

Soil methane uptake and release around Lutjewad

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Summary

The enhanced greenhouse effect is changing the earth's climate. Methane is one of the long-lived greenhouse gasses contributing to this enhanced greenhouse effect. It has, next to carbon dioxide, the second highest contribution to the total global mean radiative forcing of the long-lived greenhouse gasses (0.48 W/m^2 vs. 1.66 W/m^2). That is why it is important to know the (sizes of the) sources and sinks of methane, releasing or taking up respectively methane from the atmosphere. One of the natural sources and sinks is the soil. In aerated soils, it is likely that aerobic organisms decompose methane into water and carbon dioxide. However, under anaerobic conditions, organic material will be decomposed to methane. The Centre for Isotope Research (CIO) has an atmospheric monitoring and sampling station called Lutjewad. It is located in the north of the Netherlands on the coastal side near the Wadden Sea. Therefore it is an interesting location to measure the methane fluxes in and out of the soil.

The inverted cup method was used to determine the methane fluxes from the soil on a number of spots in the area around Lutjewad. Sampling sessions typically took an hour. An air sample from the start and end of each sampling session was analyzed with a gas chromatograph in the CIO laboratory for its methane content. Since the concentration does not increase linearly, it is not suitable to make a linear fit to those two data points. Therefore semi-continuous measurements on the carbon dioxide concentrations were performed in situ. These carbon dioxide records are used to determine the methane flux. This could be done since the relative diffusivity of methane with respect to carbon dioxide in air is known. In total 19 measurements have been performed to give an insight in the methane fluxes out of the soil at different locations around Lutjewad.

As expected almost all measurements taken on the aerated agricultural areas on the main land showed a methane uptake. The negative fluxes on these locations range from -0.7 ± 0.1 up to $-0.000 \text{ g/m}^2/\text{yr}$, with an average of $-0.15 \text{ g/m}^2/\text{yr}$. On the mudflat and wetlands outside the sea dyke the water table is near the soil surface, creating anaerobic conditions. As expected a net release of methane from these areas was recorded. The three measurements on the wetland resulted in a flux of 0.015 ± 0.01 , 0.20 ± 0.04 and $0.42 \pm 0.04 \text{ g/m}^2/\text{yr}$. The mudflat looked like a major source of methane after the first measurement of $10 \pm 3 \text{ g/m}^2/\text{yr}$, but the following two measurements of 0.2 ± 5 and $0.03 \pm 0.4 \text{ g/m}^2/\text{yr}$ couldn't confirm this.

Soil conditions like porosity and moisture content, and environmental conditions like temperature, atmospheric pressure and the water table depth influence the methane flux. No clear relationships between the methane flux and atmospheric temperature, soil temperature, soil moisture content, water table depth and atmospheric pressure have been found in this research. To find such relationships a number of measurements need to be performed at the same conditions of which the one under investigation should be varied. This was not the case and the origin of this research. The limiting number of measured fluxes was the main reason that clear relations were not visible. But the main goal was to give an indication of the methane fluxes from the soil in the area surrounding Lutjewad and that has succeeded.





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1. Introduction

1.1 Climate change

Planet earth with its current climate is a pleasant place to live. This would be different if the atmosphere would not be there. This atmosphere acts as a blanket, keeping the earth warm and protecting all living organism from the ultra violet radiation. In fact if the earth would not have its atmosphere, the average surface temperature would be about -20 °C. This can be verified by a simple calculation if one takes the incoming solar irradiation and assumes that the earth has no atmosphere, reflecting 34% of the incoming radiation and is a 'black body radiator'.

The reason why the earth is not a frozen planet, is due to the so called greenhouse gasses like water, carbon dioxide and methane. These gasses in the atmosphere let most of the incoming solar radiation pass, but absorb a major part of the thermal infrared radiation emitted by the earth itself. This is referred to as the natural greenhouse effect.

Due to anthropogenic emissions the concentration of a number of greenhouse gasses in the atmosphere is increasing. The earth's surface temperature has already risen in the past decades. The predictions are that this global warming will continue during this century (IPCC, 2007).

1.2 Methane sources and sinks

One of the greenhouse gasses is methane. Its atmospheric concentration along with the greenhouse gasses Carbon Dioxide and Nitrous Oxide of the last 2005 years are plotted in figure 1. The increase of those gasses in the atmosphere since about 1750 is due to human activities in the industrial era.

Methane enters the atmosphere by different sources like anaerobic decomposition of organic material in natural wetlands, digestion by animals and leakage from natural gas fields mainly due to human impact (EPA, 2011).

