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Spatiotemporal variation of net methane emissions and its causes across an ombrotrophic peatland

- A site study from Southern Sweden

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Abstract

Methane emissions from natural wetlands are an important contributor to methane levels in the atmosphere. These emissions are highly variable in time and space, even within sites. Further understanding of this variation is vital to successfully model the overall methane emissions from wetlands. This study investigates spatial variation through measurements of 22 plots across Fäjemyr bog. Manual measurements were taken in 16 plots across four sites at the bog during five days throughout November 2012. In addition 6 automatic chambers were used that measures emissions once every hour throughout the year. The emissions from these 6 automatic chambers were also used for assessing the temporal variation during the year 2012. The spatial variation was found to depend upon microtopography more than site location. Plot-specific variation was also found, which suggests that other variables also affect spatial variation. The temporal variation was generally best explained by temperature at soil depths of 20 and 50 cm, especially if daily averages were used. The importance of temporal scale became evident when correlations between net methane emissions and environmental variables changed depending on the time investigated. Yearly, seasonal and shorter timescales revealed different responses which were thought to depend on the seasonality of light and plant phenology at Fäjemyr in addition to the measured variables. Shorter timescales could be used to increase the process understanding of Fäjemyr. In addition, the study also reveals that the automatic chamber system poorly represents the methane emissions from hollows across the bog as emissions were lower than those measured in the manual plots. Emissions from lawns and hummocks seem to be better represented.

Keywords:
Geography • Physical Geography • Methane • Spatial Variation • Temporal Variation • Ombrotrophic peatland

Sammanfattning

Naturliga metanutsläpp sker från våra våtmarker världen över. Metan produceras naturligt genom nedbrytning i de syrefria förhållanden som en våtmark erbjuder. För att bättre kunna modellera och skala upp hur mycker metan som faktiskt släpps ut från dessa våtmarker måste ytterligare förståelse skapas över varför metanutsläppen varierar så kraftigt både i tid och rum. Denna studie försöker öka förståelsen för dessa variationer genom att följa både utsläpp och olika variabler så som temperatur, vattennivå, markfuktighet, lufttryck, och ljus för fotosyntes för at se hur de samvarierar på Fäjemyr, Skåne. Samt hur skillnader i rum, så som växtligthet och mikrotopografi påverkar utsläppens storlek i varje undersökt plot. För att mäta metan har 22 kammare använts. 16 av dessa har placerats runt om Fäjemyr under November månad 2012, medan 6 kammare ingår i ett automatiskt system som mäter utsläpp en gång i timmen under året. Dessa 6 kammare användes för att titta på den temporala variationen, medan alla kammare användes i den spatiala analysen. Främst var det skillnader i mikrotopografi som bidrog till skillnader i storleken på utsläpp. Vegetationen gav inget klart resultat i denna studie, men det är troligt att både vegetation och andra variabler påverkar. Skillnader över tid förklarades generellt bäst när utsläppen korrelerades med marktemperaturer på 20 och 50 cm djup, sambandet blev generellt starkare vid användning av dygnsmedelvärden av utsläpp. Betydelsen av temporal skala blev tydlig i denna studie då flera olika tidsperspektiv studerades. Olika variabler blev mer eller mindre viktiga för utsläppen beroende på temporal skala. Det är troligt att den bästa processförståelsen ges om kortare tidsskalor används. Vid längre tidsskalor påverkar nämligen både ljus och fenologi förutom temperatur och hydrologi. Utöver studien av spatiotemporal variation kan även slutsatsen dras att utsläppen uppmätta i fem av sex kammrar i det automatiska systemet överenstämmer väl med de som uppmättes på andra delar av myren, detta gäller dock inte kammare tre, vars resultat visar betydligt lägre siffror än korrensponderande mätningar från övriga delar av myren.

Nyckelord:
Geografi • Naturgeografi • Metan • Spatial Variation • Temporal Variation • Näringsfattig myr

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1. Introduction

Concentrations of methane in the atmosphere have increased substantially since the Last Glacial Maximum and particularly since the industrial revolution. The current level (2011) of 1874 ppb in Northern Hemisphere and 1758 ppb in Southern Hemisphere (CDIAC, 2013) far exceeds the natural variability seen over glacials (~350 ppb) and interglacials (~800 ppb) during the last 800,000 years (Loulergue et al., 2008). Both natural and anthropogenic sources contribute to current levels and individual source strengths are covered in Denman et al. (2007).

Natural emissions from wetlands are the single largest contributor to methane emissions from natural systems (Denman et al., 2007). However, the uncertainty range of these emissions continues to be very large (Denman et al., 2007). Different methods have been applied to estimate these emissions, extrapolation from direct flux measurements and observations, process-based modeling (bottom-up approach), and inverse atmospheric modeling (top-down approach) (Denman et al., 2007).

It has been stated that uncertainties in the method of extrapolation of observed or modeled methane emissions from wetlands primarily arise from the large temporal and spatial variation of fluxes (Denman et al., 2007). Therefore this study aims to study this variation at a small local scale, and its correlation with environmental conditions in hope to improve our understanding of these systems, and in extension to allow for a better approximation of the contribution of methane from wetlands to the global methane budget.

A literature study has been conducted to further improve the process understanding of the methane emissions from Fäjemyr.

1.1. Aim

This study aims to investigate the spatiotemporal variation of methane emissions, and its causes across an ombrotrophic bog in Southern Sweden. This will be addressed; firstly by introducing process understanding of the system as given by recent literature, and why it is important to study methane emissions from wetlands. Secondly, a field study aimed to measure methane emissions at different parts of Fäjemyr have been conducted to look at the spatial variation across the bog and possible causes for this variation. Thirdly, the results from these measurements are compared to automatic methane measurements that are conducted on the bog, and have been for a number of years, to see if the automatic chamber system is representative for other parts of the bog. Lastly, the temporal variation of these automatic measurements across a year are related to environmental variables to find if spatiotemporal variation could be predicted at Fäjemyr, and thus in extension, incorporated into models for extrapolation.

2. Theoretical Background

2.1. Methane in the climate system

Methane along with other important greenhouse gases, particularly carbon dioxide, contributes to the net radiative forcing of the atmosphere through their ability to absorb and emit longwave radiation. The concept of radiative forcing is used to assess and compare different drivers of climate change and is most simply described as the change in net irradiance (solar and longwave) in Wm^{-2} at the tropopause (Forster et al., 2007). When this energy amount is increased, the Earth climate system must reach a new radiative equilibrium which it does by increasing the surface temperature. Increasing concentrations of greenhouse gases makes the atmosphere less transparent to longwave radiation and thus increase the net radiative forcing. Changes in this radiative forcing are at the heart of the Climate Change debate, where it is related to changes in global mean equilibrium temperature by:

$$\Delta T_s = \lambda \mathrm{RF} \quad (1)$$

Where ΔT_s is the change in global equilibrium surface temperature, λ is the climate sensitivity parameter and RF is radiative forcing. It is clear that a change in greenhouse gas concentrations will produce a change in radiative forcing, thus affecting the global average temperature (Forster et al., 2007). However, questions remain as to how much the temperature will increase, i.e. the climate sensitivity, as this depends on feedback mechanisms within the climate system, and between the climate system and other systems, such as the biosphere. One such feedback is that natural wetlands may increase their methane emission in response to a warmer climate (Forster et al., 2007).

The change in radiative forcing that is attributed to methane was calculated based on its change in mixing ratio between the years 1750 (715 ppb) and 2005 (1774 ppb). This gave a radiative forcing of +0.48 ±0.05 Wm^{-2} which makes it the second most important long lived greenhouse gas after carbon dioxide (Forster et al., 2007).

Methane also has indirect effects on the radiative forcing as other gases are formed when it is oxidized in the atmosphere (Whalen, 2005). Complete oxidation of methane produces CO_2, but also water vapor and ozone, which all are active greenhouse gases. There are also important links between methane, ozone and aerosols by which changes in one species can affect the others (Shindell et al., 2009). These indirect effects increase the influence of methane in the climate system (Whalen, 2005). An early study estimated the importance of this indirect influence of methane on the radiative forcing to be of a size around 30 % of the direct radiative forcing (Lelieveld et al., 1998).

On a mass basis, methane is counted as 25 times more effective than carbon dioxide in terms of global warming potential (GWP) over a 100 year perspective. The indirect effects of methane on other gases is incorporated into this figure. As the lifetime of methane is lower than that for carbon dioxide, the GWP is as large as 72 on a 20 year perspective, but only 7.6 on a 500 year perspective (Forster et al., 2007).

2.2. The Methane Budget

The sum of all emissions and sinks gives the methane budget, but as mentioned the closure of this budget has been lacking, with large uncertainties remaining (Denman et al., 2007).

2.2.1. Sources

Sources of methane can be subdivided into non-biogenic or biogenic where the biogenic sources contribute to more than 70% of the global total (Denman et al., 2007). Alternatively, sources can be subdivided into natural or anthropogenic where the latter is thought to be the main reason for increasing atmospheric concentration since the industrial revolution and are now accounting for more than 60% of the global budget (Denman et al., 2007). Pre-industrial anthropogenic emissions have been estimated to be around one order of magnitude smaller (10-30 Tg yr^{-1}) than the natural emissions at this time (190-250 Tg yr^{-1}) (, Houweling et al., 2000, Ruddiman and Thomson, 2001). The important anthropogenic sources are fossil fuel burning, biomass burning, rice agriculture, ruminants, and landfills and waste (Denman et al., 2007).

Among natural sources, wetlands are the largest contributors, and also with the largest uncertainties (Denman et al., 2007). The majority of emissions from wetlands are estimated to originate from the tropical and southern regions of the planet, where a seasonal pattern of methane emissions is less evident than at higher latitudes (Chen and Prinn, 2006). However, immense carbon reserves are held within northern peatlands, and changes in temperature and hydrology could promote enhanced decomposition of these. In fact increased emissions have been found at peatlands that experience permafrost melt, and these systems close to the 0 °C isotherm have been deemed especially sensitive (Christensen et al., 2004).

Other natural sources include termites, gas hydrates, other geological sources, the ocean, wild animals and wildfires (Denman et al., 2007).

2.2.2. Sinks

Methane is in contrast to carbon dioxide destroyed in the atmosphere, primarily by the OH radical (Denman et al., 2007). Biological oxidation in soil and loss to the stratosphere are also counted as important, but are relatively small sinks in comparison. However, soil oxidation is very important in the context of methane emissions from wetlands, as it decreases the net emissions from these. Much of the produced methane in wetlands is directly oxidized before it reaches the atmosphere and the size of production and oxidation may not be captured when only the net emission is measured. This subject is described more thoroughly in the section about methane oxidation.

2.2.3. Growth rate

The growth rate of methane in the atmosphere is seen in the imbalance between sources and sinks. Growing concentrations in the atmosphere has tightly followed a temperature increase at least for the last 800,000 years (Loulergue et al., 2008). Natural variations in atmospheric methane concentrations seen over the last 800 000 years, primarily between glacials and interglacials, was theorized to result mainly from changes in wetland extent and emissions but also on the feedback between vegetation cover/composition and the OH radical through biogenic volatile organic compounds (Loulergue et al., 2008, Kaplan et al., 2006).

Around the start of the new millennia the growth rate of methane in the atmosphere stabilized after a long period of steady increase since the industrial revolution (Dlugokencky et al., 1998). After this temporary respite the growth rate began to increase once more (Dlugokencky et al., 2009) and the behavior has puzzled the scientists since. Recent theories have looked at reduced sources (Kai et al., 2011) or enhanced sink capacity at a global scale (Aydin et al., 2011) but the whole picture remains incomplete. The discrepancies between these studies highlight the need for further research within this field.

2.3. Methane emissions from peatlands

The definition of a wetland that is one of the most commonly accepted is that of the Ramsar Convention on Wetlands of International Importance; “wetlands are areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters”. This intergovernmental treaty was written in 1971 and now includes 164 contracting parties (countries). As this definition is inclusive, further classification of wetlands is commonly applied to separate between location and hydrology (Keddy, 2010). The classification within the Ramsar Convention distinguish between 42 classes (Ramsar, 2012), however for the purpose of understanding variation in methane emissions across wetland types these classes may be narrowed further.

For the purpose of this work, all attention has been focused on peatlands. Peatlands are commonly separated into bogs and fens based on their hydrology. Bogs, sometimes called ombrotrophic peatlands, receive their water primarily or solely through precipitation, which produce nutrient-poor and acidic conditions (Gorham, 1991). Fens are minerotrophic peatlands, connected to the groundwater and are therefore more alkaline and nutrient-rich (Gorham, 1991). The nutrient status reflects on their vegetation composition (Gorham, 1991).

Net methane emissions from peatlands are a result of methane production, methane oxidation (Conrad, 1996) and transport pathway within the peat before the gas reaches the atmosphere (Whalen, 2005). A thorough understanding of these processes gives insight into how soil temperature, air pressure, plant type and water table depth and perhaps other variables influence the different components. This study is however unable to quantify the size and influence of each process (production, oxidation, transport pathway) as they are not measured in separate. Yet, these processes are reviewed below for better understanding and analysis.

2.3.1. Methane Production

The methane produced in wetlands is a result of methanogenesis of respiring microbes in anaerobic parts of the soil. In wetland systems about 50% of the carbon in cellulose (a polysaccharide) is degraded into CH_4 and 50% into CO_2 (Conrad, 1996). The anaerobic degradation of organic matter is mediated in several steps by a consortium of specialized microorganisms, which is covered in full in Conrad (1999). A simplified reaction goes as follows; the larger molecules, such as polysaccharides are broken down into successively smaller units down to acetate (CH_3COOH), hydrogen (H_2) and carbon dioxide (CO_2). These products are then converted into methane by methanogenic Archaea through two main pathways (Conrad, 1999).

$$CH_3COOH \rightarrow CH_4 + CO_2 \qquad \text{(I)}$$

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \qquad \text{(II)}$$

The first pathway is mediated by acetotrophic methanogens, while the other is mediated through hydrogenotrophic methanogens (Whalen, 2005). The theoretical importance of the two pathways is in the ratio of 2 to 1, while observations show variance around this number in both directions (Conrad, 1999). In acidic environments pathway (I) becomes more important as H_2 is scavenged by homoacetogenic bacteria, producing more acetate (Whalen, 2005). However, other studies have found that at pH 4.5, which is often prevalent in bogs, the methanogens are highly hydrogenotrophic (Horn et al., 2003). This was corroborated in a study of methanogenisis in a Canadian bog and fen where it was found that the methanogenisis in the bog was conducted essentially by pathway (II) (Alstad and Whiticar, 2011). Certain species of methanogens can also produce methane from formate, methanol and methylated amines (Whalen, 2005).

Methane production is controlled primarily on the presence of oxygen, as an anaerobic condition is a prerequisite (Whalen, 2005). In fact, the methanogens appear to be highly sensitive to oxygen exposure, with temporary inhibition as a result, thus a varying water table can influence the methane production (Whalen, 2005). The second most important control has been attributed to substrate availability and quality (Whalen, 2005). Also, as this form of methanogenisis is biogenic, temperature is another important variable, with higher temperatures giving higher production rates (Whalen, 2005). However, the estimates of how much a temperature increase will affect production rates vary considerably between studies and in a review of Whalen (2005) the Q_{10} (production rate change for a 10 degrees increase) ranges from 1 to 35. This large variability is unlikely due to a true physiological response of the methanogenic microbes to temperature, but rather these results reflect a temperature sensitivity among the different microbes that provide the precursors to methanogenisis when substrate is a limiting factor (Bergman et al., 1998).

Water table position has been said to control the *net* emissions of methane on larger temporal and spatial scales as it regulates the size of the anaerobic and aerobic zone when it is shifting (Moore et al., 2011). A lower water table position creates a smaller zone of methanogenisis, and a larger aerobic soil zone where the methane is oxidized (Whalen, 2005). Secondly, as stated above, oxygen exposure decreases the activity of the methanogens. Studies have shown a negative logarithmic relationship between water table depth and net methane emissions, meaning that a higher water table position induces higher methane emissions (Moore and Knowles, 1989, Moore and Dalva, 1993).

Since methanogenic activity is dependent on substrate quantity and quality, the net methane emissions have been found to correlate with the net ecosystem production across several wetland ecosystems (Whiting and Chanton, 1993), as well as the vegetation composition (Koelbener et al., 2010, Ström et al., 2012). Studies using ^{14}C labeled carbon have shown this carbon cycling between carbon assimilation through photosynthesis and carbon release from methane emissions to be very rapid (Wieder and Yavitt, 1994, King et al., 2002). King et al. (2002) found labeled carbon incorporated into a wet sedge tundra ecosystem by photosynthesis to be emitted as methane 2 h after injection.

2.3.2. Methane oxidation

Methane oxidation has been found to occur in several ways. This oxidation takes place both in the aerobic zone and anaerobic zone in the wetland, and thus substantially reduces the amount of methane that reaches the atmosphere. The most commonly described methane oxidation is that of aerobic oxidation where methane consumption is mediated by obligate methanotrophic bacteria (Whalen, 2005). The methanotrophs belong to the group of eubacteria, and oxidize methane sequentially to methanol, formaldehyde, formate, and carbon dioxide

$$CH_4 \rightarrow CH_3OH \rightarrow HCHO \rightarrow HCOOH \rightarrow CO_2 \qquad \text{(III)}$$

Many of the metabolic processes in anaerobic oxidation of methane are still speculative, as many microorganisms are still to be identified and studied (Hinrichs and Boetius, 2002). However, evidence point towards that in the presence of sulfate, a consortium of anaerobic methanotrophic and sulfate reducing bacteria use sulfate reduction to form bicarbonate, hydrogen sulfide and water (Barnes and Goldberg, 1976, Hinrichs and Boetius, 2002).

$$CH_4 + SO_4^{2-} \rightarrow HCO^{3-} + HS^{-} + H_2O \qquad \text{(IV)}$$

This process is most important in ocean sediments, were >90% of the methane produced is oxidized by this process (Hinrichs and Boetius, 2002). Recently, a denitrifying methanotrophic microorganism have been identified which break down nitrite (NO_2^-) into N_2 and O_2 to oxidize methane (Ettwig et al., 2008, Wu et al., 2011) with the net reaction

$$3CH_4 + 8NO_2^- + 8H^+ = 3CO_2 + 4N_2 + 10H_2O \qquad \text{(V)}$$

The study pointed towards the possibility of this reaction happening in anoxic ecosystems other than the eutrophic freshwater sediment used in that particular experiment (Wu et al., 2011). Indeed, anaerobic methane oxidation have been found in other wetland systems (Smemo and Yavitt, 2007).

