the atmosphere as CO_2, only around 9 years in comparison to 34-44 years (Seinfeld and Pandis 2006), but long lived enough to have an impact on a global scale. From 2013 to 2014 the global average concentration of CH_4 increased by 9 ppb, and during the same period CO_2 increased 1,9ppm (WMO 2015).

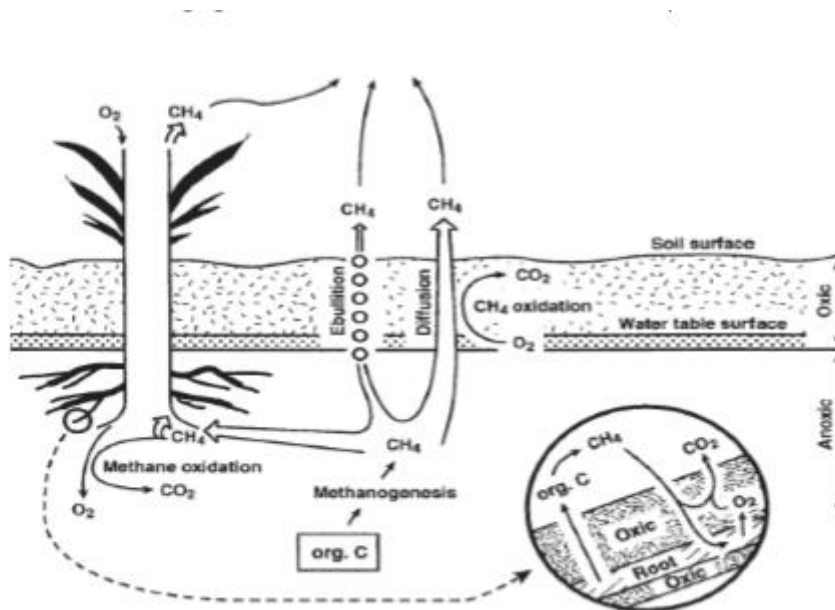Figure 1: A conceptual flow chart of the CH_4 pathway. In areas where permafrost is present this takes place in the active layer. Taken from (Whalen 2005).

There are three different pathways for methane to the atmosphere: ebullition, molecular diffusion and transportation through plants as seen in Figure 1 (Whalen 2005; Kip et al. 2010). When vascular plants are present and abundant, a large proportion of the transport and emission of methane takes place through these (Christensen et al. 2003a). If the decomposition occurs with oxygen (aerobic), CO_2 is produced and without oxygen (anaerobic) CH_4 (AMAP 2012). If the anaerobic horizon does not go all the way to the top soil there is an aerobic horizon where CH_4 can be oxidised (Whalen 2005). In this horizon a very large fraction of the diffusing CH_4 can be oxidized, but even in the anaerobic horizon in standing water there can be oxidization (Liebner et al. 2011).

Permafrost

Permafrost is permanently frozen ground, when the average yearly temperature of the soil is at or below 0^0C for two or more years. The active layer is the surface layer of the soil that thaws each summer and refreezes every winter (AMAP 2012; Schaefer et al. 2012). The active layer thickness varies depending on the type of soil, from centimeters in peat to meters in well-drained materials (Johansson et al. 2006a). Thawing of permafrost, or permafrost degradation is an increase of the active layer over time and is driven by increased air temperature and snow depth (Schaefer et al. 2012).

Approximately 50% of all soil carbon is contained in permafrost (McCalley et al. 2014). When the permafrost starts to thaw, the carbon will be available for decomposition, but not all of the carbon will be available until all the permafrost is gone (Bosiö 2013). The decomposition will either produce methane or carbon dioxide, two major greenhouse gases which increase global warming. This in turn will lead to higher air temperatures and even more permafrost thaw, which creates a "positive feedback" (McCalley et al. 2014)

Permafrost dynamics under climate change

Vast areas in the northern terrestrial environment are mires or wet tundra habitats due to the permafrost preventing vertical drainage and the lack of slope preventing horizontal drainage (Svensson et al. 1999). In these ecosystems, because of low temperatures and prevailing anaerobic conditions, the decomposition rates relative to production rates are slow and lead to the accumulation of organic matter (Svensson et al. 1999; Ström and Christensen 2007; Bäckstrand et al. 2009; Nykänen et al. 2003; Ström et al. 2015), and due to anaerobic conditions they are also a significant source of methane (Christensen et al. 2003a; Lund et al. 2009; Ström et al. 2005). For thousands of years the arctic land areas have slowly fixed carbon dioxide from the atmosphere and accumulated this carbon in plant tissues that gradually have become peat or part of the soil. Over these thousands of years, vast quantities of carbon have been stored in the permafrost (AMAP 2012; Nykänen et al. 2003; Lund et al. 2009), almost twice the amount of carbon that is in the atmosphere (Hugelius 2009; Bäckstrand et al. 2009; Grogan 2012). With global warming permafrost areas all over the arctic have started to thaw, and this is alarming due to the fact that big quantities of organic matter will be available for decomposition (Bosiö 2013), which may turn the large sink into a source of carbon (Christensen et al. 2000; AMAP 2012). Just small changes in the mean annual temperature can create strong changes for ecosystems in subarctic regions (Christensen et al. 2004).

When the permafrost thaws the hydrology in the area changes (Åkerman and Johansson 2008), and changes in vegetation composition followed by increased emissions of methane and carbon dioxide have already been reported in sub-arctic areas (Ström and Christensen 2007). More available nutrients can also affect the vegetation community and productivity (Aerts et al. 2006; Ström and Christensen 2007).

In the Torneträsk area the thickness of the active layer is currently increasing (Åkerman and Johansson 2008), and this area has during the last years experienced an increase of the annual air temperature (Figure 2) (Callaghan et al. 2010).
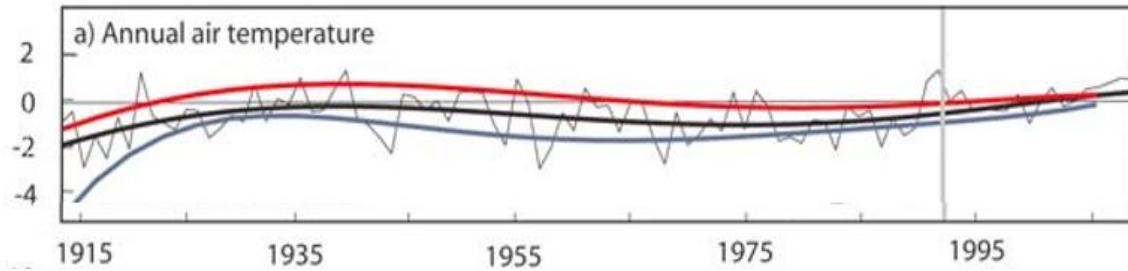
Figure 2: This Figure is taken from (Callaghan et al. 2010) and it shows the annual air temperature for the Abisko region for the last 100 years and the vertical line before 1995 shows where the annual temperature starts to rise above 0°C. The red line is a polynomial curve trough the local maxima, the blue through the local minima and the black is a smoothed mean annual air temperature.