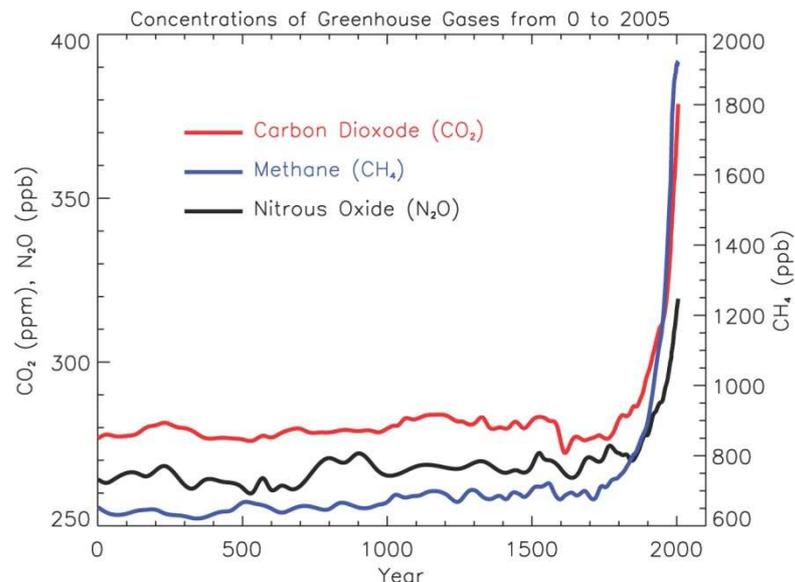


Figure 1: Atmospheric concentrations of CO₂, CH₄ and N₂O (IPCC, 2007).

Table 1: Major global methane sources and sinks (in 1999 from a top-down method) (IPCC, 2007).

Methane sources (Tg CH ₄ yr ⁻¹) (1Tg=10 ¹² g)		Methane sinks (Tg CH ₄ yr ⁻¹)	
Natural sources	260	Soil	30
Wetlands	231	Tropospheric OH·	507
Termites	20	Stratospheric loss	40
Anthropogenic sources	350		
Coal mining	30		
Gas, oil, Industry	52		
Landfills & waste	35		
Ruminants	91		
Rice agriculture	54		
Biomass burning	88		
Total sources	610	Total sink	577

The most important methane sources and sinks are listed in table 1. A major part of the methane emissions into the atmosphere are due to direct human impact (57%).

Most of the naturally emitted methane originates from wetlands. A major part of the atmospheric methane is broken down in the troposphere (and a bit in the stratosphere) due to oxidation initiated by OH radicals into water and carbon dioxide.

1.3 Global warming potential

To compare the impact on the climate of different long-lived greenhouse gasses the global warming potential (GWP) is commonly used. The GWP is the total extra energy prevented from escaping the earth in a certain time span due to a kilogram of a certain greenhouse gas in the atmosphere. Often this value is normalized to CO₂ and a time span of 100 years is used. In such a case CO₂ and CH₄ have a GWP of 1 and 25, respectively. This means that the impact on global warming of methane in a century is 25 times more severe than that of the same amount (mass) of CO₂. The disadvantage of using the GWP is the arbitrary chosen time span. Since methane has a relative short atmospheric life time of 12 years, its global warming potential over a period of 20 years would be as high as 72. (IPCC, 2007).

1.4 The soil

A minor sink for methane is the soil. It mainly depends on the presence of water if the soil acts as a methane sink or source. In a soil saturated with water, so almost no oxygen is present, bacteria will break down organic material and produce methane. That's why wetlands act as a methane source. On the other hand if there is oxygen present in the soil, it is likely that bacteria break down methane and produce carbon dioxide and water.

It depends on the conditions and type of soil how much methane is taken up or emitted by the soil. Of importance are the number, type and activity of the organisms that break down or produce methane. Often is the ease with which methane or oxygen can reach those organism from the soil surface, the limiting factor of their productivity. Important parameters in this mixing process of soil air and atmospheric air are the soil porosity, tortuosity, soil air flow and concentration gradients. Porosity is, in its turn, determined by the type of soil and soil moisture. Pressure differences influence the soil air flow. These pressure differences originate from air flows across the soil surface (winds), changes in atmospheric pressure, changes in temperature or fluctuations in the water table. Overall the temperature and soil moisture are the most important parameters in the soil methane production and consumption. For example temperature influences the productivity of the organisms and the diffusion velocity. Table 2 gives an overview of methane uptakes by different soils. The table shows the highest and lowest flux measurements.

Table 2: Global uptake of methane by different soils 1973 – 1989 (Matthias Born, 1990).

Vetgetation type	Area (10¹² m²)	CH₄ flux (-1*g m⁻² yr⁻¹)	Total (Tg yr⁻¹)
Tropical seasonal forest	7.5	0 – 0.2	0 – 1.5
Temperate forest	12.0	0.09 – 1.3	1 – 15.6
Boreal forest	12.0	0.09 – 1.3	1 – 15.6
Woodland/shrubland	8.0	0.09 – 1.3	0.6 – 10.4
Savanna	15.0	0.19 – 0.7	2.9 – 10.5
Temperate grassland	9.0	0.002 – 0.2	0.02 – 1.8
Cultivated land	14.0	0.002 – 0.2	0.03 – 2.8
Total			5.6 – 58.2

1.5 Atmospheric monitoring and sampling station

The Centre for Isotope Research (CIO) at the University of Groningen has an atmospheric monitoring and sampling station called *Lutjewad*. It is located at the northern coast of the

Netherlands directly at the Wadden Sea dike near Hornhuizen. The land side consists mainly out of agricultural area and on the other side of the dike there lies first a stretch of wetland of one kilometer before the tidal flats and the sea begins. The soils around Lutjewad consist mainly out of clay, both outside and inside the dyke. The heart of Lutjewad is its tower in which, up to 61 meter above sea level, atmospheric data is collected. Among these data are meteorological data, atmospheric greenhouse gas concentrations and isotopic ratios of a number of gasses.