More recent studies have stressed the importance of *Sphagnum* mosses, which are indicative of bogs, on methane oxidation (Kip et al., 2010, van Winden et al., 2012, Raghoebarsing et al., 2005, Larmola et al., 2009). The first step in this direction was taken when it was found that these mosses live in symbiosis with methanotrophic bacteria (Raghoebarsing et al., 2005). This relationship of mutual benefit provide the mosses with carbon for photosynthesis, and the photosynthesis provide oxygen for the methanotrophic bacteria (Raghoebarsing et al., 2005). Also, methane emissions have been found to increase if the layer of *Sphagnum* is removed, which is most probably an effect of decreased methane oxidation (van Winden et al., 2012). Methane oxidation has been found to be most efficient in places were the *Sphagnum* is submerged into water (Raghoebarsing et al., 2005, Kip et al., 2010). It is also under these conditions that the cycling of carbon and oxygen is most mutualistic between the organisms (Kip et al., 2010). It has been proposed that around 5 – 20% of the carbon fixated in *Sphagnum* mosses is derived from oxidized methane (Raghoebarsing et al., 2005). This was later corroborated by Larmola et al. (2009) who by isotope ratio analysis of incorporated carbon found that potentially 10 – 30% of the carbon in *Sphagnum* species may come from methane. This very efficient recycling of carbon within the peat ecosystem has been proposed to partly explain the paradox of high carbon burial in these systems with comparatively low primary productivity (Raghoebarsing et al., 2005).

In a global scale study of *Sphagnum* bog systems, the activity of methanotrophs were found to be highly temperature dependent with twice as high levels at 20 °C as at 10 °C (Q_{10}=2), and typically below detection limit at 4 °C (Kip et al., 2010). This, together with the evidence of high oxidization in waterlogged parts of the peat indicates that global warming may increase the methane oxidation in these systems (Kip et al., 2010). However, temperature treatments of incubated peat have shown that methanotrophs cannot increase their consumption at the same rate as methanogens increase their production at higher temperatures (van Winden et al., 2012). Comparing Q_{10} values for methane production (1-35) and oxidation (1-2) would also corroborate this statement (Whalen, 2005, Kip et al., 2010, Dunfield et al., 1993). The relative importance of methane oxidation of diffusive fluxes thus seems to depend on temperature. One study have found that 98% of the methane produced was consumed at 5 ºC, while at 25 ºC this was lowered to 50% (van Winden et al., 2012).

2.3.3. Methane transport

The amount of produced methane that reaches the surface depends on how much of the methane that is oxidized by methanotrophs while the methane travels towards the atmosphere (Whalen, 2005). This in turn largely depends on the transport pathway of methane from the soil to the atmosphere (Joabsson et al., 1999). Thus, although the transport pathway is not specifically addressed in this study, a brief description of them is given below as some clues still can be inferred as to why methane emissions are varying in time and space at Fäjemyr.

Diffusive transport is driven by the gradient of methane concentration from the deeper soil towards the surface according to Fick's first law:

$$J(C,z) = -D \times \frac{dC}{dz} \qquad (2)$$

Where J(C,z) is the diffusive flux of methane, D is the diffusion coefficient, C is the methane concentration and z is the depth of the soil. This diffusive flux is slower than the other transport pathways, and also expose the methane to the oxidizing methanotrophs (Whalen, 2005).

Methane is also released into the atmosphere in air bubbles that escapes the ground i.e. ebullition. These events of bubble release are often sporadic and local (Laing et al., 2008). The build-up and release of these bubbles from peat depend on a range of factors including methane production rate, location of hot spot production, the diffusive transport, and the physical properties of the peat (Coulthard et al., 2009). Peat porosity, bulk density and pore size all affects the entrapment of bubbles, and are all related to vegetation structure and composition (Strack et al., 2006).

Bursts of ebullition have been seen when the atmospheric pressure drops (Tokida et al., 2005, Tokida et al., 2007). The air pressure was found to control both the volumetric gas content in the peat, as stated in the ideal gas law, and the subsequent release of these bubbles (Tokida et al., 2007). It has been noted that these results may be influenced by local conditions such as the physical structure of the peat as results differ between sites (Strack et al., 2006, Laing et al., 2008,). Changes in air pressure also have the ability to affect how much of the gas that can be dissolved in water, and thereby the amount of methane in gaseous phase. One way of stating Henry's law is that *the solubility of a gas in a liquid is directly proportional to the partial pressure of the gas above the liquid*. Methane solubility in water also depends on the temperature of the soil water with higher temperatures leading to lower solubility, this in turn should produce more ebullition (Fechner-Levy and Hemond, 1996). However, due to the low thermal conductivity of the peat, temperature may be expected to play a larger role on these episodic events only if the water table is located near the peat surface, and thus more subjected to variations in air temperature (Tokida et al., 2007). Lastly, it is not a certainty that increased levels of methane in a gaseous phase directly leads to more ebullition as bubbles may be present without subsequent release as ebullitive flux (Laing et al., 2008).

For many years, ebullition was considered to be only locally important and more focus was given to the diffusive and plant mediated transport (Coulthard et al., 2009). This may also have been a result of the fact that it is difficult to quantify the ebullitive flux due to its episodic behavior (Tokida et al., 2007). However, studies from 2003 and onwards suggest that ebullition may be the dominant pathway of methane loss from peatlands, although this is still only a hypothesis, see Coulthard et al. (2009) for a more thorough review.

Methane can also be transported through vascular plants with internal aerenchymous structure. This tube-like structure acts as a conduit of diffusive gas transport whose main purpose is to provide oxygen to plant organs submerged in the anaerobic peat layer (Joabsson et al., 1999). Synchronously, methane is transported along its own concentration gradient in the opposite direction from the soil towards the atmosphere. The transport can also occur as a bulk flow. One mechanism for this bulk flow is thermo-osmosis, in which temperature differences between plant interior and exterior increase the pressure within the plant which then results in bulk movement of gas to the plant roots where the pressure is lower (Joabsson et al., 1999). When gas enters the soil from these roots, other gases such as methane are flushed into the atmosphere (Joabsson et al., 1999).

When methane is transported through plants the gas bypasses the aerobic soil layer which supposedly decreases the influence of methanotrophs on the net methane emissions (Whalen, 2005). Another effect on the net emissions caused by this gas transport is that it serves the rhizosphere with oxygen, so that methanogens may be inhibited and methane oxidation may occur in this otherwise anaerobic zone (Joabsson et al., 1999). The importance of this transport pathway has been the focus of numerous studies (Joabsson et al., 1999, Joabsson and Christensen, 2001, Koelbener et al., 2010) and severe reductions in emissions have been found when this transport pathway has been closed off (Schimel, 1995, Waddington et al., 1996, Frenzel and Karofeld, 2000). Contrary to this, Dinsmore et al. (2009) found lower methane emissions from sites containing vegetation with aerenchymous structures. They theorized that the oxygen provided to the anaerobic layer by the plants increased the methane oxidation at this site.

Species-dependent rates of transport have also been indicated among aerenchymous plants (Schimel, 1995). Emission rates through *Eriophorum augustifolium* (common cotton grass) was thought to depend on the resistance of diffusion between the rhizosphere and the root aerenchyma while *Carex aquatilis* provides the greatest resistance to methane flow at the plant stomata (Schimel, 1995).

It has also been found that dissolved methane is transported into the atmosphere by plant transpiration (Nisbet et al., 2009). This theory questions and discards the theory of substantial methane production *by* plants that was suggested by Keppler et al. (2006). A positive correlation (0.671) has been found between methane emissions and latent heat flux, which supports this theory (Long et al., 2010). They noted that this transport may be important in vegetation without aerenchymous structures.

2.4. Site description - Fäjemyr

This study is focused on methane measurements taken across an ombrotrophic peatland (Fäjemyr) in Southern Sweden (56º 15' N, 13º 33' E). Climatically, the area is classified as temperate, with a mean annual temperature of 6.2 ºC and an annual average precipitation of 700 mm (Lund, 2009). Fäjemyr is classified as an eccentric bog, with a peat layer extending 4-5 meters above the underlying bedrock, which has accumulated slowly during the last 6500 years (Lund et al., 2007). The topographical conditions prevents water from flowing into the bog from the surroundings, making it nutrient poor and acidic (surface pH generally <4) (Lund et al. 2007). On top of the bog, the surface topography is highly undulating but at micro scale, with repeating hummocks, lawns and hollows. As the bog is relatively dry, hummocks are more common than hollows (Lund, 2009).

The vegetation consists of species adapted to the harsh conditions. The moss consists mostly of different *Sphagnum* species; *S. magellanicum* Brid., *S. rubellum* Wils., *S. tenellum* (Brid.) Bory, *S. cuspidatum* Hoffm. and *S. fuscum* (Schimp.) Klinggr. The dominating vascular plants are *Calluna vulgaris* (L.) Hull, *Erica tetralix* L., *Eriophorum vaginatum* L., *Vaccinium oxycoccus* L., *Andromeda polifolia* L. and *Empetrum nigrum* L. *Eriophorum vaginatum* is classified as a graminoid, while the others are dwarf shrubs. The species are not treated individually in this study, but are separated into plant functional types with the categories Sphagnum, Heather and Graminoids.

3. Method and Materials

This study consists of two parts, one where samples of methane were taken in portable chambers and then analyzed in laboratory. The other part was to compare the results from these measurements to measurements gathered in an automatic system that is present on Fäjemyr. However, the study is not clearly divided between the two, instead data referred to as manual chamber data belong to the first kind, whereas autochamber data refers to the data from the automatic system of more continuous measurements.

3.1. General experimental setup

The data of methane emissions collected from portable chambers i.e. manual chamber data was gathered during the 15th, 21st 23rd, 27th and 29th of November 2012. Four sites were chosen arbitrarily while the four plots at each site were chosen to capture the microtopography of the bog, with one placed in a hollow, two on lawn, and one on a hummock. Site 1 was placed quite close to where the bog changes into forest, site 2 and 3 were placed within 150 m from the automatic measurement station, but in different directions from it. Site 4 was placed closer to the middle of the bog, where no measurements have been taken prior to this study.

To sample methane emissions from the bog, closed aluminum chambers with the size of 25*25*20 cm with an outlet on top were placed on the ground, enclosing existing vegetation, for

24 minutes at each plot. 10 ml air samples were taken with a syringe every eight minutes, with a total of four measurements at each plot, the last taken at 24 minutes since chamber closure. The samples were kept at room temperature overnight and were then analyzed the following day in a Gas Chromatograph (GC-2014) with a flame ionizing detector from Shimadzu. Sample separation was performed on Haysep Q column (2m long, 4 mm outer diameter and 3 mm inner diameter). As a carrier gas He 1 was used with a flow of 50 ml/min. Analytical conditions were as follows: oven temp 50 ºC, detector and injector temperature was 140 ºC. A standard of 12 ppm methane was used to solve accuracy (varied between 0.05 ppm to 0.12 ppm). Fluxes were calculated based on linear regression in Microsoft Excel 2010.

3.2. Flux calculation

The results from the GC were converted from concentration differences over time into fluxes of methane in ppm CH_4 $min^{-1}1/16m^{-2}$ with a fitted linear equation (3), done automatically by Microsoft Excel.

$$y = mx + b \quad (3)$$

Where y is ppm CH_4, m is the flux or rate of change in ppm CH_4 $min^{-1}1/16m^{-2}$, x is minutes and b is where the line intercepts the y axis at time 0. The goodness of fit was assessed by the coefficient of determination (r^2). The linear equations that could not be fitted easily ($r^2 < 0.5$) were discarded from this analysis. However, concentration changes with less standard deviation (variation) than the GC analyzer could solve (< 2 % of the average) were set to 0 irrespective of the r^2 value.

The flux was transformed into mg CH_4 m^{-2} h^{-1} through the use of the ideal gas law (equation 4), where a volume of air is converted into number of moles.

$$pV = nRT \quad (4)$$

Where p denotes air pressure in N m^{-2}, V is chamber volume in m^3, n is amount of substance or moles, R is the gas constant of 8.3145 J K^{-1} mol^{-1}, and T is temperature in Kelvin. Using the molar mass of methane, the number of moles was then transformed into grams of methane.

3.3. Autochamber data

The automatic chamber system at Fäjemyr is described in Lund (2009). This system allows for continuous measurements of the methane concentration when the chamber is closed. This system measures in all the six chambers every hour, and then repeats the process. Chamber sizes are 60*60 cm with individual heights determined by the enclosed vegetation height (around 20 cm). The analyzer is a Fast Methane Analyzer (Los Gatos Research). The data gathered within the automatic system were treated in a similar way as the manual camber data. However, the curve was fitted in a computer program (Mikhail Mastepanov, Lund University) which made it possible to align the linear curve manually. Half hourly samples of air temperature and pressure were used when transforming the concentrations into mg CH_4. When these values were not available the last previous record was used. The fluxes were also corrected for the individual chamber size.

As this system is automatized, fluxes from the six chambers are measured every hour throughout the season as long as the system is running without disruption. Unfortunately, during the year 2012, problems with electricity and other disruptions resulted in several both short and long periods without data collection. Some of the data was also discarded when the system was not giving credible results. This can be seen in figure 11 (page 22) where several disruptions in the data are visible. The longest period without data collection occurred between the 23rd of August and the 19th of October and was due to electricity failure.

The automatic chambers are located on different microtopographical features in order to capture and assess this assumed cause of variation (see table 2). They also constitute of different vegetation structure which is covered within the results section.

3.4. Environmental data

At each of the 16 plots measurements of soil temperature (digital temperature probe, 0.1 accuracy), soil moisture (ML3 –ThetaProbe soil moisture sensor, Delta T devices), and water table depth (measured within plastic tubes, 30 mm in diameter) were taken at each of the five measurement occasions. Also, as a part of the automatic system, continuous measurements of several environmental variables are taken at Fäjemyr. The variables used in this analysis are given in table 1. The names of the environmental variables are reoccurring in the result section of this study.

Table 1 Description of measurements and instruments available at Fäjemyr and used in this study.

Name	Description	Sensor
Soil T 5cm hum	Soil temperature 5 cm in hummock (°C)	Cu-Co thermocouples
Soil T 5cm rep	Soil temperature 5 cm in representative area (°C)	
Soil T 5cm hol	Soil temperature 5 cm in hollow (°C)	
Soil T 20cm rep	Soil temperature 20 cm in representative area (°C)	
Soil T 59cm rep	Soil temperature 50 cm in representative area (°C)	
Pt100	Soil temperature 5 cm in representative area (°C)	PT100
Air T	Air temperature (°C)	EMS 33 (EMS Brno)
Pressure	Barometric Pressure (hPa)	PTB110 (Vaisala Instruments)
Soil M rep	Soil moisture (vol/vol) in representative area	CS615 (Campbell Scientific
Soil M hum	Soil moisture (vol/vol) in hummock	
Soil M hol	Soil moisture (vol/vol) in hollow	
PAR	Incoming photosynthetic active radiation (umol m^{-2} s^{-1})	JYP1000 (SDEC)
Water Table Depth	Water table depth relative to the peat layer	SKPS1830 (Skye Instruments)
Precipitation	Precipitation (mm) measured by rain gauge	ARG100 (Skye Instruments)

After the measurement period, vegetation coverage and dry weight was analyzed and divided between three plant functional types, graminoids, *Sphagnum* mosses and heather. Vegetation coverage analysis was performed in the field with a simple frame of 16 sub-frames where plant functional type occurrence in 8 out of 16 frames corresponds to 50 % coverage etc. The dry weight analysis was performed by destructive sampling. The samples were then dried for 24h in a drying oven before weighing.

The individual automatic chambers are located at different height from the water table, which is only measured automatically at one point adjacent to the chambers. Corrections for individual chambers are therefore needed when the importance of water table depth is investigated. This correction was estimated by comparing 11 manual measurements of water table depth at individual chambers, taken throughout the year, with the data from the automatic sensor. The difference is expressed negatively if the water table is lower than at the automatic sensor. This average difference was removed for each individual chamber, to provide separate WTD time series for each autochamber.

A small dataset of air pressure was provided by Swedish Meteorological and Hydrological Institute (SMHI) to cover for the absence of such data from the automatic system in late October and early November. This data was generated in Ängelholm which is situated around 40 km from Fäjemyr (Euclidian distance). The data consist of half hourly values, which is the same resolution as provided by the automatic system at Fäjemyr.

3.5. Seasonal separation

The autochamber data from Fäjemyr was also separated into seasons to find if different environmental variables are more or less important throughout the year. The calendar definition used in Sweden was used for this purpose, where spring is defined as March - May, summer June - August, autumn September – November, and winter December – February.

3.6. Statistical approach

All statistical tests were performed within the SPSS ver. 17.0 software. The fluxes were checked for normality through a Shapiro-Wilk test in order to determine the appropriate statistical tests to be performed. This test showed that the data was not normally distributed. The data could also not be transformed, which excluded the use of parametric statistical tests.