In high latitudes, ecosystem functions and vegetation are greatly affected by snow. For example in cold regions where the growing season is short, a few weeks change in season length can have a great impact (Høye et al. 2007). This can also affect the hydrology and ecological systems (Callaghan et al. 2011). Climate scenarios for the Abisko region predict an increase of ≈2% of precipitation per decade over the coming 60 years, and the predicted precipitation is expected to be higher during winter than summer (Sælthun and Barkved 2003). A explanation for this is that higher surface temperature over the northern Atlantic causes higher evaporation and then increased precipitation over the Lapland region (Seppälä 2003). The majority of the projected precipitation for the Abisko area will be in autumn and winter (Sælthun and Barkved 2003), which will lead to increased snow fall and snow depth. Changes in snow cover have already been observed and evidence in the form of thawing permafrost, increases in active layer and vegetation changes have been reported during the last decade (Åkerman and Johansson 2008). With increased snow depth there is also an increased water source in the spring when the snow melts, which can lead to a higher water table (Bosiö et al. 2014).

As a rough generalization, permafrost can be formed and sustained in areas with an annual mean air temperature of 0°C or less, but when the temperature increases, the permafrost starts to thaw. When snow covers areas with permafrost during the winter, the snow acts like a blanket and slows the heat loss of the ground. When the heat loss during the winter is less than heat gain during summer, the active layer increases every year until there is no more permafrost.

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With predictions of increased snow cover thickness in the future, it is likely that the permafrost will continue to thaw or even accelerate in the area (Johansson et al. 2013), and with this bring changes in vegetation composition, productivity and trace gas fluxes (Bosiö et al. 2012).

In 2005 Margareta Johansson (Dept. of Physical Geography and Ecosystems Science, Lund university) started a snow manipulation project on a mire called Storflaket in the Abisko region (Figure 3) to study the effect of degrading permafrost by artificially increased snow cover thickness. The aim was to "advance" the degradation years into the future so that we will be able to predict the future of the permafrost, and learn more about the permafrost dynamics. Subsequently this has given us the chance to study possible changes in the methane cycle which is valuable since it is not as well-known as the general carbon cycle. Increased snow depth can increase the degradation rate of permafrost even more than positive annual temperatures. We know that this in turn will cause a change of greenhouse gas emissions, but not how much.

The snow manipulation project is located on the western part of the mire (Figure 4), where twelve different, but as homogeneous as possible, plots measuring 10 x 20 meters were established, and six of them were randomly chosen to be manipulated plots. The manipulated plots during snow season have a 1 m high and 10 m wide fence erected against the dominating wind direction, which is easterly and westerly winds. For more detailed information about this project, read Johansson et al. (2013). The measurements for this thesis were carried out within the existing snow manipulation project.

Aims

This study aims to examine the relationship between degrading permafrost and methane fluxes and specifically to answer the following research questions:

Will the manipulated (increased snow depth) areas emit more methane than the control areas? If so, then how much?

The hypothesis is that in the manipulated areas there will be a higher water table and a thicker active layer, which will increase the emissions of methane.

The growing season in the manipulated areas is shortened due to the artificially increased snow depth. With the assumed higher emission rate of methane, will the manipulated areas emit more methane over the whole season in comparison to the control areas?

The hypothesis is that there will be more accumulative emissions from the manipulated plots in comparison to control, due to higher fluxes of methane from manipulated plots and a long growing season in total.

Methods and materials

As a result of climate change, arctic and sub-arctic peatlands are expected to emit higher amounts of methane. This study was conducted at the sub-arctic mire Storflaket, close to Abisko, Northern Sweden. CH_4 fluxes were measured in an area where a snow manipulation project has influenced the permafrost. Because it was not known whether or not CH_4 concentrations during measurements would show a clear trend, CO_2 was also measured simultaneously as a quality check on the measurements of CH_4. CO_2 measurements can be used as such because under dark chamber conditions only a steady rise in CO_2 concentrations can be expected (due to no photosynthesis and only respiration taking place).

Site description

CO_2 and CH_4 fluxes were measured on a mire called Storflaket, which is located in the northernmost Sweden (Figure 3), 6 km East of the Abisko scientific research station (68°20'47.60"N 18°58'22.10"E). The mire is approximately 13 ha and has a 60-90 cm thick peat layer and the plant community is classified as tundra because of the underlying permafrost (Bosiö et al. 2014). The road E10 between Kiruna and Narvik borders the mire to the north, a railway to the south and a birch forest to the east and the west (Johansson et al. 2013). The Abisko region has relatively low amounts of precipitation

because it is located in a rain shadow of the mountains on the border between Norway and Sweden (Seppälä 2005). During the period 1913-2006 the total annual precipitation was 303 mm per year, but the precipitation has increased during the last decade (Johansson et al. 2011).

According to Johansson et al. (2011) the area is characteristic of the "sporadic permafrost" zone, and the permafrost can also be called "ecosystem protected permafrost". "Ecosystem protected permafrost" is usually found in climates where the mean annual air temperature is approximately 2°C to -2°C (Shur and Jorgenson 2007). The permafrost was formed during a colder climate than the present but can still exist during warmer climate as sporadic patches because of the properties of the mires ecosystem. In the case of Storflaket, it is the peat's insulating capacity which enables the permafrost to be present.

Figure 3: Map over Fennoscandia. The yellow dot indicates where the mire Storflaket is located, a few kilometres east of Abisko. Map taken from (Bosiö 2013).

Experimental setup

Figure 4: Aerial view of the placement of the plots at the mire Storflaket. The green dots are the control plots and the white ones are the manipulated plots. The satellite photo is from Google Earth and is retrieved on the 25th of August 2014.

By eye it was clear to see that the western side of the manipulated plots was more affected than the eastern side (more degraded). It was therefore decided to take the majority of the CH_4 and CO_2 measurements on the western side of all plots (both in control and manipulated plots).

Of the twelve plots, it measurements were taken in a total of six subplots. Subplots one to five were put out according to a grid (Figure 5) that was determined prior to the measurements, and subplot number six was put on one already installed collar on the east side of the snow fence (Figure 5). Because of the subplots' vegetation and tilt the placement of the chamber was in a radius of one meter from the original placement to find an as levelled area as possible to make the chambers as airtight as possible.
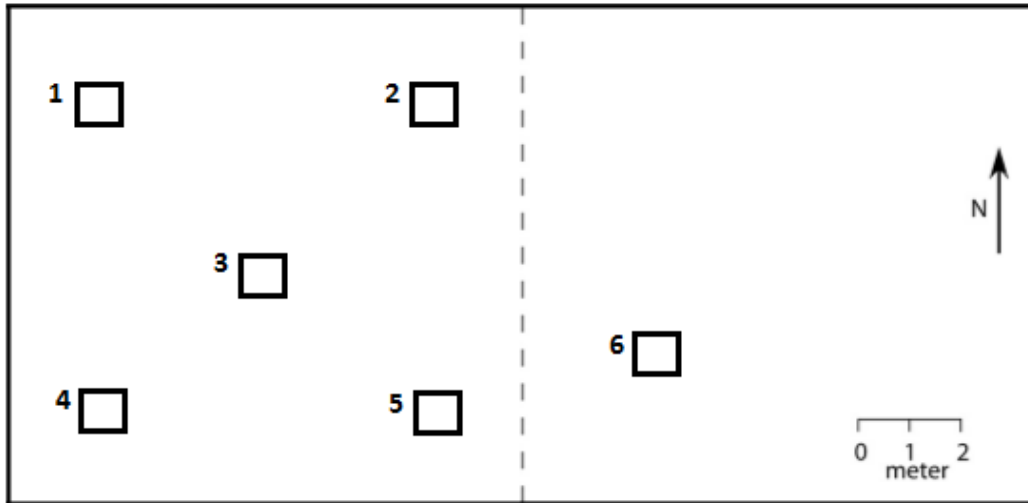
Figure 5: Aerial view of one plot. The dotted line is where the snow fence was erected. The plot measure 10x20 meters and it is the western side of the plot that is of most interest. The numbers 1 - 5 indicate where the subplots were put manually and number 6 is where a collar was installed in 2005.