Since 2011 the soil flux of different greenhouse gasses are measured at Lutjewad. In this way an estimate can be made for the size of the soil as a source of greenhouse gasses. An automatic flux chamber is placed near the Lutjewad station in which the CO₂, CH₄, CO, N₂O and SF₆ fluxes are determined. This chamber placed on top of the soil is closed for a couple of hours. The concentration difference of the different greenhouse gasses before and after closure are used to determine the soil flux. (Lof, 2011).

1.6 Research motivation

Methane is a major contributor to the enhanced greenhouse effect. Its radiative forcing is 0.48 W m⁻² (over the period 1750-2005), compared to 1.66 W m⁻² due to CO₂ (IPCC, 2007). That is why it is important to get more insight in its sources and sinks. Since methane is monitored at the atmospheric monitoring and sampling station Lutjewad, it is interesting to know how much methane is taken up and released by the soils around Lutjewad. The methane flux from the soils around Lutjewad is expected to vary over the wetlands (release) and agricultural (uptake) areas. In the current situation the methane soil flux is only measured at one fixed location with a flux chamber and predicted using the local variation in the atmospheric methane concentration and wind direction/speed. In this research a mobile flux chamber is used to measure the methane flux at a number of spots around Lutjewad. These flux measurements will give an indication of how much methane is released and taken up by the different areas around Lutjewad.

2. Soil gasses and fluxes

2.1 Soil air

A number of gasses are present in the open spaces that exist in the soil. These gasses are referred to as the soil air. The concentration of those gasses is depending on the production and destruction of those gasses in the soil and on the interaction of the soil air with the atmosphere. Diffusion and pressure differences cause the soil air to mix with the atmospheric air. The rate of diffusion is dependent on the concentration differences and the effective diffusion coefficient, the ease with which the soil air can move around in the soil. The mobility of the gasses depends on the porosity and tortuosity. More pore space gives more room to move around. Furthermore straight interconnections of the pore spaces are less restricting movement of molecules than tortuous channels. The porosity and tortuosity is depending on the conditions and type of soil. Besides diffusion also convection causes mass transport. Air flow out of and into the soil due to pressure differences cause the soil air to mix with the atmospheric air. Multiple causes can be the reason for a pressure difference between the soil air and the atmospheric air. For example the atmospheric pressure can change or temperature changes in the soil or atmosphere causes a change in pressure. Furthermore wind flow across the soil surface can suck air out of the soil. Another reason can be a change in the ground water table, which can force the soil air up or down.

2.2 Inverted cup

To determine the concentration of a certain soil gas near the soil surface an chamber/inverted cup can be placed on top of the soil. Due to diffusion, the concentration difference between air in the cup and the soil air will decline. The airflow in and out of the soil due to pressure differences can be neglected, since the cup is not connected with the atmosphere and pressure equilibrium with the soil will settle quickly. Therefore diffusion will be the main driver for the soil flux in this

setup. It is possible to calculate the flux out of, and the concentration of a specific gas in the soil air just near the surface. These values can be derived from concentration measurements in the cup of a specific gas in time. See the *experimental setup* for more details.

Sampling locations and conditions

Around Lutjewad 19 sample have been taken for this research. The sample locations roughly lie on a line from south to north. Every sample has been labeled with a character, from 'A' up to 'S'. The area surrounding Lutjewad can roughly be divided into five sections. The first is the inland area just behind the old seawall (sample N and D). The second is a polder, which lies between the old dike (build in the Middle Ages) and the new dike (build in 1923). The polder can be divided into two parts, *polder 1* (C, E, K and P) and *polder 2* (A, B, F, G, J, L and O). They are separated by a small dike (build in 1802) that has almost vanished due to agricultural activities in the past but is still visible. Outside the new dike there lies a stretch of *wetland* (H, I and Q) before the sea begins. The final area is the *mudflat* (M, R and S) which can be reached when the shoreline withdraws with every outgoing tide. All sample locations and these five sections are shown together in figure 2.



Figure 2: sample locations around Lutjewad.

During a work day it was possible to take a maximum of four samples. All 19 samples have been collected at six different days. When which sample is taken is summarized in table 3.

Table 3: Sample data, soil conditions of the different samples and the cumulative precipitation of the previous week.

The soil texture was not always the same at the same locations on different sample days. Precipitation was probably the main driver for these texture changes. At some

Dates	Sample	Soil conditions	Precipitation (mm = l/m ²)
02-07-2010	A, B, C and D	Dry, granular	2.75
07-07-2010	E, F and G	Dry, hard, compact	3.74
15-07-2010	H, I and J	Moist, fictile	38.62
20-07-2010	K, L and M	Moist	14.59
21-07-2010	N, O, P and Q	Moist, soft, cracked	14.39
03-08-2010	R and S	-	12.2

days the clay was dry, hard and cracked and a knife was needed to cut a circle in the soil to get the cup into place. On other days the clay was softer and humid and the cup could easily be pushed into the soil. Sometimes the clay was dry and consisted out of hard grains and the cup could be placed between those grains. A rough description on the soil conditions at the different days is shown in table 3. Note that those descriptions do not apply for samples that were taken in the wetland or mudflat. The soil texture on the wetland and mudflat did not change significant between the sampling days. Two examples of the soils are given in figure 3. No quantitative measurements on the soil permeability are taken. But these texture changes have probably influenced the methane fluxes, since the methane uptake is mainly controlled by the permeability of the soil.