Spatial variation of methane emissions across Fäjemyr was assessed by looking at variance among fluxes across space. Hypothesized causes for spatial variation are the microtopographical differences across the bog and also other spatial differences that would occur naturally across a system e.g. nutrient availability, vegetation, WTD, soil moisture, soil temperature etc. To allow for statistical testing of this behavior, the manual chamber fluxes were compared between the three groups hollow, hummock and lawn, and secondly separated between the four manual chamber sites or the six autochambers. The non-parametric equivalent to a one-way ANOVA, a Kruskal-Wallis test, was used for this problem. A post hoc test was needed to determine which of the samples that are different or similar as this is not specified in Kruskal-Wallis. A Mann-Whitney U-test was used for this purpose. A result from such an analysis tells whether the distribution of samples are more similar within a group than compared to samples from other groups, which would infer that spatial variation could be related to either the microtopographical features or something else occurring at site specific locations.

To analyze the causes of both spatial and temporal variation correlation (non-parametric) and regression was used. Spearman's correlation was used to find dependencies (linear associations) between methane flux and the different environmental controls; soil temperature, soil moisture water table depth, and vegetation that were taken along with the methane samples. More variables were used with the autochambers, e.g. Photosynthetic Active Radiation (PAR) and pressure, but also additional soil temperature measurements at different soil depths (see table 1). The autochamber data was correlated with half hourly samples of environmental variables, or daily averages when appropriate. Also, these tests were performed with the data divided into their microtopographical group, or separated between sites/chambers both for the manual chamber data and the autochamber data.

Regression analysis was used to generate residuals for subsequent analysis of relationships otherwise masked by the strong temperature dependencies. Curves of linear regression were also created to visualize relationships between fluxes and environmental variables.

A simple analysis of the size of the diurnal variation was made by comparing fluxes between 18:00 and 05:50, with fluxes between 06:00 and 17:50 for the different seasons.

3.6.1. Sample sizes

As soil temperature was not measured during the first day of data collection (15th of November), the correlation was calculated based on fewer samples. Also, the sample size of the microtopographical group lawn (N=36) is larger than for hollow (N=20) and hummock (N=18). Slight differences in sample size were also present when all samples were separated between sites, site 1 (N=18), site 2 (N=18), site 3 (N=19) and site 4 (N=19).

As for the autochamber data, none of the tested variables or fluxes have the same number of samples, giving that the number of coincident data within each test determine the sample sizes. However, generally the sample sizes from the autochambers are large and statistical corrections would have been needed if the significance of results would be displayed (Rogersson, 2001). Another problem is the spatial and temporal dependence between samples that also have an impact on the significance levels of the result, which is a second reason for not displaying significance for the results from the autochambers (Rogersson, 2001).

3.6.2. Outliers

The autochamber data was checked for outliers prior to statistical testing. The occurrence of ebullition likely contributed to most of the outliers found. The outliers were removed based on limits calculated within SPSS, and based on the entire dataset. These limits are statistically found, and are based on assumptions of normality. The lower limit was set to -0.78 and the upper limit to 0.96 mg CH_4 m^{-2} h^{-1}. This narrow interval still includes 94.6% of all fluxes. The autochamber data for the period November 15th to 29th which was analyzed separately for comparison to the manual chamber data was found to have the lower limit at -0.54 mg CH_4 m^{-2} h^{-1} and the higher limit at 0.89 mg CH_4 m^{-2} h^{-1} encompassing 98.5% of all fluxes. This was the only other dataset that had limits created other than the entire dataset. The data of environmental variables were not checked for outliers within SPSS, but unrealistic values (fault values) were removed.

4. Results

4.1. Meteorology

Meteorological conditions during 2012 as measured by the instruments at Fäjemyr. Annual means are not presented as there are very large gaps in the data (see figure 1). Precipitation amounted to around 730 mm in total over the year, which is a little higher than the long term (1961-1990) average (700 mm yr^{-1}) (Lund et al. 2009).

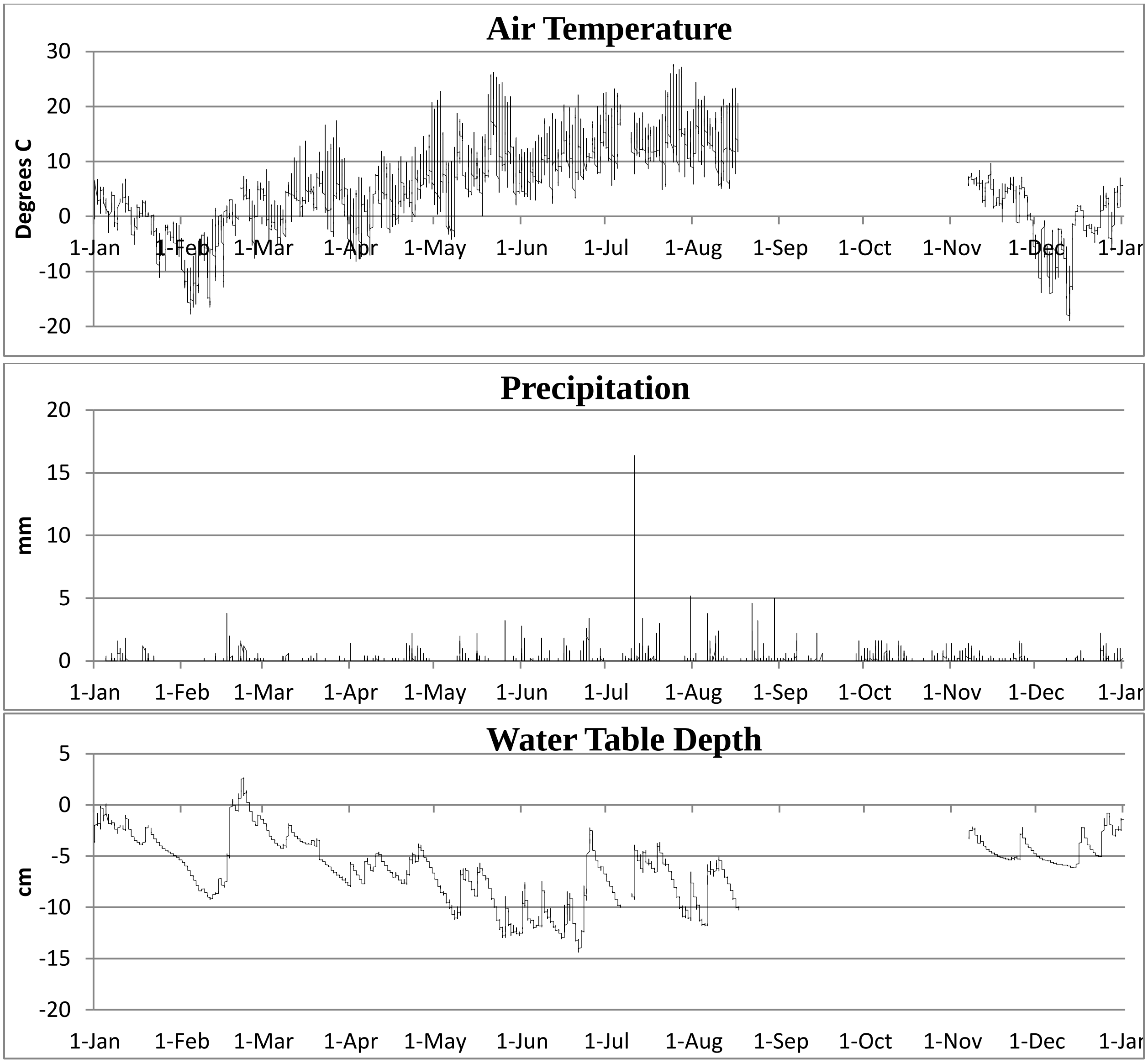

Figure 1 Half hourly records of air temperature (ºC), precipitation (mm) and water table depth (cm) recorded at Fäjemyr during 2012. All measurements are taken by respective instruments presented in Table 1. each at a location close to the autochambers.

4.2. Water table depth

The water table depth for each autochamber as compared to the half hourly records, taken at one location, is presented through the average difference and standard deviation in table 2 below.

Table 2 Description of autochamber microtopography, average difference from automatically measured water table depth and the standard deviation from this average.

Chamber	Microtopography	Average difference WTD	Standard deviation WTD
1	Lawn - high	-0.6	0.9
2	Lawn - low	3.0	1.6
3	Hollow	6.7	1.1
4	Lawn - low	1.5	1.6
5	Lawn - high	-3.2	1.3
6	Hummock	-21.6	2.9

Figure 2 below shows the average surface height above the water table (opposite sign) for the 16 measured plots. The plots were given names corresponding to their site and plot number, with 1.1 being site 1, plot 1.Hummock is here regarded as ≥15 cm above water table (plot 1.3, 2.2, 3.3, 4.1), Lawn between 5 and 15 cm (plot 1.1, 1.2, 2.3, 2.4, 3.1, 3.2, 4.2, 4.3) and Hollow <5 cm (plot 1.4, 2.1, 3.4, 4.4).

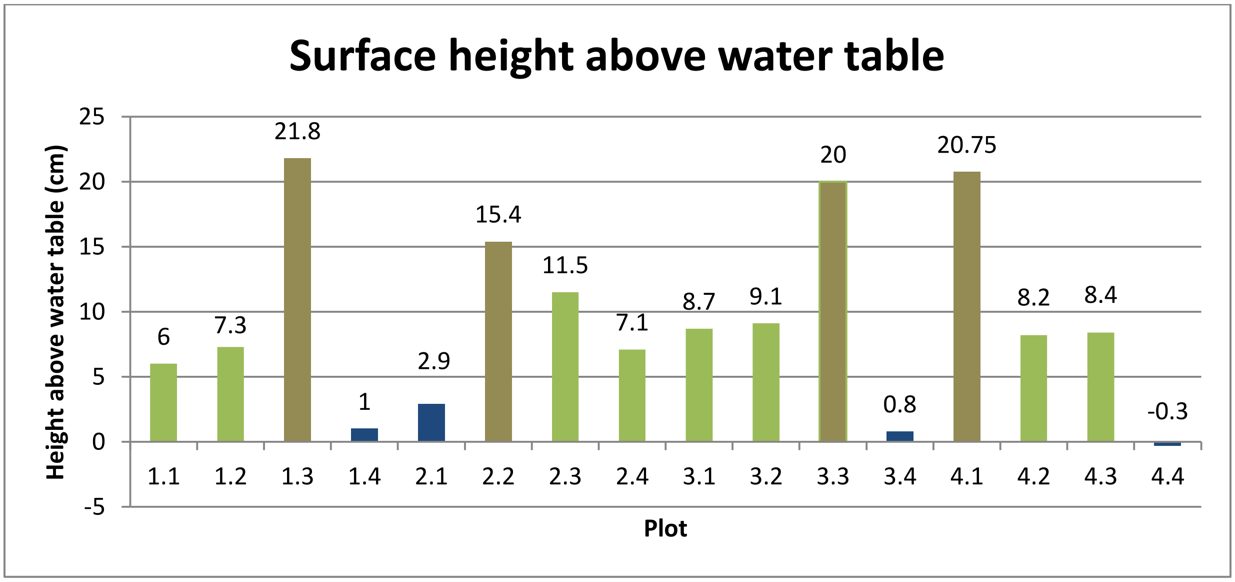

Figure 2 Microtopography of manual chamber plots inferred from surface height above the water table given in cm. Hummocks are shown as brown staples, lawns as green and hollows as blue.

4.3. Vegetation

The vegetation structure in the 16 manual chamber plots was investigated by looking at both PFT dry weight (figure 3) and PFT coverage (figure 4) which both varied between plots.

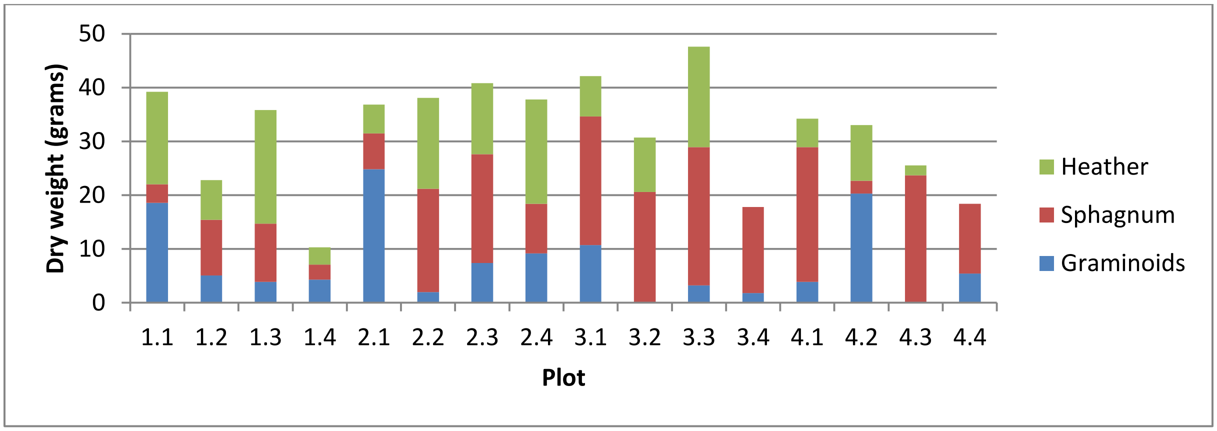

Figure 3 Vegetation structure presented through dry weight of each PFT in each manual chamber plot.

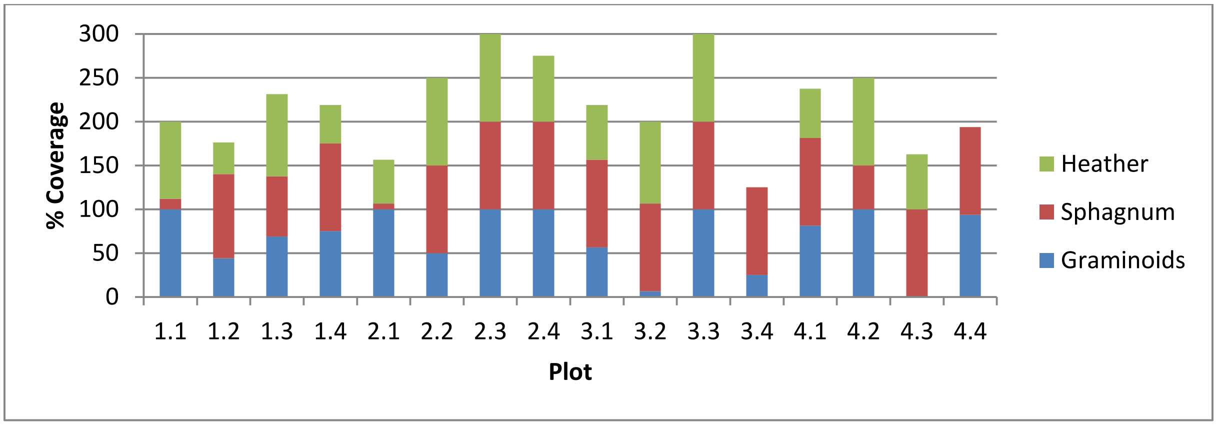

Figure 4 Vegetation coverage of each PFT in each manual chamber plot. Maximum coverage is 300% as the three PFTs can occupy 100% each if present in all sub-frames.

The vegetation structure in the six chambers was only investigated through coverage estimation as destructive sampling is not possible due to continued measurements (figure 5).

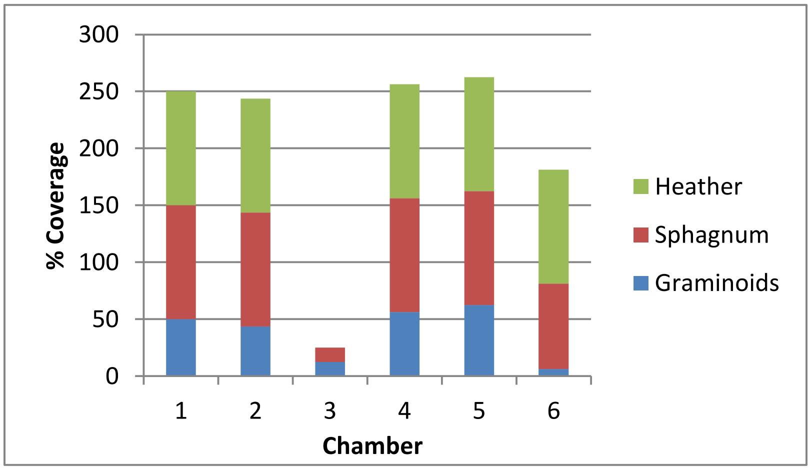

Figure 5 Vegetation coverage of each PFT in each autochamber. Maximum coverage is 300% as the three PFTs can occupy 100% each if present in all sub-frames.

4.4. Overview

The manual chamber data collected from the 16 plots at Fäjemyr shows large spatial and temporal variability with fluxes ranging from -0.02 to 3.58 mg CH_4 m^{-2} h^{-1}. In figure 6 below, the fluxes measured at each of the 16 plots during the five measurement days are shown.