Chamber measurements

Concentrations of CH_4 and CO_2 over time were measured with the closed chamber technique (Lund et al. 2009), with chambers made out of Plexiglas which were covered by non-transparent reflecting material to suppress photosynthesis and avoid overheating (Figure 6). Due to the fact that some plots had deep water, two different chambers were used, one higher for deeper waters (23 x 23 cm, height: 60 cm) and another one for vegetation and shallow waters (51 x 51 cm, height: 30 cm). If the system is airtight the concentration of CO_2 will increase over time because of respiration. The linearity of CO_2 concentration change was used as a quality criteria for CH_4 flux measurements.

The measurements of both CH_4 and CO_2 were all made in the field subplot by subplot with a Los Gatos Research ultraportable greenhouse gas analyser (UGGA), Model 915-0011 (powered with a car battery) which made measurements every second (1 hz) and saved them to a hard drive. The analyser was connected through Wi-Fi to an iPad, which visualized the concentration dynamics in real time. This made it easy to see if the chambers were airtight or not and the measurements could therefore be retaken directly if they were insufficient.

Inside of the chambers a thermometer was attached and a fan was put in to circulate the air. From the chamber two plastic tubes with a length of 40 meters and an inner diameter of 4 mm were connected to the ultraportable gas analyser for the gas content in the chamber to circulate through the machine.

In an attempt to make the chambers more airtight when they were put on vegetation, pantyhose was filled with sand and first put on the ground to fill out the unevenness and then the chamber was put on top (Figure 6).

Depending on the emission or the uptake of methane, a longer or shorter duration of time was needed. If a clear flux was easily observable, only a five minute sequence was needed. If the flux was very small with no clear concentration trend a longer duration of time was needed, up to 25 minutes. Because of technical problems, real-time

Figure 6: The top picture shows how the pantyhose was put on the ground to fill out any unevenness. The picture below is how the setup looked like, with stones on top to makes sure the covering of the chamber was on to suppress the photosynthesis during high speed winds.

concentration monitoring was not always possible; then a measurement was taken for 10 minutes as a compromise between the flux accuracy and the power consumption.

The measurements used for the thesis were conducted daily between the 13th and the 22nd of July, with the exception of rainy days during this period. There were a total of 72 subplots, which were measured three times in total. All of the 72 subplots was measured once, before the next round. Round 1 was measured between the 13th and 15th of July, round 2 between the 15th and 17th of July and round 3 between the 19th and 22nd of July.

With the concentrations over time for both CO_2 and CH_4, the fluxes were calculated by with following equation:

$$F = \frac{\partial C}{\partial t} * \frac{60}{1000000} * h * \frac{M * (P * 100)}{R * (T + 273.15)} * 1000$$

Equation 1: F = flux of the analyzed gas in mg m^{-2} h^{-1}. C is the concentration (ppm), t is time (min), h is the height of the chamber (m). M is the molar mass (g mol^{-1}), where M_{CH_4} is 16 and M_{CO_2} is 44. T is the air temperature (°C), P is the air pressure (hPa) and R is the universal gas constant (Pa m^3 mol^{-1} K^{-1}) which is 8.314.

Measurements were done carefully to avoid ebullition , but in a few subplots there were CH$_4$ bubbles observed in the beginning of the measurement. This only occurred in manipulated subplots with standing water. Depending on air pressure and wind these methane bubbles would probably be released sooner or later, but perhaps not in the magnitude that happened at once during measurements.

Other variables

Water table was measured in every subplot with a water alarm that was stuck down into a hollow pipe that was put into the soil some minutes before. The pipe had small holes drilled into it so that potential water in the soil could drain into it. When the water alarm reached the water it made a sound. Then a measurement was taken of how far into the ground the alarm went.

A thermometer was put inside of the chamber to register the air temperature and another one was also put outside of the shadow side of the chamber if the weather was sunny.

Weather data for the area over the duration of the field work was collected from the Abisko Scientific Research Station. This included air pressure, temperature, wind speed and wind direction. Yearly averages of temperature and precipitation between 1950-2014 were also collected.

Photosynthetic Active Radiation (PAR) sensors (Minikin QT logger) measure hourly averages all year round and were already placed in all of the plots. Values of the PAR

over the duration of the field work were downloaded in the beginning of October. Snow does not disappear from control and manipulated plots at the same time, and with PAR it is possible to determine the day of snow melt (DOSM). The snow has a high albedo and when the snow melts there is a clear drop in the reflected PAR. Every plot was checked individually and the latest date of all the plots was used for DOSM.

Soil temperature was also measured at every plot at the depths of 15 cm and also has hourly averages. These data were downloaded from loggers (Tinytag Plus 12G) in September.

Active layer was measured manually. The measurements were retrieved after the field work between the end of September and the beginning of October. Measurements of the active layer only took place on the western side of the plot where subplots 1-5 were located. Subplot 6 was on the eastern side and was consequently without value of the active layer.

A Paersons test, a linear correlation test between variables was performed with all the collected variables to calculate the correlation between them. A t-test was also made to determine if there was a statistical difference or not. These test was both done in SPSS.

Every subplot was photographed and with these photos a rough vegetation inventory was made, with the categories with and without the vascular plant *Eriophorum vaginatum*.

Results

The first research question in this study was to determine if the areas manipulated with increased snow depth emit more methane than the control areas. The results show that, yes, the manipulated plots emit more CH_4 than the control plots. Figure 7 shows this result with the total average for all measurements of CH_4. Specifically, for control plots the value is 0.15 mg CH_4 m^{-2} h^{-1} and for manipulated the value is 0.66 mg CH_4 m^{-2} h^{-1}.
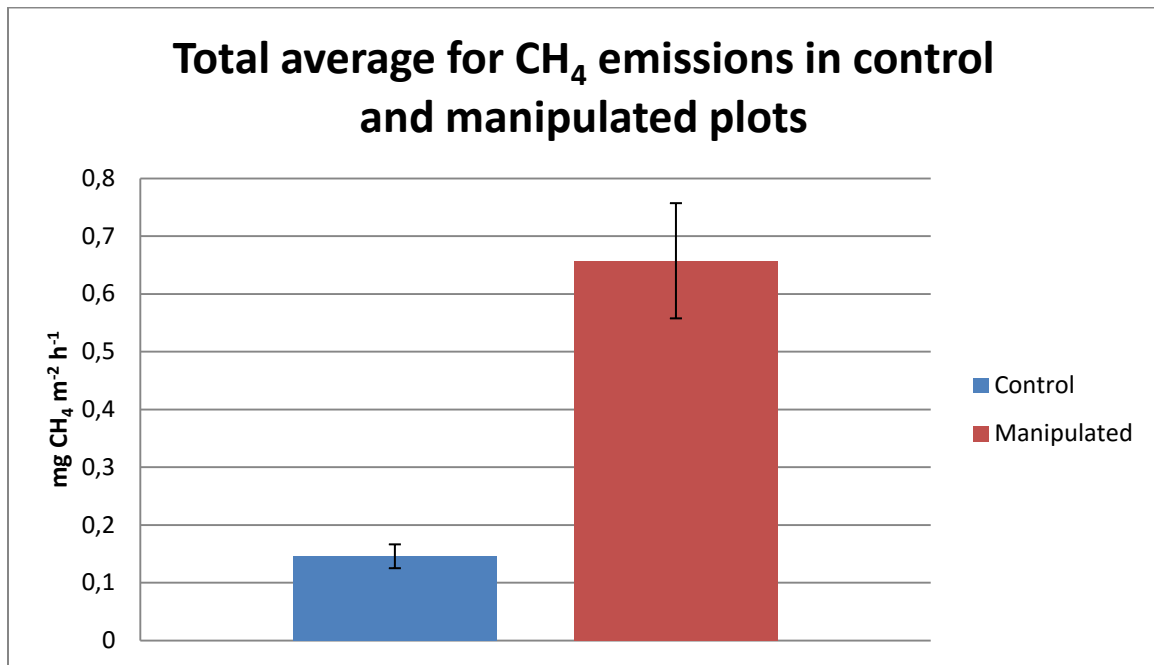

Figure 7: The average CH_4 flux for both control and manipulated plots.