Figure 3: A dry clay agricultural soil (left) and a wet soil on the mudflat (right).

Samples are taken at sites with different vegetation covers. For example, in the polders different crops (potato, corn and wheat) were growing. Dörr et al. (1993) have not found an influence of the vegetation cover on the methane uptake rate. Therefore it should not matter if a sample was taken for example in a potato or grain field.

In the wetland the water table is close to the soil surface, leaving (almost) no room for the soil air. The soil surface in the wetlands is flat, however minor height differences are present. These variations are barely visible for the naked eye, but different vegetation covers could indicate these minor changes in height. It could be possible that these variations in height have a significant influence on the methane flux from one place to the other. That is why the three samples taken in the wetland are located a couple of meters apart from each other and placed in different vegetation covers. Sample I and Q were taken at the same spot at different days.

On all days when samples were taken on the land side of the new dike (In land, Polder 1 and 2), there was a sample taken at a reference location (samples: A, G, J, L and O) in polder 2 near the measurement station Lutjewad. In this way it would be easier to find an explanation for a sample that would read a total different methane flux. If the sample from the reference location would also give a total different uptake rate, it could for example be due to some meteorological parameters. But if this was not the case the explanation should be found in some spot-specific parameters.

Three other locations were measured twice at different days to investigate if they would give the same fluxes. Sample I and Q on the wetland are already mentioned. The other two are D and N at the inland area and E and K in polder 1.

4. Experimental setup

4.1 The sampling system

The alignment of the total experimental setup of the inverted cup that is used in this research is drawn schematically below in figure 4. Besides a connection with the soil air it is a closed system. This system consist out of an *inverted cup*, *air dryer*, *air filter*, *12 V pump*, *barometer*, *pressure relief valve*, *CO₂ detector* (flow trough Vaisala CARBOCAP® Carbon Dioxide Probe GMP343, range 0 - 1000 ppm), two 2.5 liter flasks and a *flow meter*. In total the volume of the system is $14.2 \cdot 10^{-3} \text{ m}^3$ and the soil surface that is covered by the inverted cup is $4.95 \cdot 10^{-2} \text{ m}^2$.

To keep the concentration throughout the system the same as in the cup, the *pump* pumps the air clockwise through the system. The two flasks of 2.5 liter are installed to take an atmospheric air sample (*sample A*) and a sample of the same air that has been influenced by the soil air due to diffusion for a certain amount of time (*sample B*). The *barometer* and the *flow meter* monitor the pressure and the air flow in the system. In this way it can be easily checked if the system is operating well and no major leaks or jams are present. To be able to analyze the air *samples A* and *B* in a gas chromatograph, these samples need to be clean and dry. That is why a *filter* and a compartment with the water absorbing Magnesium Perchlorate ($\text{Mg}(\text{ClO}_4)_2$) is added to the system. The *CO₂ detector* provides a semi-continuous (with intervals of 15 s) set of the *CO₂* concentrations during the sampling session. It is connected parallel to an *adjustable valve* so the air flow through the *CO₂ detector* can be controlled. The *pressure relieve valve* prevents the *pump* from overheating when the pressure in the system would build up for some reason.

To give an impression how this system looks like after it was built, a picture is shown in figure 5.