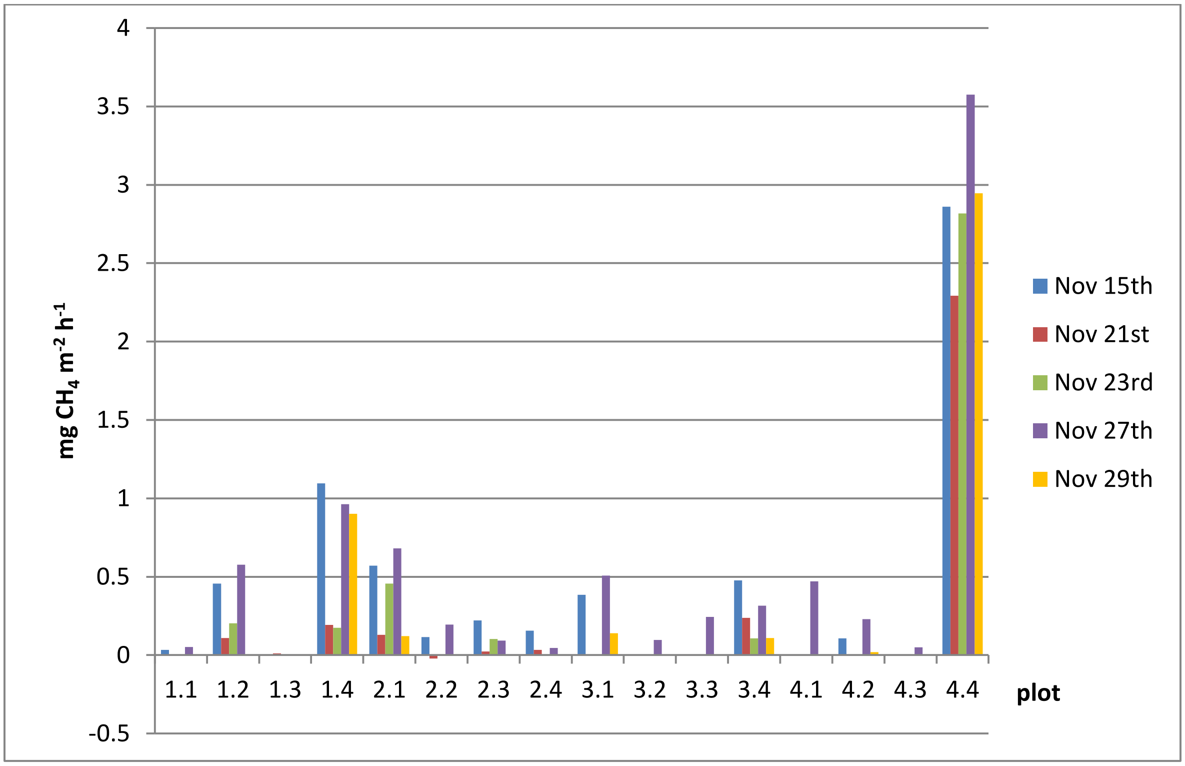

Figure 6 Sampled methane fluxes (mg CH_4 m^{-2} h^{-1}) from the 16 manual chamber plots during five days at Fäjemyr, November 2012. Bar color correspond to a certain date.

As seen in figure 6, plot 4.4 releases the highest fluxes during all days, and the size of these fluxes stand out in comparison to the others. It can also be seen that the fluxes released during the 27th of November are the highest in general within plots. Although this is far from a striking feature, it is also during this day that many plots had any measurable flux at all. In figure 7a-d some environmental variables measured during this period is presented. It is clear from these graphs that something occurred during the 25th to 27th of November, which could possibly have induced the comparably high fluxes during the 27th. There is a marked drop in both atmospheric pressure (figure 7a) and soil moisture (figure 7d). It should be noted that the soil temperature and soil moisture, which both vary in space, are measured close to the automatic chambers, and not directly adjacent to the manual chamber plots. Records of soil moisture taken at the plots do not show this behavior but continues with similar values throughout the five days. In contrast, soil temperature drops markedly in the water saturated manual chamber plots during the 29th.

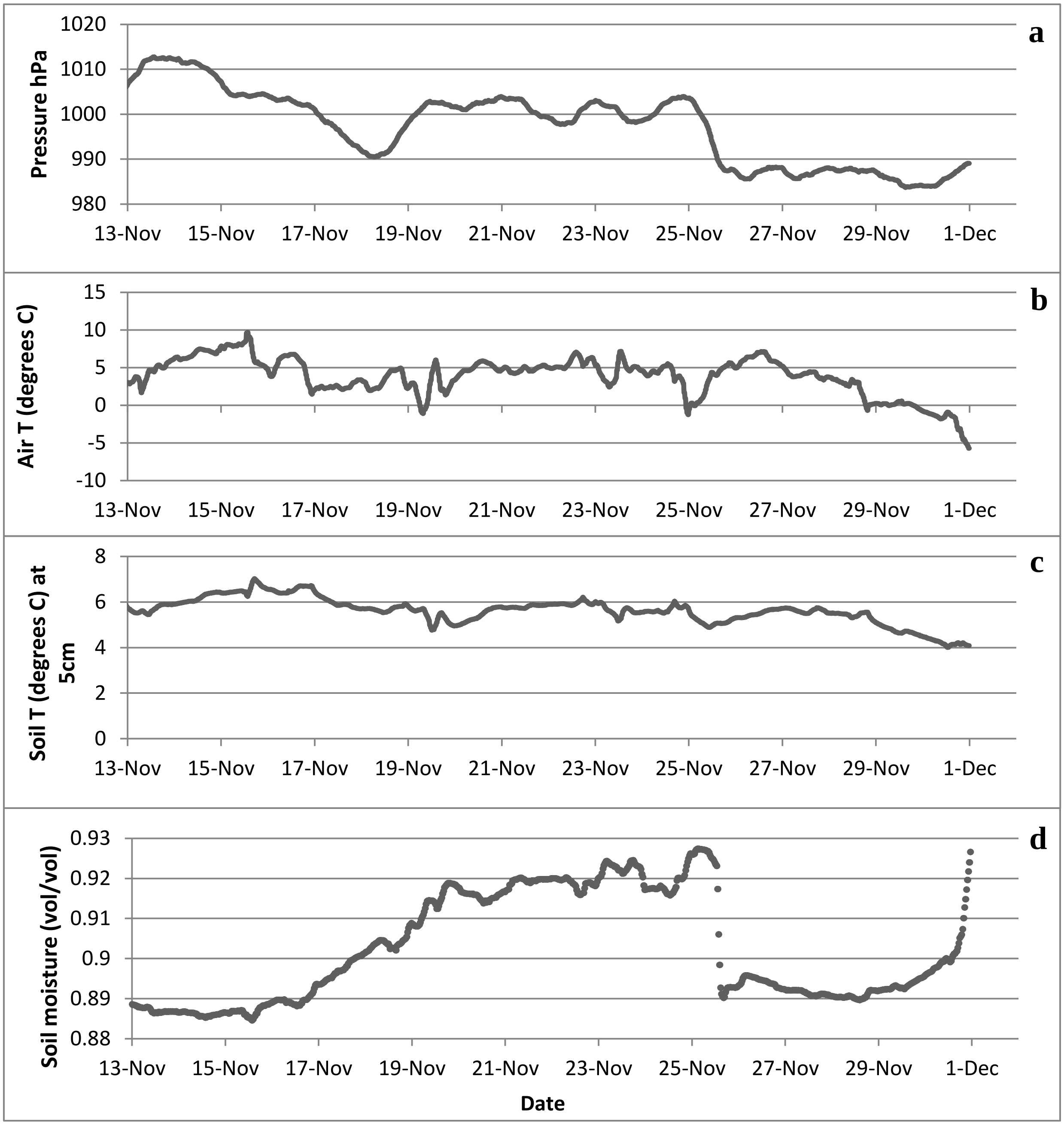

Figure 7a-d Development of (a) atmospheric pressure (hPa), (b) air temperature (°C), (c) soil temperature at 5cm in representative area(°C), and (d) soil moisture at hollow area (vol/vol) from the 13th of November to the 1st of December.

The fluxes measured in the automatic chambers also show high daily average fluxes during the 27th (figure 8) especially in chambers 3 and 6, but the response of the other chambers are less clear.

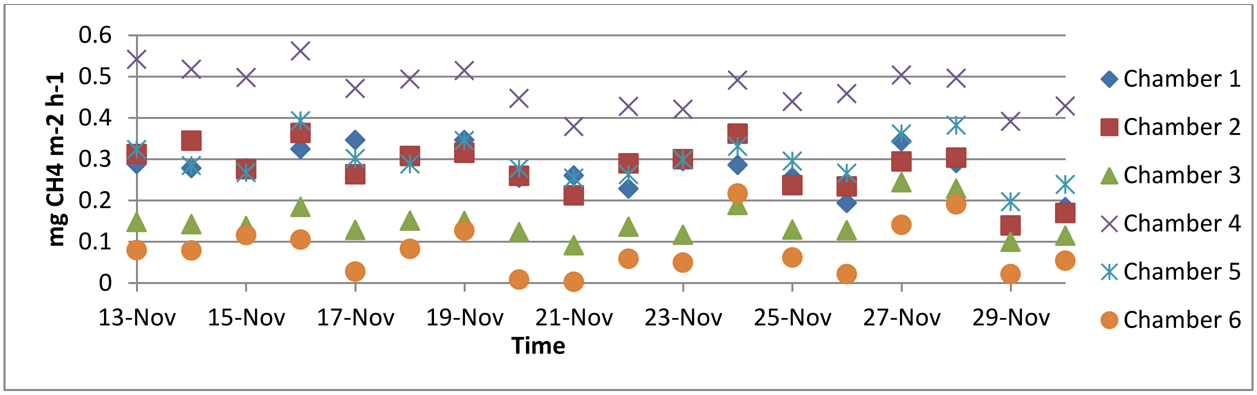

Figure 8 Daily averages of autochamber methane fluxes (mg CH_4 m^{-2} h^{-1}) separated between autochambers from the 13th to the 30th of November 2012.

Earlier in November, several very high individual fluxes (not averaged) were recorded (see figure 9). Some of these fluxes are much higher than any other fluxes measured in the autochambers during 2012 and point towards an event of ebullition release induced at several chambers within a short time-interval. Note that it is chamber 3, which otherwise emits comparatively low fluxes, that produces the highest fluxes. Unfortunately, no records of environmental variables were taken during this period. However, pressure data from SMHI recorded in Ängelholm is shown in figure 10 to give some clues as to what could have initiated this short but extensive burst of methane. As seen in figure 10, the pressure dropped during the 1st and 2nd of November after a period of high pressure. Both the high pressure of around 1030 hPa and the low pressure of 985 hPa are very uncommon in the dataset from Fäjemyr 2012.

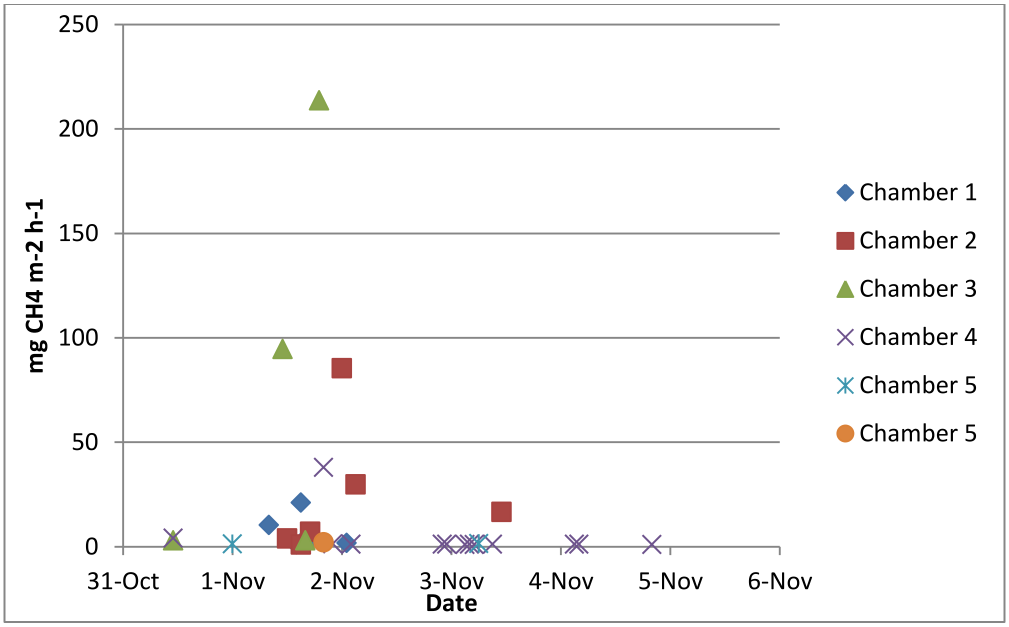

Figure 9 Individual methane fluxes (not averaged) >1.0 mg CH_4 m^{-2} h^{-1}measured by the autochambers between the 31st of October to the 5th of November. Lower fluxes are not shown for better visualization.

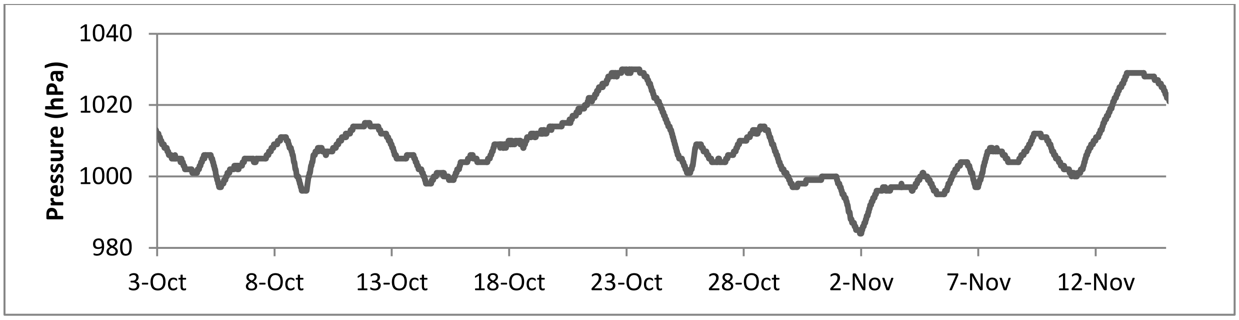

Figure 10 Air pressure (hPa) from SMHI, Ängelholm, October 3rd to November 14th 2012.

The autochambers measures methane continuously throughout the year, except during system failure. Two-day averages (used for better visualization) of these fluxes are demonstrated in figure 11. It is clear that the fluxes vary with season, with highest fluxes during summer and lowest during late winter to spring. It is also possible to see when the system has not been running. It is also demonstrated that each chamber has a certain individual range of emissions throughout the year indicating that spatial variation (environmental differences) between chambers produce differentiated emission patterns.

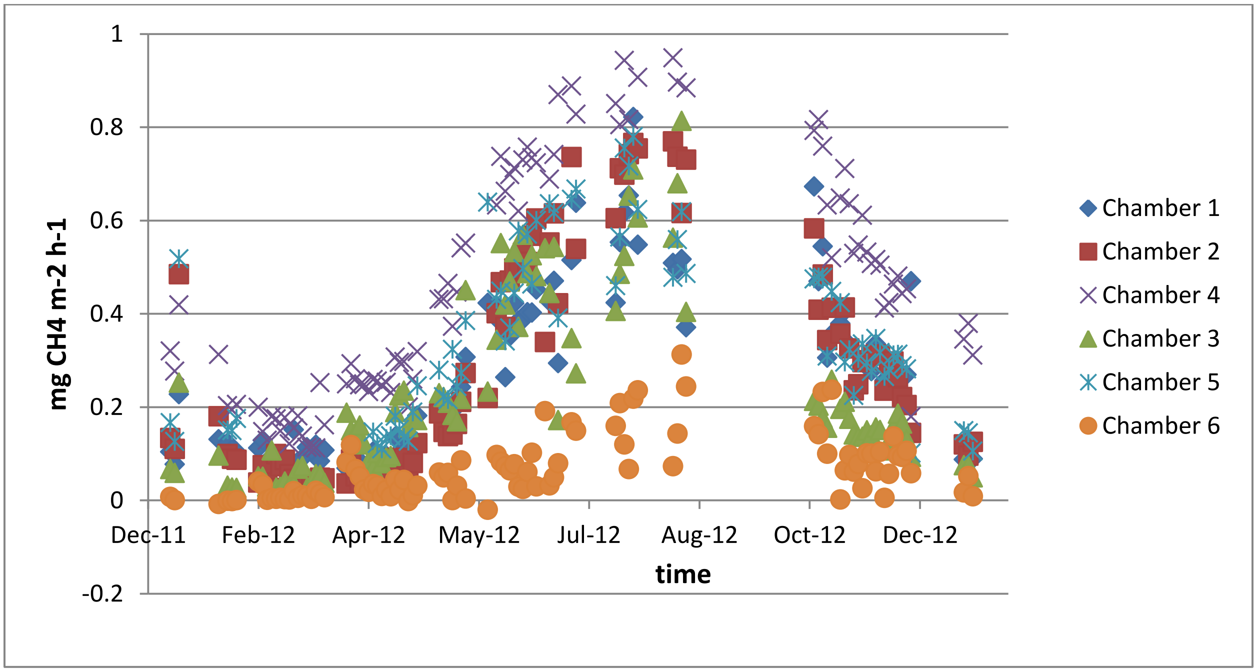

Figure 11 Two-day averages of autochamber methane fluxes (in mg CH_4 m^{-2} h^{-1}) during 2012, separated between chambers.

4.5. Comparison between autochambers and manual chamber plots

It is possible to compare the methane emissions sampled at the 16 manual chamber plots with the autochamber data from November. The overall aim with this is comparison is to determine whether the autochambers represent the methane fluxes well at Fäjemyr. As the plot measurements were taken at daytime, the comparison was made between the individual chamber averages of the automatic fluxes from 10.00 to 15.00 during the 15th, 21st, 23rd, 27th and 29th of November and the averages at the manual chamber plots, see table 3. It would seem that the fluxes from lawns (marked green) are higher in the automatic chambers than at the manual plots, while the flux from the hollow automatic chamber is very different from these fluxes measured at the manual plots (marked blue). The fluxes from hummocks (marked grey) could be considered similar among manual plots and automatic chambers.