There is a consistent big difference (t-test, $p<0,01$) between the control and manipulated plots in emissions, in every round (Figure 8). The manipulated plots have higher emissions and there is also an increase for every round, and the emissions in the control plots are decreasing. For control plots the values for round 1, 2 and 3 were 0.16, 0.14 and 0.14 mg CH_4 m^{-2} h^{-1} and for manipulated the values were 0.51, 0.55 and 0.91 mg CH_4 m^{-2} h^{-1}. Every dot in the Figure is an average of 36 different measurements during one round and for the control plots it varied between -0.02

(negative numbers is an uptake) and 0.93 mg CH_4 m^{-2} h^{-1} and for manipulated plots it was from -0.03 to 5.51 mg CH_4 m^{-2} h^{-1}.
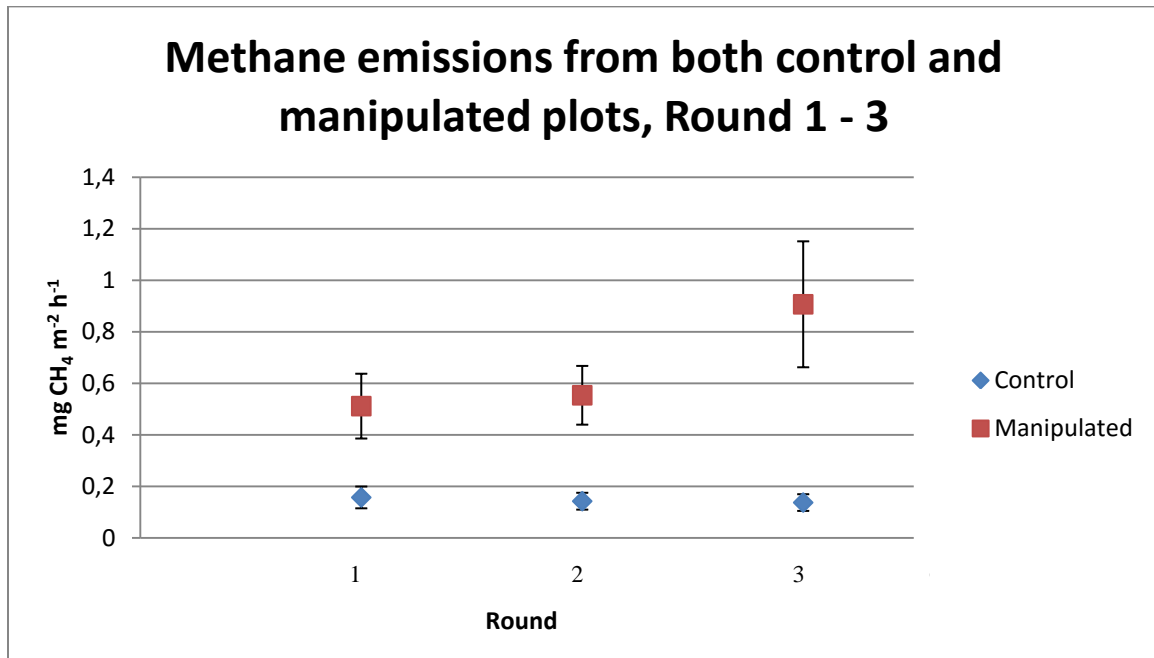

Figure 8: The average CH_4 flux for every round.

A Paersons test was made to calculate the correlation between the CH_4 flux and the other variables that were collected. The closer to 1 it is the higher the correlation. As illustrated in table 1, in both control and manipulated plots the highest correlations are between CH_4 flux and water table and also active layer. The correlation of CH_4 flux with active layer thickness was highest at the control plots and with the water table it is highest at the manipulated plots.

Table 1: Paersons correlation values between methane flux and different parameters and the number of corresponding measurements in control and manipulated plots. Also the p-value is presented, and when the value is below 0.05 it means that it is statistical significant.

Control plot values					
	Methane flux (mg CH$_4$ m^{-2} h^{-1})	Water table (cm)	Soil temperature (°C)	Active layer (cm)	PAR (µmol/m^2/sec)
Correlation with methane flux	1	0.584	0.307	0.605	-0.12
P-value		0.000	0.001	0.000	0.214
Number of measurements (n)	108	108	108	90	108

Manipulated plot values					
	Methane flux (mg CH$_4$ m^{-2} h^{-1})	Water table (cm)	Soil temperature (°C)	Active layer (cm)	PAR (µmol/m^2/sec)
Correlation with methane flux	1	0.503	0.183	0.435	-0.069
P-value		0.000	0.084	0.000	0.519
Number of measurements (n)	108	108	90	90	90

Plots with a higher water table shown higher emissions of CH$_4$ and the majority of the manipulated plots were located in a cluster with high water table and high emissions (Figure 9).
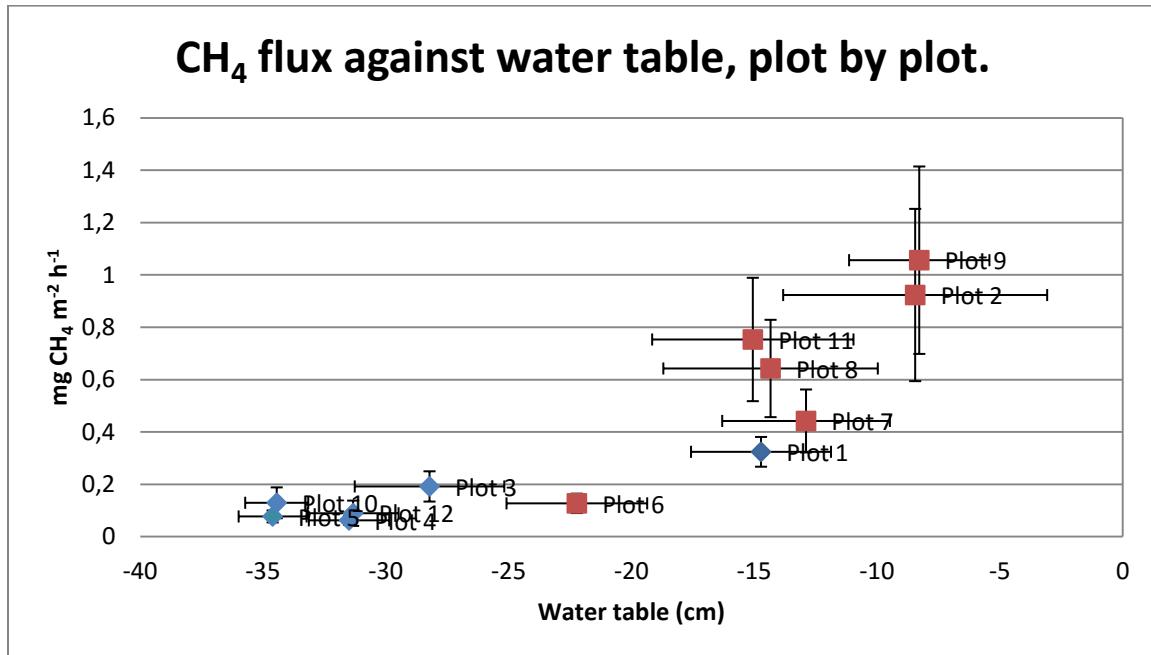