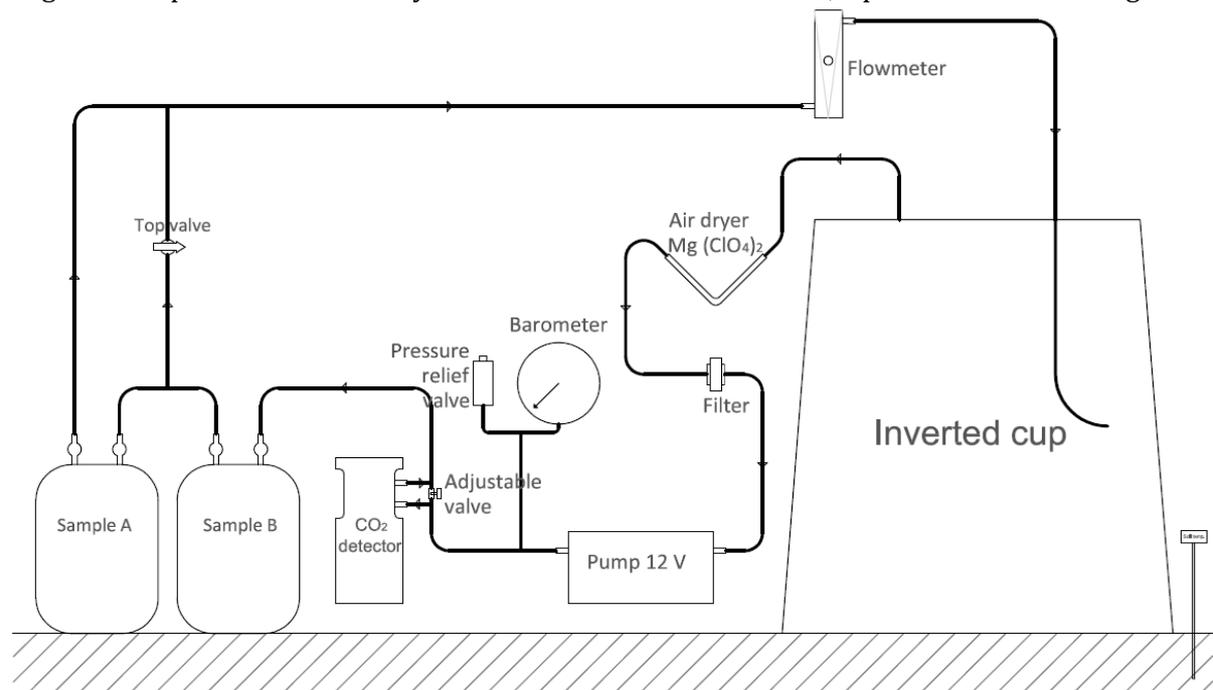


Figure 4: schematic alignment of the system that is used.

4.2 Sampling procedure

The procedure that is required to take a sample, to determine the soil flux, is described in this section. The initial and final methane concentration is required to determine the methane flux from the soil. That is why sample A and B are taken, respectively. We start the sampling procedure by taking an atmospheric air sample. That is why the system needs to be flushed with atmospheric air. First the tube that runs from the *flow meter* (see figure 4) to the *inverted cup* is disconnected, so no 'old air' out of the system will flow through the *inverted cup* back into the system. Second the cup is put on its side in the direction of the wind after it is put back and forward a couple of times, so it contains 'fresh' air. After closing the *top valve* the *pump* is turned

on. Now the air flows through the whole system (both flask A and B are flushed). When the system is flushed with roughly ten times its own volume of air, the top *valve* is opened again and the flask with *sample A* is closed. Now the airflow takes a shortcut between the two flasks to the *flow meter* and is bypassing *sample A*. The air in the system and *sample A* in particular is now representative for the air in the nearby atmosphere. After closing *sample A* the connection between the *flowmeter* and the *inverted cup* is restored, making the system closed again.

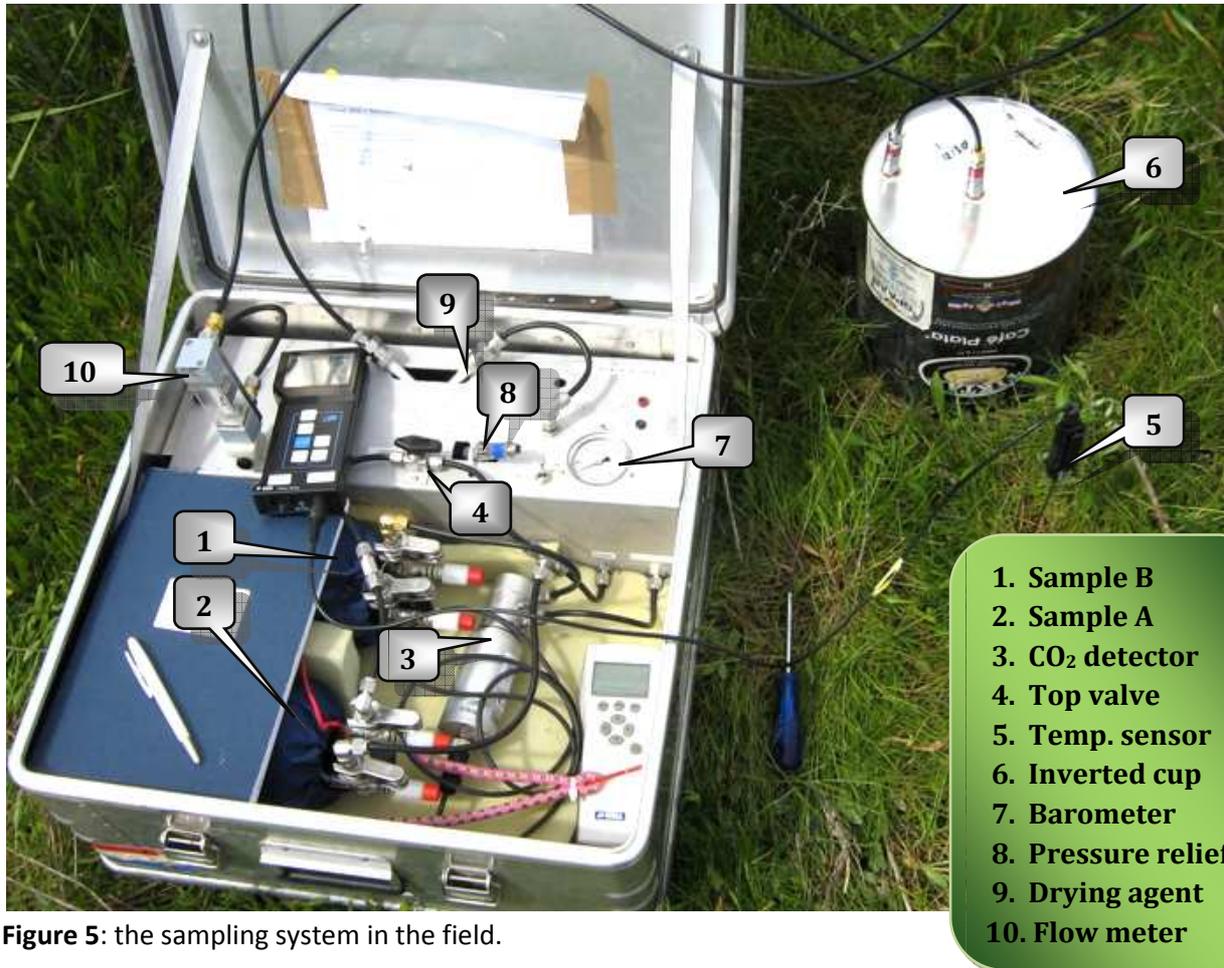


Figure 5: the sampling system in the field.