Table 3 Average fluxes (mg CH_4 m^{-2} h^{-1}) based on five measurement occasions of the 16 manual chamber plots where site 2, plot 1 corresponds to plot name 2.1. Below the site-plot table is also autochamber averages of fluxes between 10.00 to 15.00 during the five measurement days (15th, 21st, 23rd, 27th and 29th of November).

	site 1	site 2	site 3	site 4	
plot 1	0.02	0.39	0.21	0.09	
plot 2	0.34	0.06	0.02	0.07	
plot 3	0.00	0.09	0.06	0.01	
plot 4	0.67	0.08	0.25	2.90	
Chamber 1	Chamber 2	Chamber 3	Chamber 4	Chamber 5	Chamber 6
0.29	0.20	0.11	0.39	0.24	0.03

Plot 4.4 is markedly different from all other plots investigated at Fäjemyr during this study, with a mean flux of 2.90 mg CH_4 m^{-2} h^{-1} averaged over the five different measurement days. The fluxes are comparatively very high during all measurements (see figure 6), a pattern which is not found among the automatic chambers where sporadic events of high emissions occur but not continuous ones.

4.6. Statistical analysis

4.6.1. Variance

4.6.1.1. Manual chamber plots

The Kruskal-Wallis test of variance applied to the data from the 16 plots revealed a significant difference between the microtopographical groups ($p<0.001$). The Mann-Whitney U-test showed significant difference between fluxes from hollows and lawns ($p=0.001$) as well as between hollows and hummocks ($p=0.001$). However no significant difference could be seen between fluxes from lawns and hummocks ($p=0.22$). The distribution of fluxes within each group can be seen in figure 12a.

The Kruskal-Wallis was also applied to determine differences between the four manual chamber sites, but no significant differences were found ($p=0.89$). This would suggest that the microtopographical setting is more determining for small scale spatial variations of methane fluxes, than location across the bog. However, it is easily seen in figure 12b that site number four support higher fluxes. This is mostly due to the behavior of manual chamber plot 4.4 which have comparatively large fluxes throughout the measurement period.

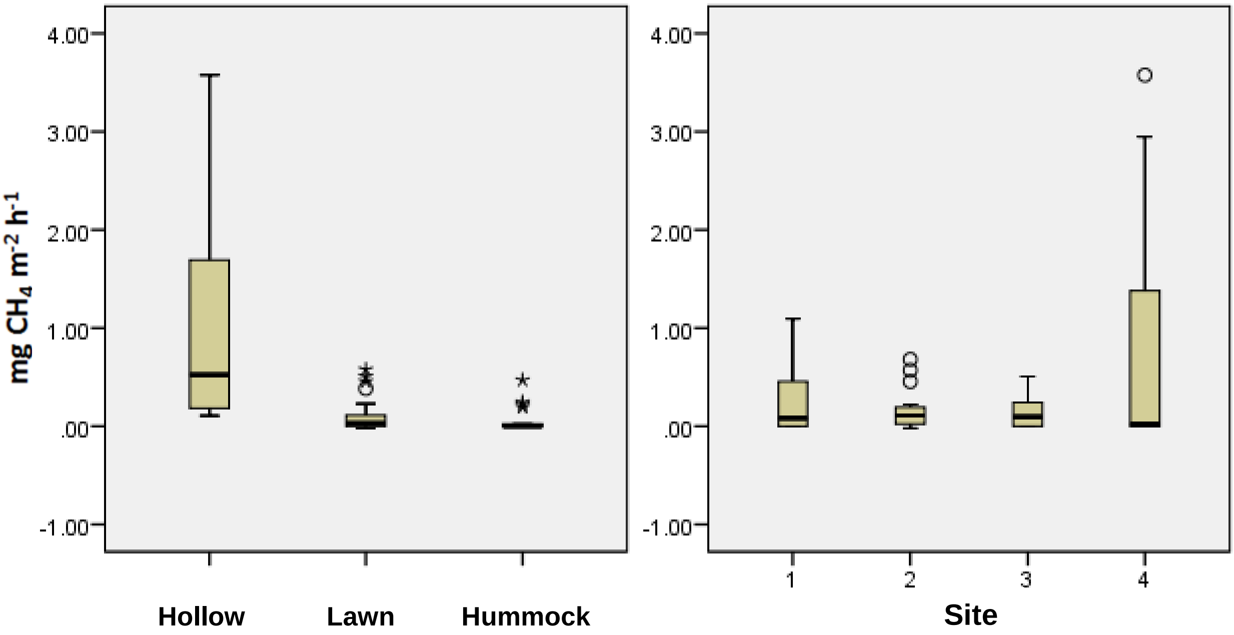

Figure 12a and b Comparison of the measured chamber plot methane flux distribution (mg CH_4 m^{-2} h^{-1}) between hollow, lawn and hummock in the left window (a), and the same comparison but between sites are depicted in the right window (b). The thick black line corresponds to the median flux, the bottom of the box shows the 25th percentile, while the upper shows the 75th percentile, allowing 50 % of the values to occur within the box. The T-bars extend 1.5 times the height of the box, or to the min or max value. Circles denote outliers, while asterisks denote extreme outliers.

4.6.1.2. Autochamber data

The Kruskal-Wallis analysis was also run to analyze the distribution of values across the different automatic chambers and microtopographical groups. Significant differences ($p<0.05$) were found for both categorizations, and figure 13a and b below shows boxplots of the distributions within each group. It should be noted that outliers relative to the complete dataset already have been removed.

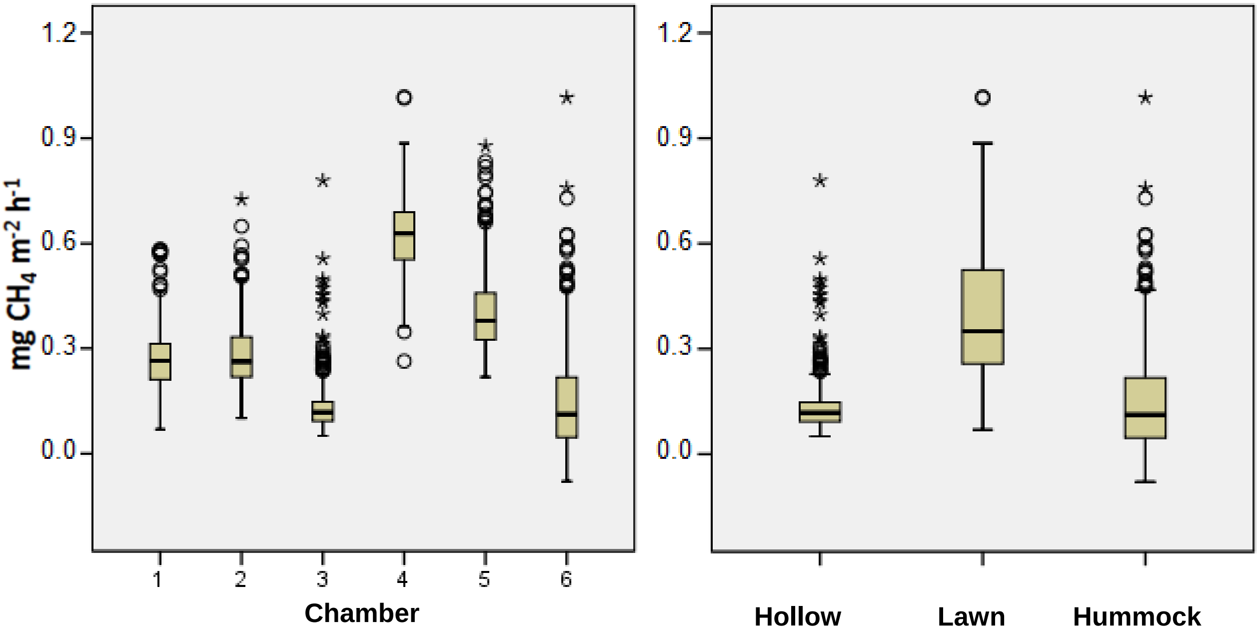

Figure 13a and b Comparison of the distribution of hourly methane fluxes (mg CH_4 m^{-2} h^{-1}) between autochambers (a) and microtopography (b). For figure explanation see figure 12 a and b.

The Kruskal-Wallis analyses point towards spatial variation across small scales at Fäjemyr.

If looking into the figure 13a in more detail, differences can be seen between the six autochambers. Chambers 1 and 2 seem to behave similarly to each other. Chamber 3 seems to have most of its fluxes within a very narrow range, but with a lot of events producing outliers (comparably high fluxes). Chamber 4 has the highest median, chamber 5 has the second highest median while chamber 6 has the lowest, and also produces most of the negative methane fluxes. This corresponds to the apparent ranges visible in figure 11.

When looking at the fluxes when divided into microtopographical groups (figure 13b), it is clear that the highest fluxes are produced at lawns, (chamber 1, 2, 4 and 5). Comparing this result from the autochambers to the manual chamber fluxes it is clear that chamber 3 (hollow) does not follow the same pattern as the manual chamber hollow-plots (figure 12a). Throughout 2012, chamber 3 has not supported any large amount of vegetation (see figure 5), rather the chamber is filled with water which makes it difficult to compare this chamber to any other plot sampled in this study.

4.6.2. Correlation

4.6.2.1. Manual chamber plots

By separating the manual chamber fluxes into microtopographical groups or sites, possible reasons for temporal variation within groups can be explored by correlating the fluxes with the measured environmental controls (soil temperature, soil moisture, water table depth and vegetation). Results from these analyses are given in table 4.

Table 4 Spearman's Correlation between environmental variables and; (a) all manual chamber plot methane fluxes as well as the same analysis but with fluxes divided into their microtopographical group, (b) fluxes separated between sites. Lastly part (c) describes the Spearman's correlation between coverage and dry weight of each PFT and the average flux from each of the 16 plots.

(a) All fluxes, and separated between microtopographical groups

	All	Hollow	Lawn	Hummock
Soil Moisture	0.60**	0.23	0.16	0.37
Soil Temperature	0.23	-0.37	0.08	0.57*
Water table Depth	0.63**	0.56*	0.16	0.48

(b) Site separation

Site	1	2	3	4
Soil Moisture	0.70**	0.60**	0.50*	0.57*
Soil Temperature	0.30	0.45	0.20	0.01
Water table Depth	0.68**	0.52**	0.16*	0.75**

(c) Vegetation analysis

	Graminoids	Heather	Sphagnum	Total
Coverage	0.03†	-0.70**†	0.11†	
Dry weight	0.34†	-0.63**†	-0.21†	-0.39†

*significant at the 0.05 level,
**significant at the 0.01 level.
† calculated based on plot averages

For the entire manual chamber dataset the most important environmental variable is water table depth (0.63) closely followed by soil moisture (0.60), see table 4.

The importance of environmental variables varies between the microtopographical groups (see table 4). If the fluxes originate from a hollow, the water table depth is statistically most important, while temperature is most important if the flux originate from a hummock. Fluxes from lawns show low dependencies with environmental variables. Note that the relationship between soil temperature and fluxes changes from negative to positive between hollows, lawns and hummocks.

When separated between sites, it becomes clearer that soil moisture and water table depth are important. Higher water table, or higher soil moisture content gives higher fluxes.

The vegetation analysis proposes that the absence of heather at a plot is more indicative of higher methane fluxes, than the presence of otherwise known supporters of methane emissions (aerenchymous graminoids). However, it should be noted that several species of graminoids and *Sphagnum* mosses are present across Fäjemyr, with niches ranging from wet to relatively drier conditions. Heather was not found in very wet areas. Fitted curves of the dependencies between average methane flux and vegetation are seen below in figures 14a-c (coverage) and 15a-d (dry weight).

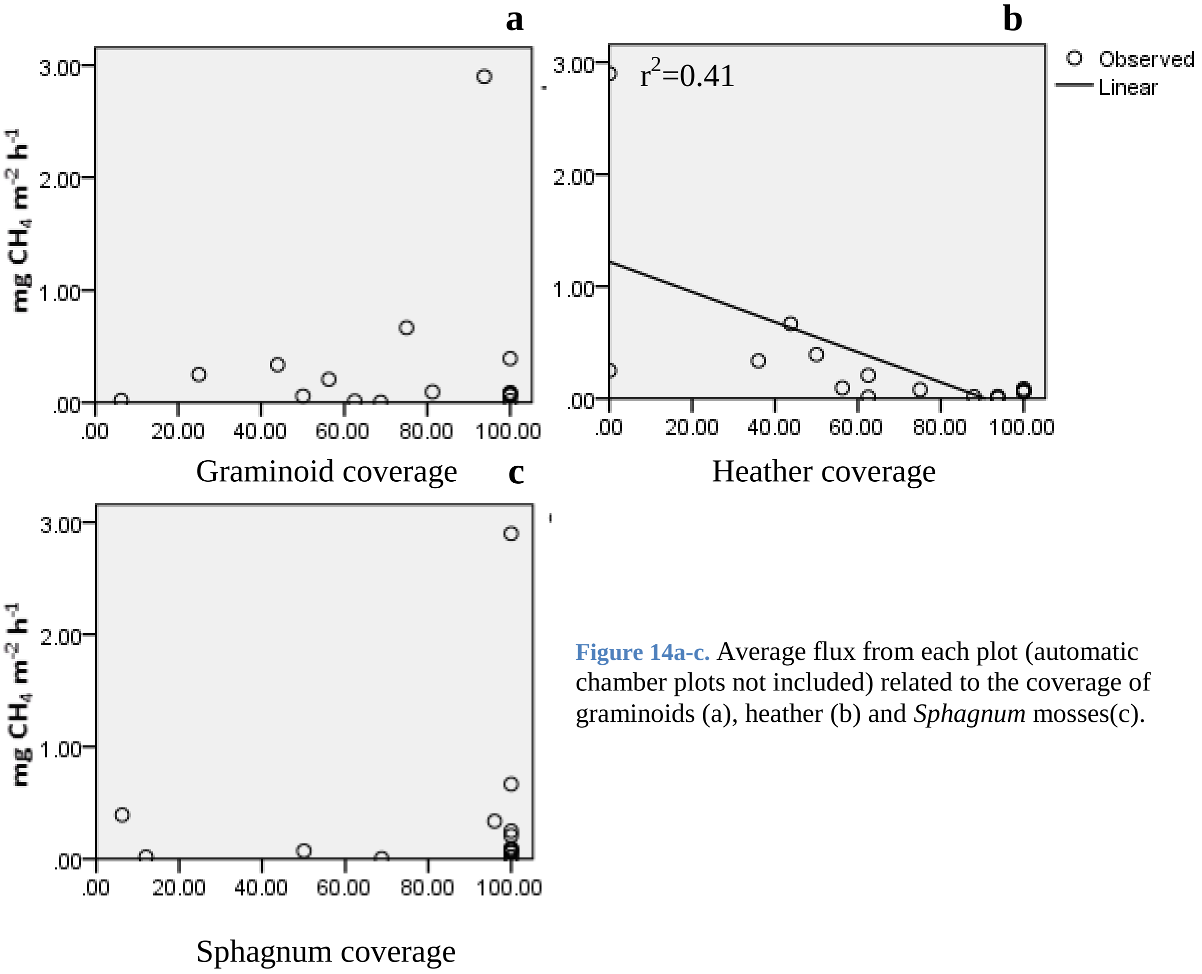

Figure 14a-c. Average flux from each plot (automatic chamber plots not included) related to the coverage of graminoids (a), heather (b) and *Sphagnum* mosses(c).

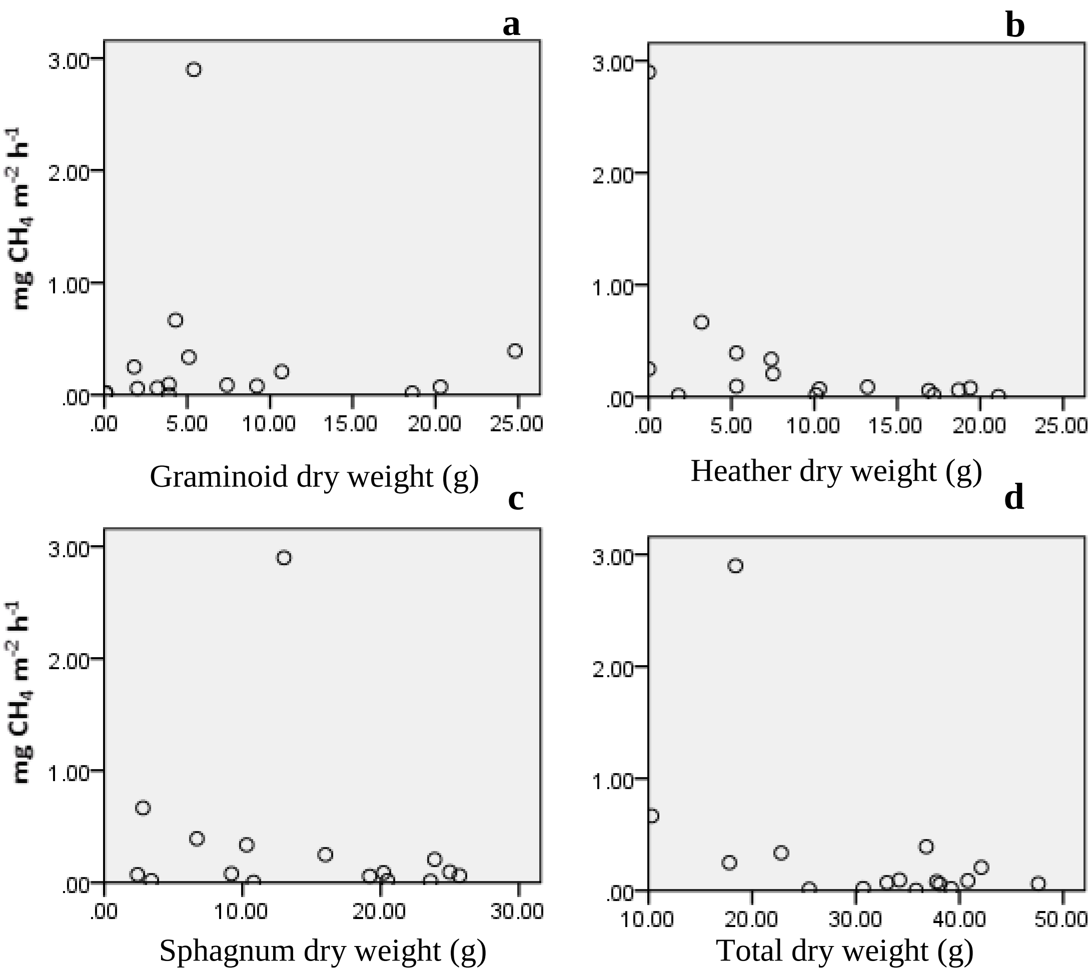

Figure 15 a-d Average flux from each manual chamber plot (automatic chamber plots not included) related to the dry weight of graminoids (a), heather (b) and sphagnum(c) and total (d) found at each plot.