Figure 9: Emissions of CH$_4$ versus the level of the water table. Blue dots are the control plots and red dots are the manipulated plots

Higher emissions of CH_4 were found to correspond with thicker active layer and the majority of the manipulated plots had thicker active layer (Figure 10). Figure 10 shows the average values of CH_4 against the measured active layer for every plot with data.
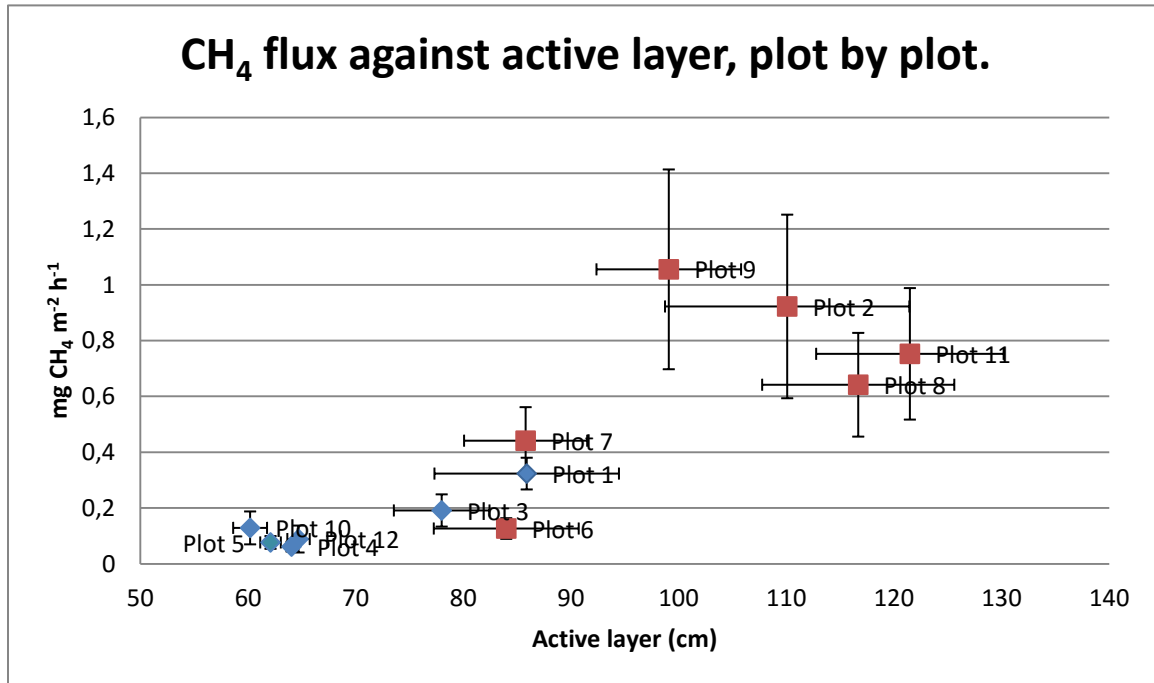
Figure 10: Emissions of CH_4 versus the thickness of the active layer. Blue dots are the control plots and red dots are the manipulated plots.

With the photographs of every subplot, a rough vegetation inventory to document whether a given plot contained vascular plant (mostly *Eriophorum*) or not. Figure 11 and 12 show how the inventory was made. Within the manipulated subplots 23 contained *Eriophorum* and 13 did not. Within the control subplots 17 contained *Eriophorum* species and 19 did not.

Figure 11: A few examples of how a subplot could look like when *Eriophorum* was occurring. From the left: Subplot 9:2, 11:1 and 2:2.

Figure 12: A few examples of how a subplot could look when Eriophorum was not occurring. From the left: Subplot 3:2, 2:1 and 5:2.

There is a greater difference in CH_4 emissions when comparing subplots with and without *Eriophorum*, than between manipulated and control plots (Figure 13). Figure 13 shows the total average of CH_4 emissions for all the subplots. The subplots where *Eriophorum* is occurring had an average flux of 0.70 mg CH_4 m^{-2} h^{-1} and the subplots without *Eriophorum* had an average flux of 0.02 mg CH_4 m^{-2} h^{-1}.
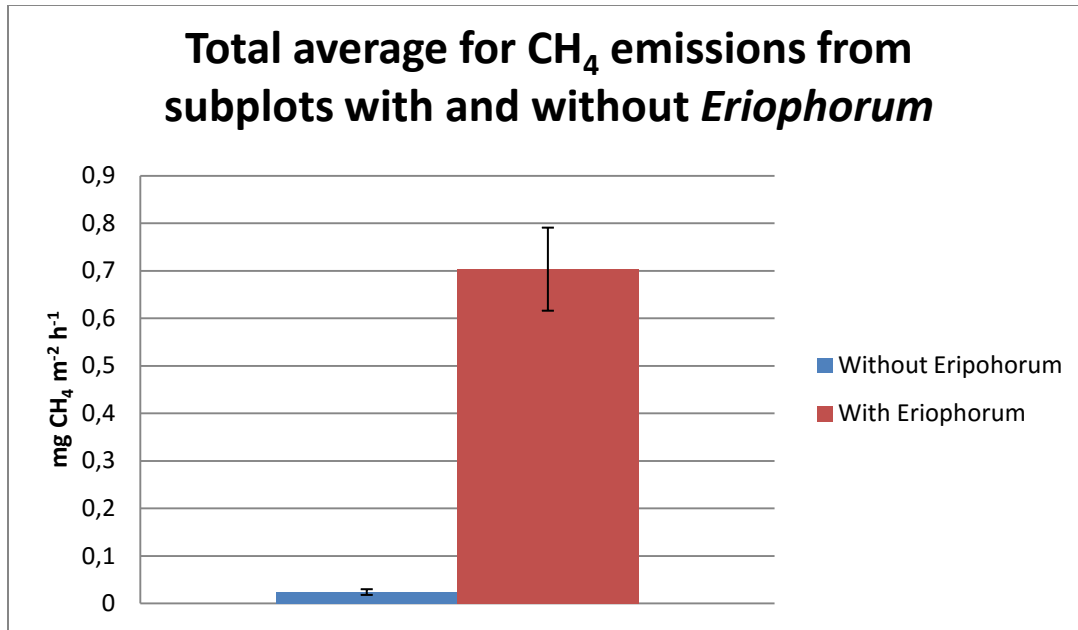
Figure 13: The total average of CH_4 emissions for all the subplots with and without *Eriophorum* occurring.