In the next step the *inverted cup* is placed on top of the soil. In order to make a seal between the edge of the cup and the soil, the rim of the cup is driven about two to three centimeters into the soil. For about an hour the pump circulates the air around the system, while the soil air is interacting with the atmospheric air in the cup/system.

It is tried to design the two tubes into and out of the cup in such a way that the air in the cup mixes and stays homogeneous, without creating a strong airflow along the soil surface. In this way the air at the bottom of the cup does not get saturated slowing down the diffusion process nor creating an airflow out of the soil through pressure differences created by this airflow.

During the collection of each sample, the soil temperature at 5 cm and 10 cm below the surface and the temperature of the surrounding air was measured. A temperature difference in the system during sampling would cause a pressure difference in the system. Since the system is closed above ground, air would be forced into or out of the soil influencing the total methane flow. Therefore, on sunny days the system was shielded from the sun by an umbrella, preventing the system from heating up. Especially the metal cup could accumulate heat and the flasks could act as a greenhouse. During most of the sampling time an airflow between two and three l/min was measured through the system.

4.3 Measurements

Back at the CIO laboratory flask A and flask B were connected to the gas chromatograph and the concentration of methane was determined. Now the methane concentration before and at the end of the sampling sessions are known. The gas chromatograph at the CIO automatically measured the CO₂ and CO concentrations too. The CO₂ concentrations have been used to calibrate the CO₂ detector in the sampling system in figure 4. However, nothing has been done in this research with the CO data.

5. Calculations

5.1 Carbon dioxide

The CO₂ concentrations in the system during a sampling session measured with the CO₂ detector are used to determine the CO₂ flux. By fitting equation 1 to these CO₂ concentrations the flux can be calculated.

$$C(t) = C_{soil} - (C_{soil} - C_{atm})e^{-k t} \quad (1)$$

With $C(t)$ the concentration over time, C_{soil} the concentration just below the surface of the soil, C_{atm} the concentration in the surrounding atmosphere and k a constant with dimensions s^{-1} .

By taking the derivative at $t=0$ of equation 1 one can find the concentration increase at the start of the measurement. This is

$$\frac{dC}{dt} \Big|_{t=0} = (C_{soil} - C_{atm})k \quad (2)$$

Therefore the flux F out of the soil is $F = \frac{dC}{dt} \frac{V}{S}$ (piston velocity) and combined with equation 2 gives:

$$F = (C_{soil} - C_{atm})k \frac{V}{S} \quad (3)$$

Here V is the volume of the system ($14.2 \cdot 10^{-3} \text{ m}^3$) en S the surface that is covered by the inverted cup ($4.95 \cdot 10^{-2} \text{ m}^2$). Due to a concentration increase or decrease in the cup, the concentration gradient between the cup and the soil air will decrease. That's why the absolute soil flux will decline in time. Only the flux at the start of the sampling will be representative for the natural emission or uptake of a certain gas by the soil.

The CO₂ detector (Vaisala CARBOCAP® GMP343) possesses four compensation options for temperature, pressure, humidity and oxygen. Since the corrections algorithms were unknown, these settings were kept the same for each sample. In this way it is sure that all raw data is comparable to each other and corrections for the different circumstances can be made afterwards. The temperature was set at room temperature, the pressure at 1000 hPa, the relative humidity at zero and the oxygen concentration on 21%. The relative humidity is put at zero because the air in the system is dried.

It is assumed that the oxygen concentration did not vary significantly during sampling time. However, the oxygen concentration is not monitored. Roughly a one on one exchange of CO₂ molecules with O₂ is expected. The CO₂ concentration increased from atmospheric values up to 1416 ppm on average and in the most extreme sample up to 3765 ppm. This means that de oxygen concentration would decline roughly by 0.1% (1000 ppm). At ideal circumstances the build in correction factor on the CO₂ concentration is 1.926% for an oxygen concentration of 21.0%. This correction factor would change to 1.917% for an oxygen concentration of 20.9%. This results in an deviation of tenths of ppm's in the measured CO₂ concentration. On top of that the measurements from the CO₂ detector are calibrated with a number of measurements

performed with the gas chromatograph, making a correction factor for oxygen superfluous. (van Leeuwen, 2010).

Corrections are made afterwards for two of the four compensation options on the CO₂ detector, namely the pressure and temperature. According to the ideal gas law a correction for the air pressure and temperature is made by multiplying each data point by $\frac{1000 \text{ hPa}}{\text{air pressure}} * \frac{\text{air temperature}}{298.15 \text{ K}}$.