The dry weight of the vegetation groups are also poorly related to the methane flux as seen in figure 15 a-d.

4.6.2.2. Autochamber data

Applying Spearman’s correlation to the autochamber data and environmental variables provide very different results depending on the data treatment (resolution and timescale). Daily averages of fluxes at longer or shorter time scales, seasonal separation of non-treated data etc., all produce different correlations between environmental variables and fluxes. However, the importance of temperature is reoccurring throughout the analyses (tables 5 through 16, exempting table 11). Similar for all these tables is that the highest correlation is marked with green and that invalid correlations according to chamber microtopography (e.g. Flux from lawn should not be correlated with soil temperature taken in hummock) are denoted with (-). Significance is not displayed because of autocorrelation and large sample sizes. Units for the environmental variables are given in table 1.

November

In order to compare the autochamber data with the manual chamber data the timescale was restricted to November only. Table 5 presents correlations between fluxes and environmental variables. When the fluxes are separated between the different chambers (compare column all chambers to 1, 2, 3 etc.), the correlations generally increases. Temperature seems to be the most important variable, while the correlation with water table depth changes signs between chambers. This is not consistent with the results from the manual chamber data where water table depth seems to be of more importance and temperature less so. Soil moisture is also negatively related to methane fluxes in November which is in direct contradiction to the results from the measured chambers.

Table 5 Spearman’s Correlation between autochamber methane flux (mg CH_4 m^{-2} h^{-1}) and all measured variables for all data and separated between chambers in November. The highest correlation within each column is marked with green,

November	All chambers	1	2	3	4	5	6
Soil T 5cm rep	0.15	0.30	0.43	-	0.49	0.35	-
Soil T 5cm hol	0.12	-	-	0.25	-	-	-
Soil T 5cm hum	0.08	-	-	-	-	-	0.15
Soil T 20cm rep	0.19	0.44	0.51	0.27	0.43	0.41	0.18
Soil T 50cm rep	0.11	0.30	0.33	0.10	0.38	0.19	0.19
PT100	0.13	0.27	0.40	0.23	0.47	0.31	0.14
Air T	-0.02	-0.07	0.11	-0.02	0.25	-0.05	-0.02
Soil moisture rep	-0.05	0.00	-0.09	-	-0.44	-0.15	-
Soil moisture hum	-0.01	-	-	-	-	-	0.11
Soil moisture hol	-0.08	-	-	-0.32	-	-	-
Pressure	0.13	0.29	0.45	0.12	0.12	0.19	0.18
Water table depth	0.13	-0.12	-0.07	0.22	0.39	0.05	0.16
PAR	-0.09	-0.13	-0.14	-0.11	-0.11	-0.16	-0.11

When the high resolution data of fluxes and environmental variables are translated into daily averages the diurnal pattern of both methane fluxes and environmental variables is removed. This results in increased correlations with temperature and that the influence of water table depth becomes positive in all chambers (table 6). The correlation with PAR also becomes positive although very low, while the influence of soil moisture remains negative in general.

Table 6 Spearman's Correlation between daily averages of autochamber methane flux (mg CH_4 m^{-2} h^{-1}) and all measured variables for all data and separated between chambers in November. The highest correlation within each column is marked with green.

Nov – daily averages	All chambers	1	2	3	4	5	6
Soil T 5cm rep	0.59	0.44	0.45	-	0.68	0.39	-
Soil T 5cm hol	0.57	-	-	0.15	-	-	-
Soil T 5cm hum	0.52	-	-	-	-	-	0.11
Soil T 20cm rep	0.45	0.63	0.62	0.34	0.56	0.44	0.27
Soil T 50cm rep	0.19	0.35	0.22	0.03	0.47	0.04	0.15
PT100	0.58	0.39	0.43	0.18	0.68	0.34	0.10
Air T	0.31	-0.11	0.01	-0.18	0.42	-0.09	-0.09
Soil moisture rep	-0.39	0.08	0.10	-	-0.55	-0.12	-
Soil moisture hum	-0.17	-	-	-	-	-	0.11
Soil moisture hol	-0.49	-	-	-0.19	-	-	-
Pressure	0.26	0.33	0.56	0.22	0.14	0.11	0.33
Water table depth	0.23	0.23	0.29	0.29	0.03	0.35	0.03
PAR	0.24	0.04	0.36	0.11	0.37	0.01	0.54

The high correlations with temperature are visualized through linear regression in figure 16a-f.

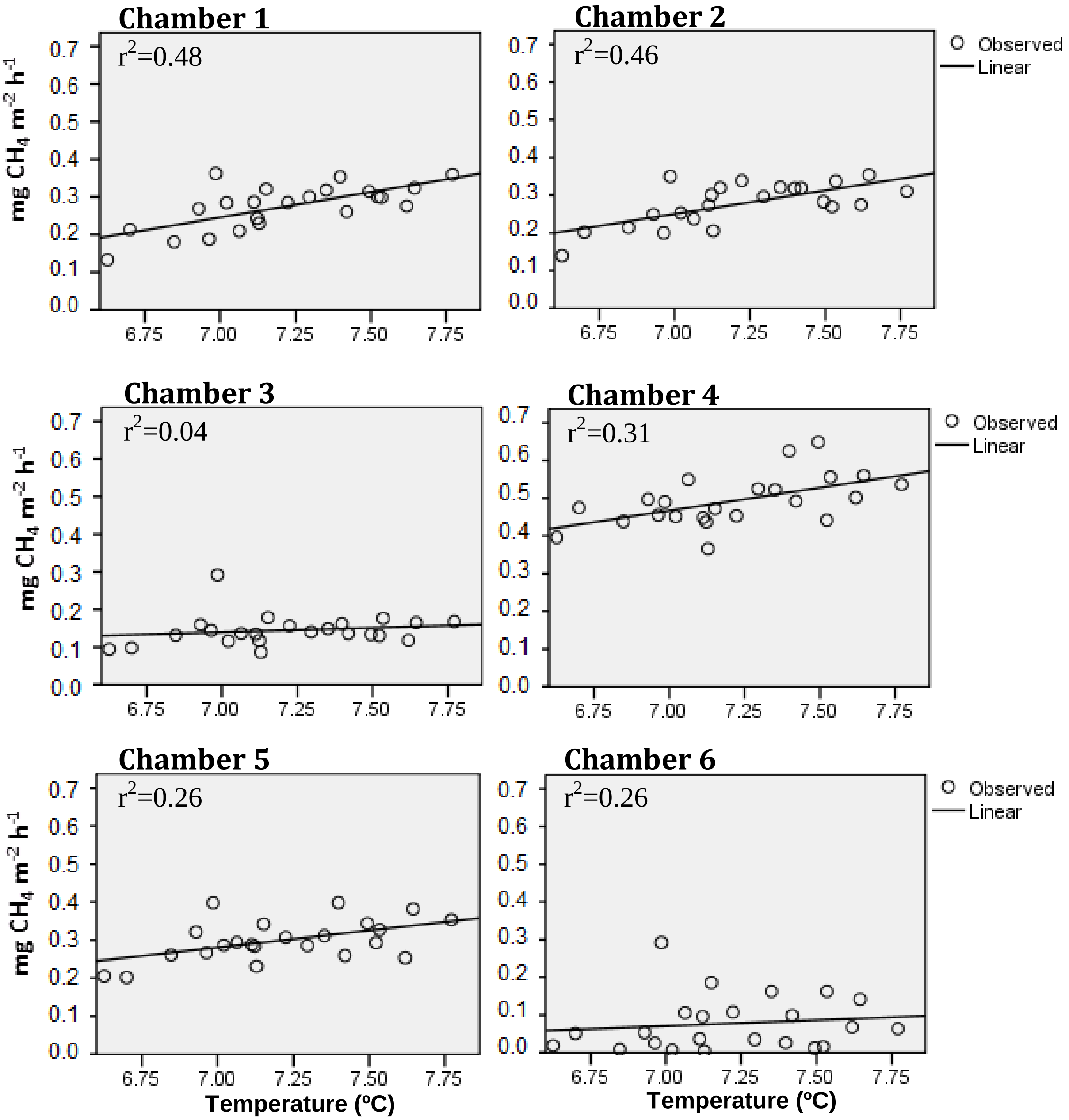

Figure 16a-f Linear regression of autochamber methane fluxes (mg CH_4 m^{-2} h^{-1}) and soil temperature at 20 cm (°C) for all autochambers as daily averages during November. The coefficient of determination is presented in each figure window.

Vegetation analysis

As with the manual chamber data, the vegetation analysis is made from averages fluxes from each autochamber. Since the number of autochambers is less than the number of plots, the analyses are hard to compare. However, the analysis shows that the presence of heather or *Sphagnum* mosses have very little influence on the methane fluxes ($r^2 < 0.05$) The presence of graminoids seems to increase the averages flux from a chamber (figure 17).

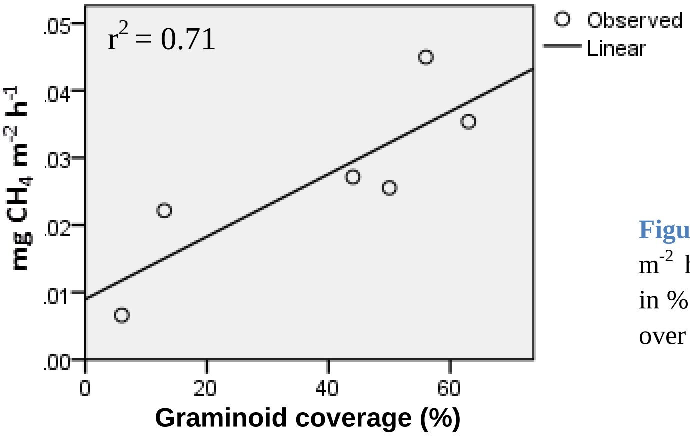

Figure 17 Methane emissions in mg CH_4 m^{-2} h^{-1} related to coverage of graminiods in %. The methane flux is the average flux over the entire year from each chamber

Year 2012

Daily averages of fluxes show very strong temperature dependencies as shown in table 7. This is not hard to imagine if looking at the appearance of figure 11 where a strong seasonal pattern in fluxes are visible. Especially soil temperature at depth seems to be of major importance.

Table 7 Spearman's Correlation between daily averages of autochamber methane flux (mg CH_4 m^{-2} h^{-1}) and all measured variables for all data and separated between chambers. The highest correlation within each column is marked with green.

2012, Daily averages	All chambers	1	2	3	4	5	6
Soil T 5cm rep	0.92	0.80	0.83	-	0.91	0.88	-
Soil T 5cm hol	0.84	-	-	0.80	-	-	-
Soil T 5cm hum	0.89	-	-	-	-	-	0.58
Soil T 20cm rep	0.95	0.84	0.87	0.88	0.94	0.90	0.65
Soil T 50cm rep	0.93	0.83	0.91	0.80	0.94	0.87	0.59
PT100	0.92	0.81	0.83	0.89	0.91	0.86	0.57
Air T	0.75	0.61	0.67	0.79	0.76	0.76	0.43
Soil moisture rep	-0.56	-0.50	-0.61	-	-0.55	-0.70	-
Soil moisture hum	-0.25	-	-	-	-	-	-0.05
Soil moisture hol	-0.6	-	-	-0.68	-	-	-
Pressure	-0.01	0.12	-0.05	-0.07	-0.07	0.30	0.15
Water table depth	-0.58	-0.52	-0.46	-0.69	-0.50	-0.52	-0.30
PAR	0.31	0.21	0.22	0.53	0.26	0.34	0.18

As soil temperature has such a strong correlation with fluxes at this scale, a residual analysis was performed to see if other variables increase or decrease in their importance when the temperatures signal is removed. The result from this analysis is presented in table 8, where it can be seen that the influence of soil moisture decreases and most importantly the water table depth goes from having a negative to positive correlation with daily average flux (compare table 7 and 8). Soil moisture and water table depth co-varies with soil temperature in negative relationships which would explain why the influence of soil moisture and water table depth changes when the influence of temperature is removed.

Table 8 Spearman's Correlation between methane flux (mg CH_4 m^{-2} h^{-1}) residuals of daily averages after regression with soil temperature at 20 cm and the non-temperature variables for all data and separated between chambers. The highest correlation within each column is marked with green.

2012, residuals of Daily averages (t20)	All chambers	1	2	3	4	5	6
Soil moisture rep	-0.22	-0.03	-0.25	-	-0.21	-0.14	-
Soil moisture hum	-0.14	-	-	-	-	-	0.17
Soil moisture hol	-0.11	-	-	-0.15	-	-	-
Pressure	0.14	0.34	0.21	-0.02	-0.03	0.11	0.32
Water table depth	0.02	0.46	0.75	0.02	-0.42	0.59	-0.01
PAR	-0.06	-0.20	-0.09	0.40	-0.15	0.04	-0.06

When correlation is applied to the entire dataset without any data alterations other than removal of outliers as described in the methods and materials section, the results are weaker but with the same tendencies as with the daily averages (compare table 7 and 9). Soil temperature at depth is still the most important determinant if seen across chambers.

Table 9 Spearman's Correlation between hourly autochamber methane flux (mg CH_4 m^{-2} h^{-1}) and all measured variables for all data and separated between chambers. The highest correlation within each column is marked with green.

Year 2012	All chambers	1	2	3	4	5	6
Soil T 5cm rep	0.56	0.68	0.75	-	0.84	0.77	-
Soil T 5cm hol	0.38	-	-	0.76	-	-	-
Soil T 5cm hum	0.53	-	-	-	-	-	0.34
Soil T 20cm rep	0.59	0.74	0.82	0.83	0.89	0.82	0.42
Soil T 50cm rep	0.59	0.74	0.86	0.75	0.90	0.81	0.38
PT100	0.53	0.63	0.73	0.82	0.84	0.68	0.33
Air T	0.34	0.31	0.48	0.63	0.58	0.43	0.12
Soil moisture rep	-0.28	-0.33	-0.49	-	-0.43	-0.48	-
Soil moisture hum	-0.07	-	-	-	-	-	0.12
Soil moisture hol	0.38	-	-	-0.57	-	-0.62	-
Pressure	-0.01	0.08	-0.06	-0.11	-0.14	0.24	0.09
Water table depth	0.09	-0.31	-0.33	-0.60	-0.42	-0.30	-0.11
PAR	0.04	-0.05	0.06	0.24	0.11	0.03	-0.13

It would seem yet again that the temperature dependency of fluxes mask the influence of other variables as seen when looking at the influence of water table depth which is negative, but positive when applying a residual analysis.

The temperature dependency across a year is also shown in figure 18a-f where the soil temperature at 50 cm is related to daily averaged methane flux for each individual chamber. In these figures each chamber responds differently to temperature (slope of the curve), which implies spatial differences across chambers that influence the amount of methane emitted, produced or oxidized at a given temperature.

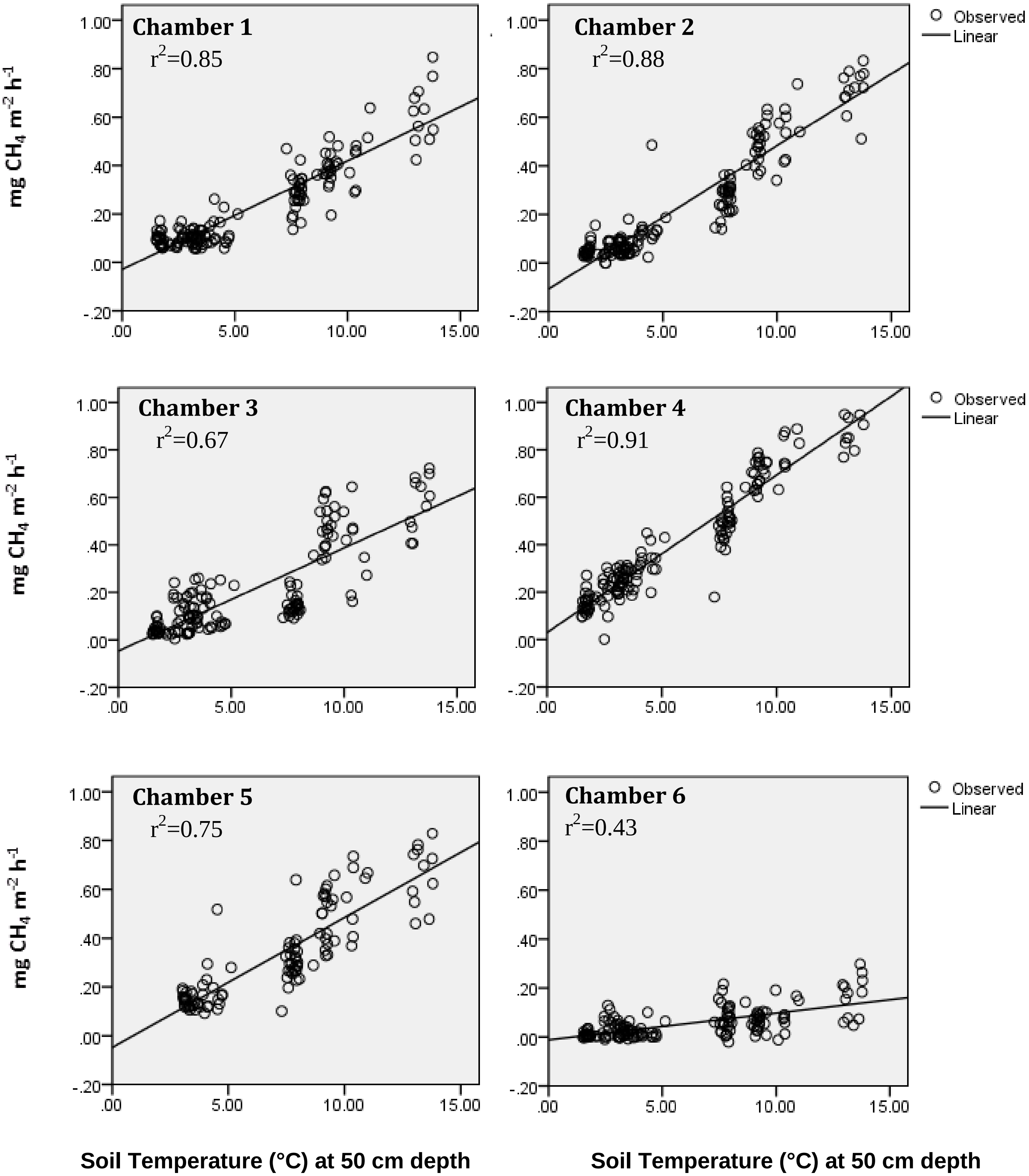

Figure 18a-f Relationships between daily averaged methane flux (mg CH_4 m^{-2} h^{-1}) and daily averaged soil temperature (°C) at 50 cm depth, measured at representative area, for individual automatic chambers during 2012 at Fäjemyr . All regressions are significant ($p<0.001$) but values are autocorrelated.