There is a significant difference (t-test, p<0.05) in emissions between the two categories, and the emissions for the subplots with *Eriophorum* occurring are increasing for every round. For the subplots without *Eriophorum* occurring the emissions are very small and decreasing from round 1 to 3 (see Figure 14). The values for plots with *Eriophorum* from round 1, 2 and 3 were 0.58, 0.60 and 0.93 mg CH_4 m^{-2} h^{-1} and for plots without *Eriophorum*

0.03, 0.03 and 0.02 mg CH_4 m^{-2} h^{-1}. In Figure 14 every red dot is an average of 40 different measurements and every blue dot is an average of 32 different measurements.

Figure 14: The average CH$_4$ emissions per round for plots with and without Eriophorum.
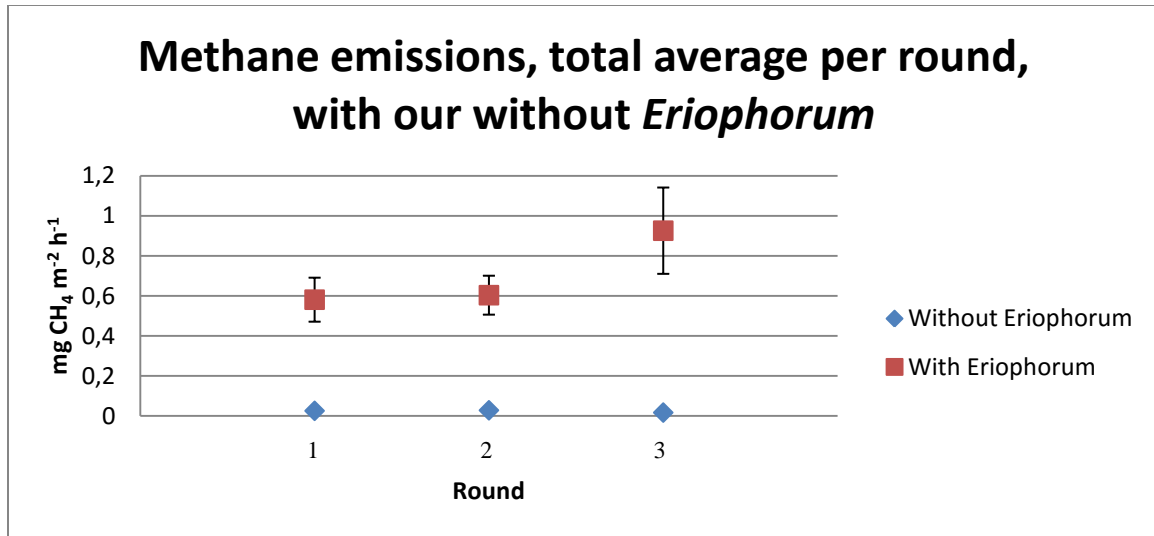
Table 2, as well as table 1, shows that the CH$_4$ flux had the highest correlation with water table and the active layer. For both with and without *Eriophorum* water table was the one with the highest correlation followed by active layer.

Table 2: Paersons correlation values between methane flux and different parameters and the number of corresponding measurements all the subplots, separated by the occurrence of *Eriophorum*. Also the p-value is presented, and when the value is below 0.05 it means that it is statistical significant.

With *Eriophorum* values					
	Methane flux (mg CH$_4$ m^{-2} h^{-1})	Water table (cm)	Soil temperature (°C)	Active layer (cm)	PAR (μmol/m^2/sec)
Correlation with methane flux	1	0.43	0.105	0.34	0.15
P-value		0.000	0.289	0.004	0.877
Number of measurements (n)	120	120	105	87	111
Without *Eriophorum* values					
	Methane flux (mg CH$_4$ m^{-2} h^{-1})	Water table (cm)	Soil temperature (°C)	Active layer (cm)	PAR (μmol/m^2/sec)
Correlation with methane flux	1	0.429	0.205	0.371	-0.25
P-value		0.000	0.048	0.001	0.021
Number of measurements (n)	96	96	93	90	87

Figure 13 shows very clearly that where *Eriophorum* species are occurring the CH$_4$ emissions were a lot higher than where they were not, both in control and manipulated plots. The subplots with *Eriophorum* also had a higher water table and a thicker active layer as seen in Figure 15 and 16. Because the categorization with and without *Eriophorum* was made on a subplot level the two graphs that follow will not show values plot by plot, but instead the total average.

The highest emissions of CH$_4$ were from subplots with *Eriophorum* and Figure 15 shows clearly that the water table is much closer to the soil level where *Eriophorum* is occurring in comparison to where it is not.
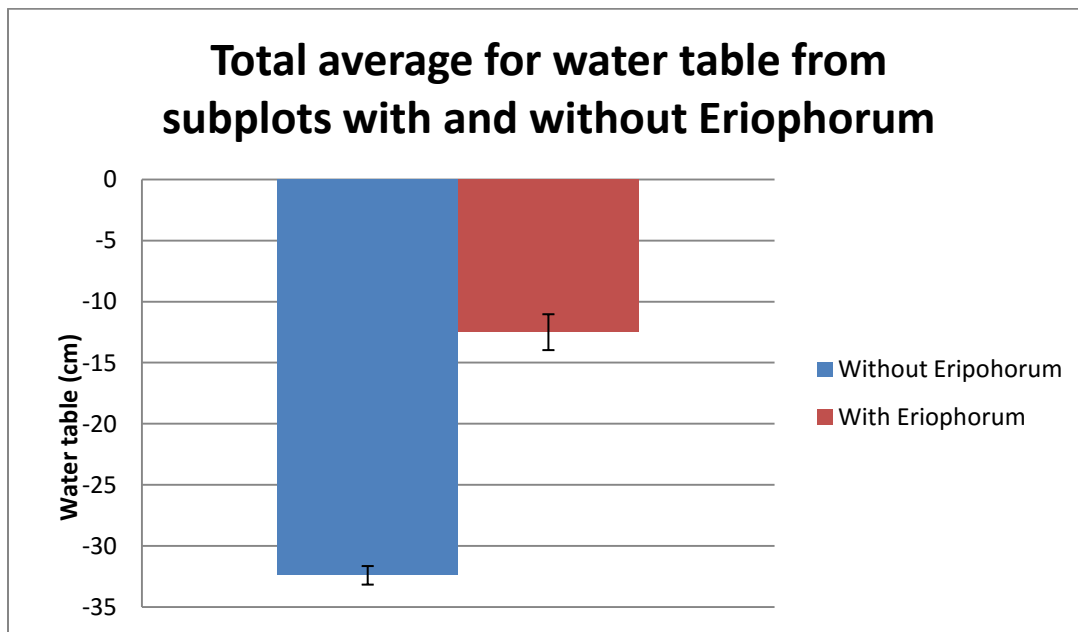
Figure 15: The average water table at subplots with and without *Eriophorum*.