Seasonality

In another attempt to further analyze the influence of variables without the strong temperature, or seasonal signal, the fluxes were divided into seasons and then correlated with the environmental variables. The distributions of fluxes from the six chambers are shown with boxplots in figure 19a-d to give an indication of their behavior within each season. All chambers support higher fluxes during summer (June, July, August) and with more consistent variation (larger box and less outliers) and lowest fluxes in winter (December, January, February). Chamber 4 supports the highest fluxes throughout the seasons, while chamber 6 supports the lowest. The other chambers have a less consistent response, for instance chamber 2 peaks in summer, showing the second highest methane fluxes (median), while its fluxes during other seasons are rather modest.

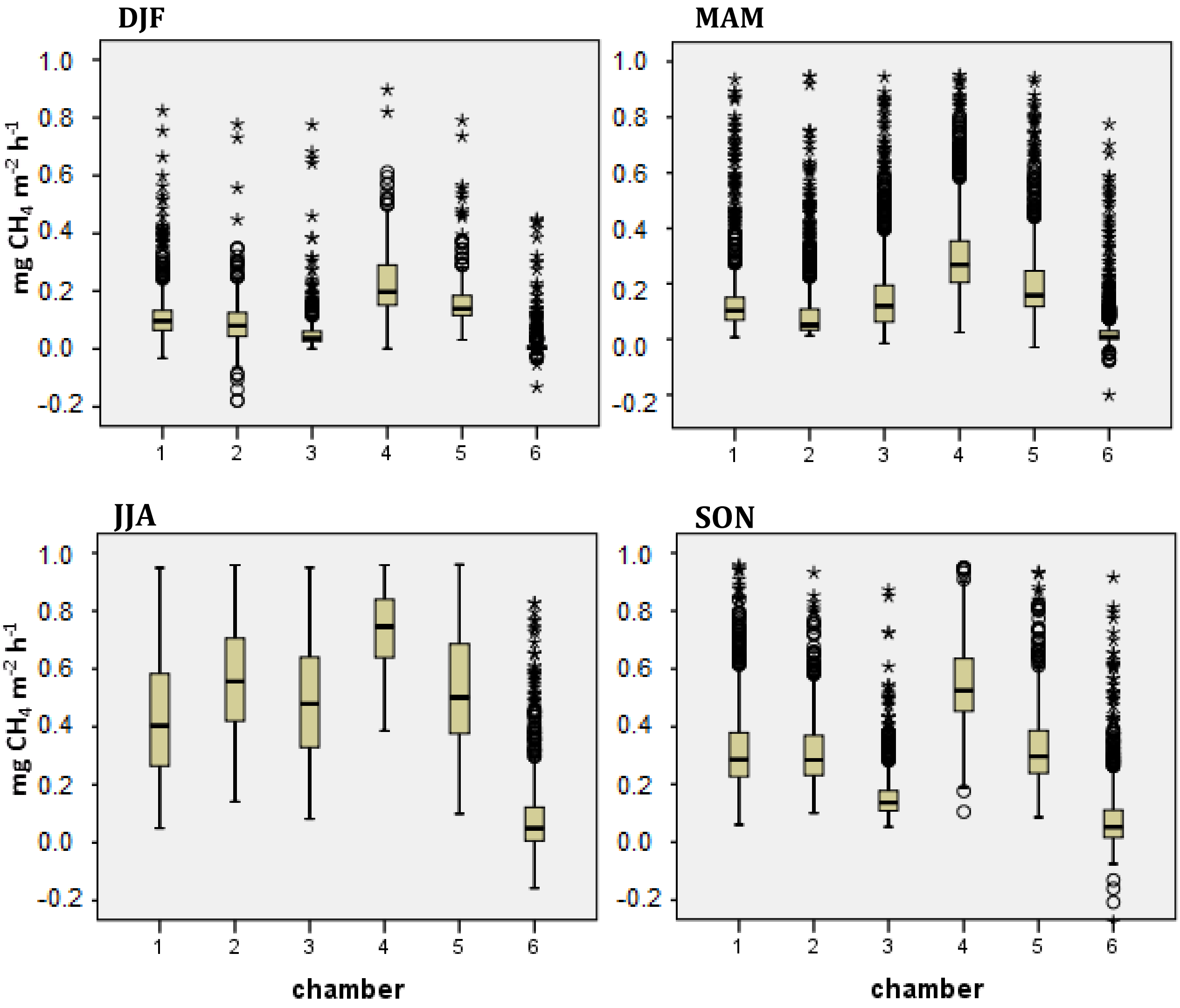

Figure 19a-d Comparison of the distribution of hourly methane fluxes (mg CH_4 m^{-2} h^{-1}) between chambers in (a) DJF – December, January, February, (b) MAM – Mars, April, May, (c) JJA – June, July, August, and (d) SON – September, October, November. SON only include data from late October and November as nothing was recorded from late August to the late October. Explanation of boxplot traits are given in figure 12 a and b

The variation within each chamber is generally largest in JJA – June, July, August (exempting outliers). This stands in contrast to the environmental variables that generally have the highest variation (standard deviation) during winter and spring, see table 10. This is probably a result of the diurnal variations of methane fluxes that are described further in pages 41 and 42 while the values displayed below also reflects seasonal variation.

Table 10 Mean values and variation of environmental variables described through one standard deviation from the mean during different seasons.

	DJF	MAM	JJA	SON
Soil T 5cm rep	1.23±0.95	5.40±4.99	14.48±2.05	5.74±0.60
Soil T 5cm hol	1.35±0.32	13.77±4.09	13.21±1.77	5.63±1.13
Soil T 5cm hum	0.09±1.23	4.93±2.55	14.58±2.85	5.07±1.32
Pressure	997.27±15.42	997.15±9.89	995.53±6.39	996.01±8.06
Soil T 20cm rep	2.26±1.43	4.06±3.30	13.71±2.03	7.20±0.34
Soil T 50cm rep	3.95±1.50	3.89±2.15	11.73±1.89	7.79±0.17
Soil T 5cm PT100	1.70±0.90	6.57±3.97	14.95±1.91	6.20±0.60
Air T	-2.31±5.27	6.58±6.04	13.87±4.43	4.45±2.51
Soil moisture rep	0.79±0.04	0.79±0.04	0.72±0.03	0.79±0.03
Soil moisture hum	0.57±0.08	0.54±0.04	0.50±0.03	0.61±0.01
Soil moisture hol	0.91±0.03	0.90±0.04	0.84±0.02	0.90±0.01
Water table depth	±2.56	±2.64	±2.69	±0.95
PAR	38.07±90.95	252.37±352.48	313.21±377.38	74.40±154.00

Table 11 Spearman's Correlation between autochamber hourly methane flux (mg CH_4 m^{-2} h^{-1}) and measured variables for all data and separated between seasons. In SON, only data from late October and November is available. The highest correlation within each chamber is marked with green background.

Season	all	DJF	MAM	JJA	SON$^+$
Soil T 5cm rep	0.56	0.32	0.35	0.15	0.15
Soil T 5cm hol	0.38	0.01	-0.15	0.06	0.12
Soil T 5cm hum	0.55	0.22	0.28	0.09	0.08
Soil T 20cm rep	0.59	0.32	0.35	0.21	0.19
Soil T 50cm rep	0.59	0.32	0.33	0.20	0.11
PT100	0.53	0.28	0.36	0.12	0.13
Air T	0.34	-0.08	0.15	0.04	-0.02
Soil moisture rep	-0.28	0.09	-0.25	-0.03	-0.05
Soil moisture hum	-0.07	0.28	-0.14	0.08	-0.01
Soil moisture hol	0.38	0.19	-0.33	-0.04	-0.08
Pressure	-0.01	-0.01	-0.02	0.13	0.13
Water table depth	0.09	0.21	0.19	0.43	0.13
PAR	0.04	-0.04	-0.07	-0.15	-0.05

$^+$ November only

When looking at the correlation for all chambers together but separated into seasons (table 11), the correlation with temperature is lower and the correlation with water table depth become positive without the use of a residual analysis. It is still soil temperature at depth that is the most important temperature influence across seasons.

It is probable that the rather low correlations (table 11) are a result of the use of all data together – not separated between chambers. This can be seen in table 12, which describes individual chamber fluxes in JJA where correlations increase.

Table 12 Spearman's Correlation between autochamber hourly methane flux (mg CH_4 m^{-2} h^{-1}) and all measured variables for all data, and separated between chambers from June, July and August. The highest correlation within each chamber is marked with green background.

June, July, August	All chambers	1	2	3	4	5	6
Soil T 5cm rep	0.15	0.37	0.42	-	0.23	0.39	-
Soil T 5cm hol	0.06	-	-	-0.03	-	-	-
Soil T 5cm hum	0.09	-	-	-	-	-	0.05
Soil T 20cm rep	0.21	0.49	0.54	0.23	0.43	0.43	0.40
Soil T 50cm rep	0.20	0.49	0.53	0.17	0.48	0.40	0.45
PT100	0.12	0.30	0.39	0.10	0.17	0.36	0.18
Air T	0.04	0.08	0.24	0.03	-0.01	0.24	-0.10
Soil moisture rep	-0.03	0.00	-0.11	-	0.24	-0.20	-
Soil moisture hum	0.08	-	-	-	-	-	0.52
Soil moisture hol	-0.04	-	-	-0.21	-	-	-
Pressure	0.13	0.30	0.43	0.21	0.07	0.28	0.18
Water table depth	0.46	0.06	0.03	-0.21	0.27	-0.03	0.25
PAR	-0.15	-0.35	-0.19	-0.16	-0.32	-0.25	-0.31

When looking at the summer season only (JJA), fluxes from individual chambers generally correlate most strongly with soil temperature at depth, and not water table depth which is the strongest determinant when the fluxes are analyzed irrespective of chambers. The only exception from this is chamber 6 where soil moisture seems to be of highest importance.

To further decrease the temporal scale the first two weeks in June were analyzed and are shown below. Table 13 shows Spearman's correlation for all autochamber data and separated between chambers. Here a strong diurnal signal is prominent (see figure 20), giving PAR a strong negative relationship with methane fluxes, which occurs as the methane fluxes peak around midnight, while the PAR peak around midday. The temperature dependency decreases markedly, especially at shallow soil depths, while the deeper layers still show correlations around 0.40. The reason for the inconsistent response to temperature also depends on this diurnal signal as soil temperature at depth lag behind the air temperature, and therefore reach its highest during the night (see figure 21). The shallow soil layers have a stronger diurnal pattern than deeper layers, but are reaching their daily peak earlier than the methane flux (compare figure 20 and 21).

Table 13 Spearman's Correlation between autochamber hourly methane flux(mg CH_4 m^{-2} h^{-1}) and all measured variables for all data, for the first two weeks in June 2012.

First two weeks in June	All chambers	1	2	3	4	5	6
Soil T 5cm rep	0.04	0.08	0.06	-	0.12	0.12	-
Soil T 5cm hol	0.01	-	-	-0.01	-	-	-
Soil T 5cm hum	-0.07	-	-	-	-	-	-0.22
Soil T 20cm rep	0.20	0.34	0.35	0.34	0.43	0.24	0.43
Soil T 50cm rep	0.23	0.47	0.44	0.32	0.43	0.28	0.51
PT100	-0.04	-0.09	-0.08	-0.12	-0.01	0.01	-0.10
Air T	-0.12	-0.27	-0.18	-0.21	-0.19	-0.01	-0.38
Soil moisture rep	0.13	0.28	0.22	-	0.23	0.13	-
Soil moisture hum	0.18	-	-	-	-	-	0.31
Soil moisture hol	0.12	-	-	0.24	-	-	-
Pressure	0.10	0.17	0.24	0.20	0.13	0.15	0.06
Water table depth	0.47	-0.06	-0.18	-0.12	-0.08	-0.05	-0.19
PAR	-0.31	-0.63	-0.57	-0.51	-0.56	-0.50	-0.36

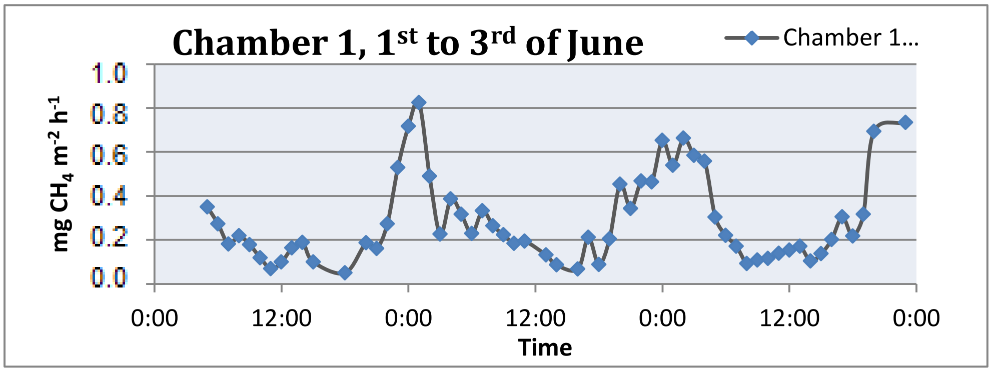

Figure 20 Diurnal development of autochamber methane flux (mg CH_4 m^{-2} h^{-1}) measured in chamber 1 between the 1st to 3rd of June 2012.

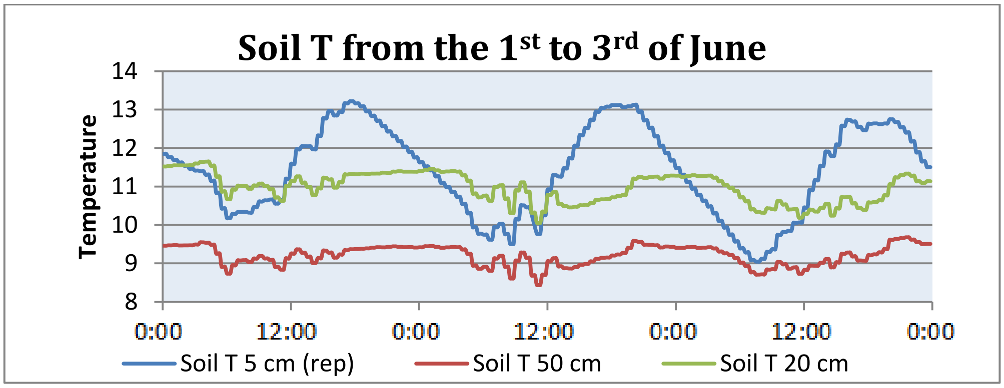

Figure 21 Soil temperature (°C) at 5, 20 and 50 cm depth from the 1st to the 3rd of June 2012. A diurnal cyclical pattern is visible, with the highest temperature reached around midnight at 20 and 50 cm, while it reaches its maximum at around mid-evening at 5 cm.

This diurnal pattern is reoccurring throughout the year, with methane fluxes generally peaking close to midnight, however the diurnal variation is larger during summer which would explain the results in figures 19a-d where the variation is more consistent (less outliers, larger boxes) during summer. Nighttime fluxes were found to be around 18 % higher than daytime fluxes in JJA, and 41 % higher in MAM when all chambers were considered together. No such differences could be determined for SON or DJF.

As apparent in table 13 the diurnal signal produces high correlations with environmental variables that are less prominent at other timescales e.g. PAR. To get rid of this signal, daily averages of both methane fluxes and environmental variables were used, and once again the correlations with temperature are all positive and generally high (table 14).

Table 14 Spearman's Correlation between daily averages of autochamber methane flux (mg CH_4 m^{-2} h^{-1}) and daily averages of all environmental variables, for the June, July, August, separated between chambers.

JJA – daily averages	1	2	3	4	5	6
Soil T 5cm rep	0.75	0.73	0.35	0.67	0.67	0.44
Soil T 5cm hol	0.49	0.49	0.00	0.30	0.55	0.04
Soil T 5cm hum	0.74	0.71	0.31	0.68	0.65	0.42
Soil T 20cm rep	0.75	0.73	0.39	0.70	0.59	0.55
Soil T 50cm rep	0.73	0.69	0.33	0.73	0.54	0.60
PT100	0.76	0.73	0.35	0.67	0.67	0.45
Air T	0.65	0.63	0.19	0.57	0.60	0.24
Soil moisture rep	-0.28	-0.27	-0.53	0.16	-0.40	0.15
Soil moisture hum	-0.30	0.25	-0.13	0.66	.0.11	0.51
Soil moisture hol	-0.30	-0.28	-0.51	0.20	-0.45	0.19
Pressure	0.60	0.55	0.12	0.40	0.35	0.45
Water table depth	0.15	0.17	-0.07	0.56	0.04	0.29
PAR	0.10	0.05	-0.25	0.09	0.02	0.01

5. Discussion

5.1. Spatial Variation

Spatial variation occurs over very small scales at Fäjemyr. This is in accordance with other studies of Fäjemyr (Lund et al., 2009), and other peatlands across the world (Denman et al. 2007). This is particularly evident in the autochamber measurements, where ranges can be seen for each and every chamber, suggesting that each spot have their own response to the environmental variables (see figure 11). This was also corroborated by the Kruskal-Wallis analysis that showed that the chambers had distributions of fluxes that deviated from one another. It is also clear from the comparison with the manual chamber data that the size of the methane flux varies across the bog. The highest fluxes were found at a plot located close to the center of the bog, however this was only one plot and conclusions cannot be drawn from this limited data i.e. the Kruskal-Wallis did not yield any significant results.

The automatic system seems to produce higher fluxes from lawns than was seen in the manual measurements (table 2), this could be due to a higher probability of leakage from the manual chambers, or other reasons not specifically addressed in this study. It is also clear that the autochamber 3 “hollow” poorly represents the fluxes from hollows by underestimation. The manually measured fluxes from hollows were consistently much higher during the studied period (November). The fluxes from hummocks seem to be fairly similar in both automatic and manual measurements.

The causes for spatial variation across Fäjemyr have been addressed by looking at the 16 manual chamber plots and the six autochambers. However the analysis has not addressed spatial conditions other than vegetation and microtopography. A more thorough analysis of nutrients, acidity, substrate quantity and quality, etc. could possibly have given a more complete picture.

5.1.1. Microtopography

The microtopography has an impact on many of the environmental variables that control methane emissions. It is the spatial differences of these variables, such as water table depth, soil temperature etc. due to the microtopography that makes this feature interesting.

In order to assess the importance of microtopography both the automatic chambers and the 16 plots are placed to capture this. The statistical analysis for the 16 plots confirms that the microtopographical setting influence the methane fluxes more than the site location. The clearest result is given by the four manual chamber plots from hollows that had consistently higher methane fluxes than all other plots across the four manual chamber sites, which was reflected in the Kruskal-Wallis analysis. However, this difference could not be statistically validated between fluxes from lawns and hummocks; instead these groups are statistically similar. The results from the group hummock in the manual chamber data should be interpreted carefully, as few samples were deemed suitable for analysis. However, the lack of sufficient usable flux data from this group clearly shows that emissions are low and most of the time not detectable by the used method and instrumentation.

Applied to the autochamber measurements, the results showed a significant difference in distribution between the groups. However, the group hummock and hollow only include one chamber each, which makes it difficult to draw any robust conclusions. Also, the chamber representing hollow is not a good example of any conditions present on the bog as the vegetation is unhealthy and partly absent. Because of this, the results from the microtopography analysis from the autochambers should not be given too much attention.

5.1.2. Vegetation

The influence of vegetation is in this study was hypothesized to mainly affect the spatial variation across Fäjemyr. Each PFT is discussed in separate below. Overall, low dry weight seems to indicate higher methane fluxes, which is most probably a consequence of low dry weight in very wet areas. Hence, it is doubtful that any conclusions can be drawn from the results found in this limited study where the two influences are not separated from each other. It is also important to remember that vegetation at this time of year (November) is more or less inactive. This is especially important for the manual measurements where fluxes are not known for other parts of the year.

Graminoids

The influence of graminoids on methane emissions from wetlands has been repeatedly studied, and the results from these studies are generally that their presence increase methane emissions (Ström et al., 2005, Koelbener et al., 2010, Ström et al., 2012). However, there are no robust conclusive evidences of such influences in this study. There are many possible reasons for this, one being that graminoids were not separated into species, and thus graminoids at Fäjemyr cover both hummocks, lawns, and hollows. It is possible that the microtopographical setting masks the influence of graminoids as the conditions may not be favorable for methane emissions. The results from the 16 plots therefore remain inconclusive. There is an indication from the six chambers that a higher coverage of graminoids contribute to higher fluxes, but the results is based on six chambers only which does not allow for any robust conclusions.

Sphagnum

The influence of *Sphagnum* species on the net methane emissions have recently been highlighted after finding the symbiotic relationship between *Sphagnum* and methanotrophs (Raghoebarsing et al., 2005). It is impossible to address this influence with the data from Fäjemyr as the production and oxidation is not separated. No conclusions can be drawn from the vegetation analysis of the 16 plots, nor from the six chambers. As chamber 3 has little vegetation it could possibly be used as an example of a plot where the *Sphagnum* has been removed, as tried in other studies. In one such study by van Winden et al. (2010) the net emissions increased when *Sphagnum* was removed, which was taken as evidence of decreased methane oxidation.

However, the vegetation in chamber 3 has died on its own accord, probably due to the intrusion of the chamber, which makes it problematic to compare with other studies.

Heather

The influence of heather has not been addressed specifically in any of the studies reviewed. It was therefore surprising to find a relationship between the coverage/dry weight and methane flux (14b and 15b). The relationships found are negative, but not very strong. A probable cause for these results is that the heather occupied dry areas only; therefore the low fluxes are not necessarily due to the heather, but more probably due to the drier condition. The overall conclusion on the influence of heather is that the species perhaps could be a good indicator of drier areas across the bog, which is most probably a better predictor of low emissions than the heather itself.

Overall, the vegetation analysis did not yield any conclusive results, which is probably due to the methods used. Firstly, the use of PFTs was most probably to coarse as different species of *Sphagnum* and graminoids occupied different niches (water conditions), which then influenced the results. Secondly, the chambers could not be analyzed for dry weights since they must retain healthy vegetation for of the ongoing measurements. This, and the fact that both *Sphagnum* and heather covered around 100% in all chambers but chamber 3 made any attempt of analysis meaningless. Thirdly, there are too few chambers to draw any robust results of the influence of vegetation.

5.2. Temporal Variation

The temporal variation across Fäjemyr is high on very small scales (hours). This behavior causes the correlation coefficients based on environmental variables to be lower at high resolution (30 min), than with daily averages. The influence of each environmental variable on the temporal variation is given below.

5.2.1. Temperature

Soil temperature at depth (20 - 50 cm) seems to be the strongest determinant for temporal variation of methane fluxes from the autochamber plots across all timescales and time resolutions used in this analysis. This could point towards several things; 1) Higher temperatures close to the soil surface probably increase both the methane oxidation and production, which would then counter each other and give a lower temperature dependency at this depth. This would be supported by the results from chamber 3 where methane oxidation could be assumed as non-existent due to the high water table. In this chamber the soil temperature at 5 cm is of higher importance than in the other chambers where oxidation occurs. 2) Methane production is occurring in deep parts of the peat, not just close to the water table. Other studies have also stressed the importance of soil temperature on net methane emissions (Christensen et al., 2003, Bellisario et al., 1999, Moore et al., 2011)

The manual chamber data showed a weaker response between soil temperature and methane flux. But they are comparable to the results from the autochamber plots in November. There could be a number of reasons for this relatively low dependency; 1) the temperature was measured close to the soil surface (5cm). 2) Very few measurements were taken in comparison to the autochambers, and they were all taken only during daytime which decrease the temporal signal one shorter timescales (e.g. table 14 and figure 20). 3) The surface layer was probably cooler than the underlying peat due to the cold air temperatures experienced in November when the measurements were taken, and if the production of methane is occurring in deeper layers, the real relationship is not measured. 4) Especially the hollows showed low soil temperatures as these were measured in water in contact with the colder air, in contrast to the more insulated soil layers beneath lawns and hummocks. This would then produce a negative relationship between soil temperature and methane flux which is seen in table 4.

Reason number 4 above is a typical example of influences that override each other. The microtopographical setting of hollows allows the water table to reach close or above the soil surface. This is hypothesized to decrease the influence of oxidation as the aerobic zone is small or non-existent before the methane reaches the atmosphere. This could then be hypothesized to have a higher influence than the relatively low soil temperature. However, none of these hypotheses can be properly assessed in this study as it is the net emissions that are measured, not production and oxidation rates.

5.2.2. Water Table Depth

A high water table is a prerequisite for methane emissions as the methanogens needs anaerobic conditions. Water table depth has been pointed out as one of the most important controls (Bubier et al., 1993, Moore et al., 2011). When this requirement is fulfilled however, other factors increase or decrease the net emissions of methane, which could be one reason why the influence from this factor is found to be inconsistent on Fäjemyr. No clear results can be seen from the autochambers, but it could be hypothesized that it is the low water table that makes chamber 6 a low emitting chamber. However, it is the temporal variation of the water table that is of concern here, and at a yearly scale, the influence of temperature is so much stronger than the height of the water table that the relationship becomes negative in all chambers. When the temperature signal is removed by residual analysis the relationship with water table depth becomes positive and relatively strong in several chambers (see table 8). This suggests that the variation of water table depth is important for the temporal variation of net methane emissions.

In November, the influence of temperature is relatively low in the autochambers, and the influence of water table depth increases, especially when daily averages are analyzed (see table 5 and 6). Comparing this to the manual chamber fluxes, one can see that the results from the 16 plots show higher dependences on water table depth in general. It is interesting to see that the microtopographical group lawns has a low relationship with water table depth, which could corroborate the findings of low dependence among the autochambers, as four out of six chambers are classified as lawns. The fluxes from hollows increase with water table depth, which would suggest its influence on the temporal variation, this is also valid for hummocks, but the sample group is very small, so the relationship was not statistically significant.

When the manual chamber plots are separated into sites instead of microtopographical groups, the influence of water table depth generally increases. The question here is whether this perhaps tells more about the spatial variation in relation to water table depth (microtopography) than temporal variation. At each site the fluxes from hollows with a low water table is higher than the fluxes from lawns and hummocks.

It is difficult to draw any conclusions on the influence of water table depth on the temporal variation of methane emissions, but there is a clear evidence of a spatial influence, especially from the 16 plots.

5.2.3. Soil Moisture

The influence of soil moisture is very difficult to grasp in this study, but by breaking down the temporal scale it becomes clearer. One would initially think that higher soil moisture content would provide better conditions for the methanogens, and therefore it should show a positive relationship with methane fluxes. This positive relationship was found by Levy et al. (2012) who investigated methane flux over a broader spectrum of soils and ranges of soil moisture content, where dryer soils <60% volumetric soil moisture content had relatively small fluxes. Then why does the results from the autochambers point in the opposite direction - that lower soil moisture content would increase fluxes? These results should be regarded cautiously. Firstly, nearly all of the measurements of soil moisture at Fäjemyr have soil moisture above 60%, which means that it is less probable to find a similar relationship that Levy et al. (2012) found. Also the influence of soil moisture may perhaps decrease with increasing volumetric content as conditions could be approaching satisfactory levels before complete saturation. Secondly, as with the influence of water table depth, the results across a year seem to be addled by the influence of soil temperature or perhaps other parameters that change with the season, such as substrate quality and quantity. Soil moisture generally increases during the cold months, when the production of methane is low due to restricting temperature conditions. However, the residual analysis did not alter the results in the same way as it did for the water table depth results. Soil moisture continues to have a negative relationship with methane flux at an annual scale. It is first when the temporal scale is decreased that something happens. When looking at the first two weeks in June only, the relationship becomes positive in all chambers. The same results are given by the manual chamber plots in November (positive correlation), but not by the autochambers at this time.

5.2.4. Pressure

The influence of pressure on methane emissions have been discussed in some studies (Tokida et al., 2005, Tokida et al., 2007). Foremost it is the influence on ebullition that has been given most attention. In this study, ebullition is only touched upon because of an episodic burst of methane in early November within the autochambers. This event did coincide with a pressure drop but the importance of the pressure drop is impossible to verify within this study as the event was not repeated during the year. However, the physical relationship between lower pressure and higher ebullitive flux, as given in the theoretical part about ebullition, certainly suggests that the pressure drop could have induced this burst of methane.

Otherwise pressure, at least in theory, should have a negative relationship with methane emissions as lower pressure allows more of the dissolved methane (in water) transfer into its gaseous phase. However, the results are mostly of weak positive correlations or very weak negative correlations. These inconsistent results makes it difficult to draw any relevant conclusions, but it would seem that pressure have little to do with the temporal variations of methane emissions, at least when the ebullitive fluxes most probably are filtered away by the outlier analysis.

5.2.5. PAR

PAR is in this study used as a coarse proxy for substrate availability, although it is unlikely to be a good proxy, and it is not determined in this analysis if instantaneous PAR is correlated with substrate quality and quantity. However, studies have shown evidence of rapid carbon turnover in similar peat ecosystems (Wieder and Yavitt, 1994, King et al., 2002). It is more probable that this proxy could be used based on cumulative methods on longer timescales. Therefore it is rather subjective, and incorrect to draw conclusions about temporal variability, especially at smaller timescales with high resolution data. For instance, methane emissions during the first two weeks in June are highly negatively correlated with PAR. The reason for this is the diurnal pattern of methane emissions that move in the opposite direction of the light conditions. At longer timescales (annual), the influence of PAR is positive, and relatively high. This result would be more in line with current theory (if PAR is connected to NEP (Whiting and Chanton, 1993)), but when the temperature signal is removed, the influence diminishes, which would propose that PAR is a bad determinant for temporal variation of methane emissions.

5.2.6. Diurnal variation

In this study, the highest fluxes of methane occurred around midnight, this was especially pronounced in MAM (41 % higher on average) and in JJA (18 % higher in average). A diurnal pattern like this was also found for an Irish blanket bog (Laine et al., 2007) whereas other studies have found methane emissions to be higher during the day (Thomas et al., 1998, Long et al., 2010). The study by Long et al. (2010) was conducted in a fen, while the study by Thomas et al. (1998) was a laboratory study, although with bog peat cores. The presence of plants with aerenchymous structures, were proposed as one reason for the high daytime fluxes of methane (open versus closed stomata) in the study by Thomas et al. (1998), and such plants were indeed present at the fen studied by Long et al. (2010) as opposed to the relatively low amount of graminoids in the autochambers of this study. Discrepancies could also be due to measurement errors. Results from a Canadian study show that the use of chambers similar to the ones used in this study, overestimate methane fluxes during night and underestimate them during day as a result of atmospheric turbulence (Lai et al., 2012). It would be interesting to develop the understanding of diurnal controls as there are apparent discrepancies between studies.

5.3. Method and Data

The methods used in this study have been applied on numerous occasions, and roughly for the same purpose. The measurement of net methane emissions is very simple, but as it does not separate between production, consumption and transport of methane, it is impossible to verify the influence of many variables that affects all these processes simultaneously. This is a problem when it comes to grasp the importance of the environmental variables and therefore also an issue if one was to construct a process based model over the area.

The study also suffers from few manual chamber measurements, and at few sites. To catch the spatial variation across the mire, and to be able to conclude something with robust statistics, more sites would have been preferable. The number of measurement days severely restricts the analysis of temporal variation among the manual chamber measurements. The time period chosen could also be debated, particularly since the vascular vegetation is quite inactive during this time of the year. The role of graminoids might have showed a different result if the analysis was made in summer instead of late autumn.

The data from both the automatic and manual chambers are most likely affected by leakage, especially during windier days. Turbulence has been mentioned before as a cause for both over- and underestimation of methane fluxes from automatic chambers. It is possible that this effect also affects the measurements at Fäjemyr.

The automatic chambers have also been present at the bog since 2008, and the vegetation inside them may well suffer from the intrusion of these. This can be seen foremost in chamber 3, where the vegetation has declined as a result. In other chambers, the vegetation might have increased due to altered micrometeorological conditions because of the protective chamber walls. This problem is most likely not an issue among the manual chamber plots, as these was considered non-disturbed prior to the study.

The accuracy of the manual chamber fluxes depended on the performance on the GC, which varied through the period. Especially the very low fluxes could suffer from this as the slope of the line is less steep. The automatic system seems to perform well, and have sufficiently many measurements for each chamber closure that the accuracy could be considered a non-issue, especially as it is the slope of the line (k in equation 3) , that determine the flux, and not the placement of this line in regard to the y-axis (m in equation 3).

6. Conclusions

This study aimed to investigate the spatiotemporal variation of methane emissions, and its causes across an ombrotrophic bog in Southern Sweden.

Spatial variation in methane emissions was connected to microtopography, especially fluxes from hollows were much higher than fluxes from lawns and hummocks. The data was insufficient to distinguish differences between the last two groups. The influence of vegetation on spatial variation could not be determined due to the masking influence of microtopography. However, it is unlikely that it is only microtopography that influences the spatial variation across Fäjemyr.

The temporal variation was assessed mainly through the use of the autochamber data of methane emissions, and the variation found to depend mostly on soil temperature at depth. High correlations between soil temperature and methane emissions were found when daily averages were used on longer timescales. However, this behavior of fluxes may have several co-existing explaining parameters, such as substrate quantity, light etc. that follow the development of temperature over the season, thus extrapolation of the results based on temperature alone from this study is to be discouraged, and modeling will have to depend on several variables to capture variation.

The issue of scale is also something that has become apparent within this study. The temporal scale affects the correlation with drivers, which probably has to do with the seasonal signal caused by the differences in light conditions and phenology aside from temperature and water table depth development. Looking at smaller temporal scales would give a better process understanding as fewer parameters (light, phenology) are allowed to vary.

This study also provides evidence that the automatic chambers represent hummocks and lawns well, while hollows are poorly represented and underestimation of methane fluxes from this type of microtopographical group may be substantial if values are extrapolated.

Further studies of Fäjemyr should extend an analysis to include more spatial variation, and determine if other factors such as vegetation, nutrient status, peat depth, etc. influence this variability. It is also important to further assess the appropriateness of the location of the current hollow plot of the automatic system.

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