The highest emissions of CH$_4$ were from subplots with *Eriophorum* and Figure 16 shows that the subplots with *Eriophorum* had a thicker active layer than the ones without *Eriophorum*.
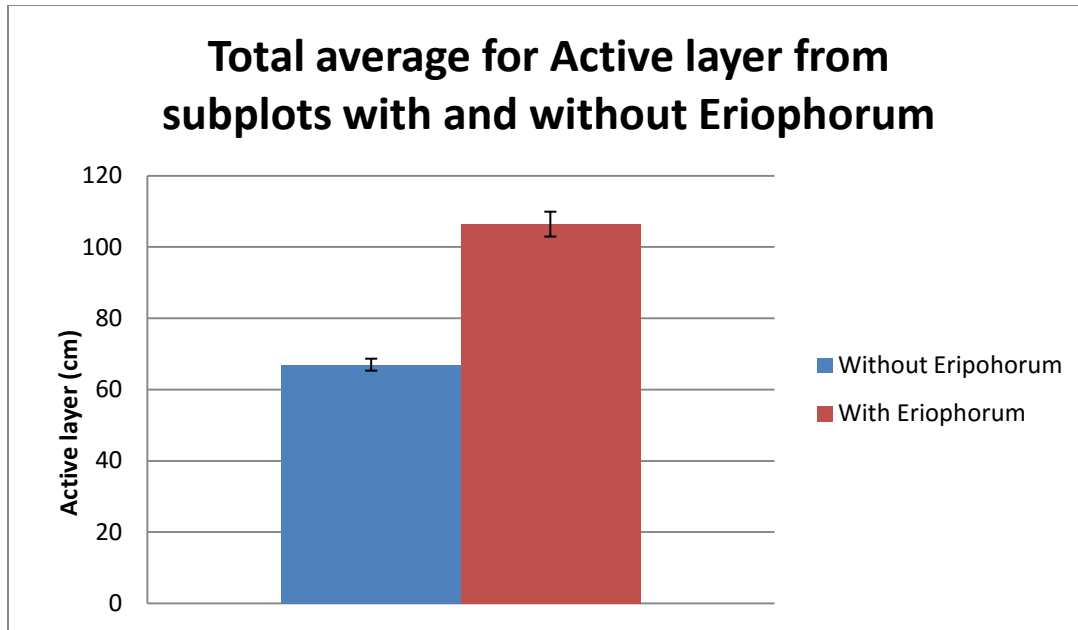
Figure 16: The average active layer at subplots with and without *Eriophorum*.

In Figure 17 every measurement of the CH_4 flux is visualized against the measured water table. For plots with the water table far from the soil level the emissions of CH_4 were low, but above a threshold around -10cm they increased rapidly. When the water table reaches over 10 cm above soil level there is a decrease which continues the higher the water table gets.
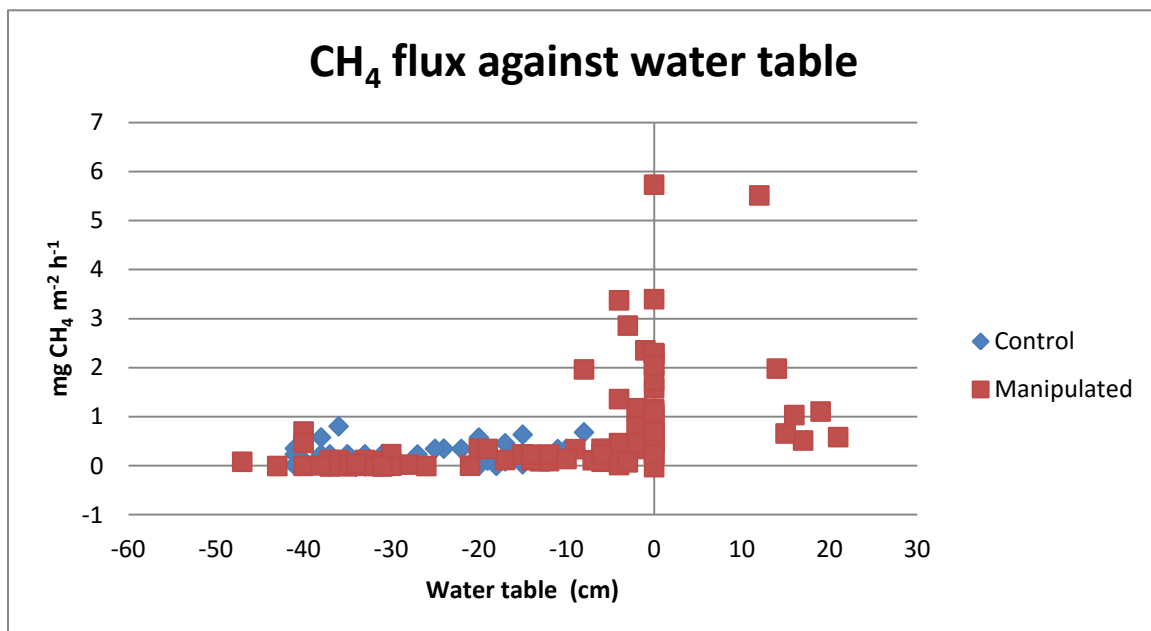
Figure 17: Emissions of CH_4 versus the water table level.

Discussion

Permafrost

The permafrost on this mire is classified as ecosystem protected (Johansson et al. 2011), and according to Shur and Jorgensson (2007) ecosystem protected permafrost exists where the mean annual air temperature is approximately 2$^{\mathbf{o}}$C to -2$^{\mathbf{o}}$C, which matches well with Storflaket. However, according to Sælthun and Barkved (2003), there will be a 3$^{\mathbf{o}}$C increase of the mean annual air temperature by 2050 and 4.5$^{\mathbf{o}}$C by 2080. In Abisko the mean annual air temperature has been -0.6$^{\mathbf{o}}$C (1913-2006), but during the last decade temperatures have increased. This has put the mean annual air temperature at positive degrees (Johansson et al. 2011; Callaghan et al. 2010). With these predictions and considering today's mean temperature, it is not likely for these permafrost areas around Abisko to survive.

Equipment

Due to technical issues causing problems with the real-time display of the concentrations, a duration time of ten minutes was used during the measurements. If the subplot had a very low flux, a longer measurement time was needed to estimate the flux with a proper precision. Before the technical malfunction, when visual aid was lost, the longest duration used was 25 minutes, more than twice as long as the predetermined 10 minutes. Hence a few measurements may not be totally accurate. This problem, however, was actual for subplots with very low fluxes, and therefore the absolute error in the determined flux values was small and could not change the conclusion of the study.

The active layer measurements were conducted by several different people on different occasions. This may have an impact on the measurement accuracy since different people may use different ways of measuring. Also some of them were students and may not

have experience conducting these kinds of measurements. Still, the overall trend with a deeper active layer in the manipulated compared with the control plots shown in the data is considered very solid.

Soil temperature from plot number 9 (Figure 3) and PAR values from plot number 7 (Figure 3) are missing, probably due to faulty equipment.

Methane

To justify the measurements of the field work for this thesis, a comparison was made between them and the results presented in Lund et al. (2009), who also measured CH_4 at the Storflaket mire. Only mean values of the CH_4 fluxes are provided in Lund et al. (2009), three in total from control plots. Moreover the values are from different seasons. Two of those were chosen for comparison; summer 0.30 and autumn 0.45 mg CH_4 m^{-2} h^{-1}, due to the timing the fieldwork for this thesis. It is also not known if the control values are from dry or wet areas of the mire. The CH_4 fluxes originating from this thesis are mean values of the data from control plots (0.15 mg CH_4 m^{-2} h^{-1}) and manipulated plots (0.66 mg CH_4 m^{-2} h^{-1}). Combining those two gives a mean value of 0.40 mg CH_4 m^{-2} h^{-1}. The measurements from this study are therefore within the span of Lund et al.'s (2009) measurements.

Our study shows that summertime CH_4 emissions are higher at locations where snow was accumulated in winter. In the manipulated plots it was easy to see with the naked eye how the snow has affected the ground. All of the manipulated plots have a large degraded part in the middle, an area in which the snow has been deepest. Figure 10 shows clearly that the active layer is thicker in the manipulated plots. However, in the control plots there has also been some degradation of permafrost, especially in plot number 1. This can perhaps be explained by the fact that the annual temperature in the area has been positive the last decade (seen in Figure 2). The fact that plot 1 is located close to the border of the mire could also be an aspect of this degradation.

The increased active layer means that the upper part of the permafrost has thawed and the ice lenses within it have melted, causing a "gap" in the soil, which most of the time is

filled with water. This can be seen in Figure 9 where the average height of the water table is shown plot by plot, and again the manipulated plots have the highest water table.

Johansson et al. (2013) show that the snow between the period of 2005 and 2013 began to fall around mid October and mid November and the start date is similar in all of the plots. However, over the years there has been a variation when the snow starts to melt, and the time difference of snow melt between control and manipulated plots. In 2007, 2008 and 2011 the snow disappeared three weeks later from the manipulated plots than in the control plots, but in 2012 there was only three days in between. This year the snow disappeared from the control plots around the 10th of May and from the manipulated plots around 25th of May, a little more than two weeks difference. Snow depths measurements from Abisko research station were used as a reference for, when the snow disappeared from the station. They have ten different plots they measure snow depths in, and the DOSM is determined when there is no snow left in any of them, which was the 27th of May. But the Swedish Metrological and Hydrological Institute (SMHI) have determined the DOSM in Abisko to the 18th of May. Using empirical calculations with the average CH_4 fluxes from both control (0.15 mg CH_4 m^{-2} h^{-1}) and manipulated (0.66 mg CH_4 m^{-2} h^{-1}) plots during the fieldwork, it will only take around 4 days until the manipulated plots have emitted the same quantity that the control plots have during 2 weeks. Because of the manipulated plots emits more than four times CH_4 than control, it is easy to assume that the accumulative emissions from the manipulated plots will be much higher, despite a shorter growing period and different fluxes for spring and autumn.

Two previous studies from a nearby mire(Jackowicz-Korczyński et al. 2010; Johansson et al. 2006b) have reported that there are higher emissions of CH_4 from wetter parts which is a direct response to permafrost degradation. They both studied a mire named Stordalen, which is located approximately three kilometres east of the mire Storflaket.

A statistical use of the Pearson test was conducted to quantify the correlation between all the variables collected at the mire. The largest correlation is between CH_4 flux and water table and active layer as seen in table 1. It is not a surprise that the water table is an important driver as this has been shown repeatedly in the literature. The water table is a major regulator of the CH_4 production (Bellisario et al. 1999; Christensen et al. 1995;

Whalen 2005). However in the same studies soil temperature was shown to be another factor, which was not seen in this study. This is probably due to the short duration of the measurement campaign in the current study.

Vascular plants

Due to the predetermined grid of the subplots inside the plots, the subplots did not have the same conditions as the average of the whole plot. To account for this, the rough vegetation inventory of every subplot individually was made because the water table and the thickness of the active layer have a great impact on the vegetation. When the permafrost thaws it releases nutrients that were frozen in the soil, that is becoming available for plants. Theoretically the amount of released nutrients is very high because just below the thaw-front there are nutrients that have been leached from the active layer into the frozen layer at the end of the summer. When the active layer increases due to global warming (or snow manipulation), those nutrients are free for the vegetation (Keuper et al. 2012). This could be an explanation for the quick increase of vascular plants biomass in areas where the permafrost is disappearing. Also when permafrost thaws, the area can become wetter or drier depending on how the hydrology is affected (Christensen 2014). On the Storflaket mire, the majority of the manipulated subplots and some of the control subplots became wetter.

In the majority of the wet subplots, a vascular plant family named *Eriophorum* was identified. Every subplot that had such vascular plants was put in the category with *Eriophorum*, although in some of the subplots this was not the dominating species.

Eriophorum species thrive in these wet habitats, especially when the permafrost is disappearing (Ström et al. 2015), which is seen in Figure 15 and 16. *Eriophorum* species show a strong relation to increased CH_4 emissions, which can be explained by the fact that *Eriophorum* species have a high gross primary production (GPP) (Ström et al. 2015). Emissions of CH_4 are higher in areas with *Eriophorum* than without (Figure 13) at the Storflaket mire, but it is not clear if this is because of the higher gross primary production or the fact that the *Eriophorum* species thrives in areas where CH_4 emissions already are

high. *Eriophorum* may also increase the emissions of CH_4 to the atmosphere due to the fact that they can act as a "chimney" for CH_4 and bypass the oxidation horizon, where a large portion of the CH_4 usually is oxidized (Christensen et al. 2000; Macdonald et al. 1998). In wetlands, with, for example, dominating vegetation like S*phagnum*, diffusion is the most common pathway for CH_4. During diffusion a large portion of the produced methane is oxidized (Mastepanov et al. 2012). It is not only the *Eriophorum* species that has this "chimney" effect, but in fact most of the vascular plants. Depending on the species, the level of efficiency can vary (Joabsson et al. 1999).

(Ström et al. 2005) measured the emissions of methane from peatland monoliths with different dominating vegetation, and one of them was *Eriophorum*. It was experimental and the monoliths were kept under constant light and temperature and a high water table over the duration of the experiment. They measured the average CH_4 flux to 2.38 mg CH_4 m^{-2} h^{-1}. The flux measurements originating from this thesis where *Eriophorum* was occurring and the water table was high the average flux was 1.41 mg CH_4 m^{-2} h^{-1}, which is not that much lower. The average flux in this study was measured during cold temperature, cloudy skies and small amounts of rain, not the most favourable conditions for emissions.

Before the industrial revolution the atmospheric CH_4 was around 715ppb, but in 2005 it was up in 1774ppb which is an increase of 148% and it the greatest increase of all the greenhouse gases (Forster et al. 2007). For comparison, CO_2 only increased 35% over the same time period (Miao et al. 2012). The majority of the methane emissions is man-made, but wetlands are the greatest single emission, accounting for around 20% of the global CH_4 budget (Christensen et al. 2003b; Jackowicz-Korczyński et al. 2010; Miao et al. 2012). As seen in both Figure 9 and 17 there is an exponential increase of CH_4 emissions from when the water table is 10 cm below surface and increasing. When the water table is over 10 cm above ground there is a decrease of the emissions again. This is shown in Figure 17, and not in Figure 9. That is why Figure 17 is shown, so that will not be an assumption from Figure 9 that the exponential increase will continue. When the water table is higher than 10 cm above the soil other processes in the wetlands take over which favours oxidation (Mastepanov et al. 2012). This is called the water table on/off-

switch (Christensen et al. 2003b) and during large scale variations of CH_4 emissions this on/off-switch is very important (Mastepanov et al. 2012).

To be able to make projections of Earth's climate changes we must learn more about the global budget of CH_4 (Miao et al. 2012). For instance, it is not possible today to predict if an area is becoming wetter or drier when permafrost thaws (Christensen 2014). This is an important process regarding if the decomposition will produce CH_4 or CO_2. Also if a wet area where high emissions of CH_4 occurs becomes wetter the emissions can decrease. This can work the other way around as well; a very wet area that becomes drier substantially increases the emissions because the water table is now inside the -10 +10 span from the soil surface.

Conclusions

There is a substantial difference between the emissions of CH_4 from the control and the manipulated plots with the latter showing much higher fluxes. Probably one of the main factors effecting the emissions is the presence of the *Eriophorum* species in the plots with artificially increased snow depth.

Accumulative emissions of CH_4 are also much higher for manipulated plots than the control plots over a growing season, despite that the season for the manipulated is shorter.

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Institutionen för naturgeografi och ekosystemvetenskap, Lunds Universitet.

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