The atmospheric pressure measured at a height of 7 meter in the tower of Lutjewad is used for this pressure correction. The temperature is measured on site with a temperature sensor. As an example the result of this pressure/temperature correction on sample B (not flask B) is shown in figure 6. This correction is rather small, and is even smaller if the atmospheric pressure and temperature deviates less from 1000 hPa and respectively 25 °C. On average this pressure of 1000 hPa was exceeded by 11.5 hPa (with a max of 20.6 hPa) and the temperature deviated on average 3.8 °C (with a max of 10.3 °C). The pressure and temperature correction factor based on these two average values is 1.2‰.

In the first 25 minutes of sample B the system is flushed with the ambient air before the cup is places on top of the soil. This explains the first 25 minutes in figure 6.

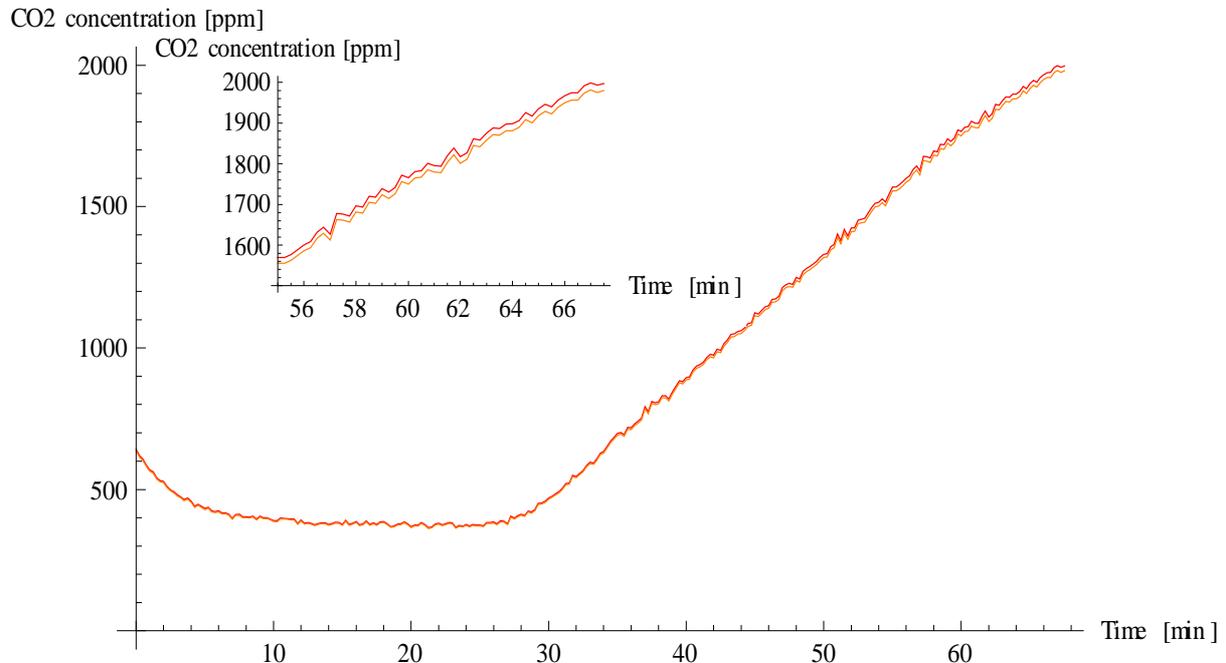


Figure 6: CO₂ concentration in time of sample B before (Orange) and after a pressure and temperature corrections (Red) of 1012.1 hPa and 31.3 °C.

The CO₂ detector is calibrated using the CO₂ concentrations obtained from a set of samples analyzed by the gas chromatograph (GC). By comparing both the CO₂ concentrations determined by the CO₂ detector and the GC, a linear calibration curve is obtained and applied to the data from the CO₂ detector. The linear calibration that is used is:

$$C_{GC} = 0.93 \pm 0.02 * C_{vaisala} + 17.77280 \pm 0.00001. \quad (4)$$

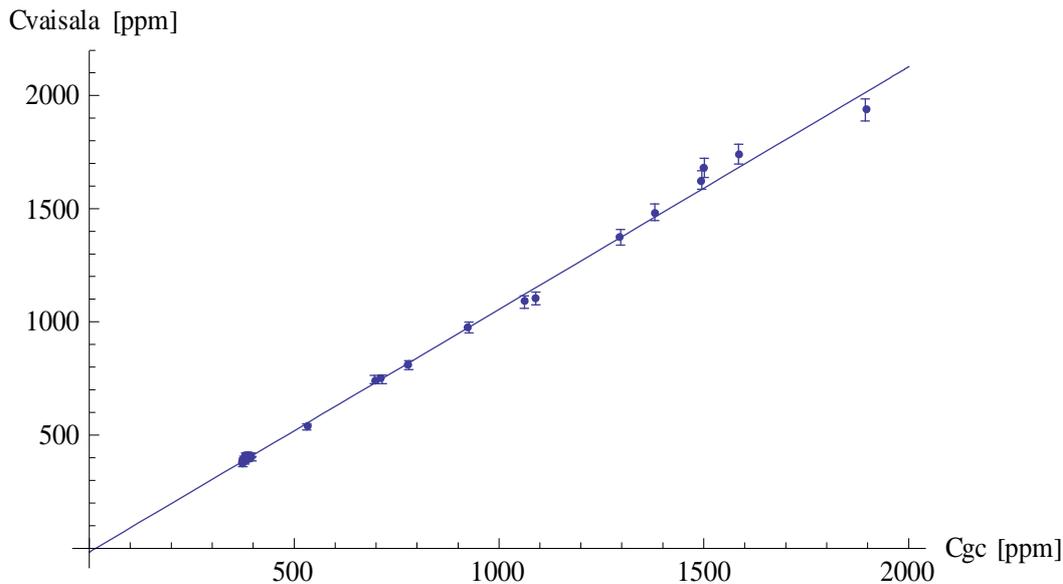


Figure 7: linear calibration fit for the CO₂ detector by using the GC data ($\sigma = 29$ ppm).

and is shown, along with the data points used for this fit, in figure 7. The square root of the sample variance (sample standard deviation) of the deviations of the data points from this linear line is $\sqrt{S_{n-1}} = 29$ ppm. Like figure 7 suggest, the uncertainty is concentration dependent. The measurement uncertainty in the CO₂ data obtained by the CO₂ detector is taken as large as 2.5% of the measured concentration¹. The measurement uncertainty in the CO₂ concentration obtained by the GC is neglected, since this uncertainty is in the order of tenths of ppm for atmospheric concentrations. The exact uncertainty of the GC for higher concentrations is not known, since it is mainly used to determine the content of atmospheric samples.

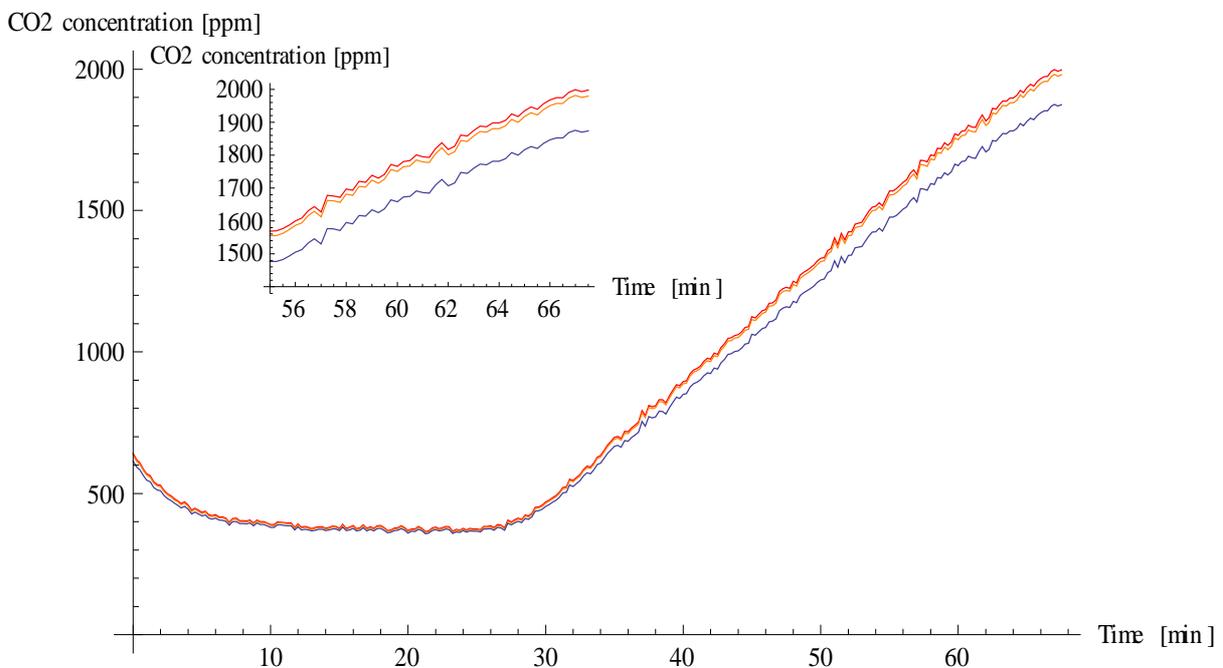


Figure 8: besides the raw data (orange line) and the pressure/temperature corrected data (red) on the CO₂ concentrations of sample B, the calibration corrected data (blue) are shown.

¹ According to the manual of the Vaisala: 'accuracy after factory calibration: 2.5% of reading'

After applying the pressure and temperature corrections, the calibration correction is applied on the CO₂ concentrations. In figure 8, besides the lines from figure 6, the calibration correction is shown. Of these two corrections the calibration correction has the most significant impact on the data.

The corrected data points are used to fit to Eq. 1. The obtained fit parameters C_{soil} and k can be used in combination with Eq. 3 to find the CO₂ flux. To fit the CO₂ concentrations to Eq. 1, the function 'NonlinearModelFit' in Wolfram Mathematica (version number 7.0.0, Microsoft Windows 32 bit version) is used. In figure 9 an example is shown of a part of the final CO₂ concentrations of sample D with the belonging fit. The obtained parameters are in the case of sample D: $C_e = (167 \pm 2) * 10^1$ ppm and $k = (207 \pm 5) * 10^{-6} \text{ s}^{-1}$.

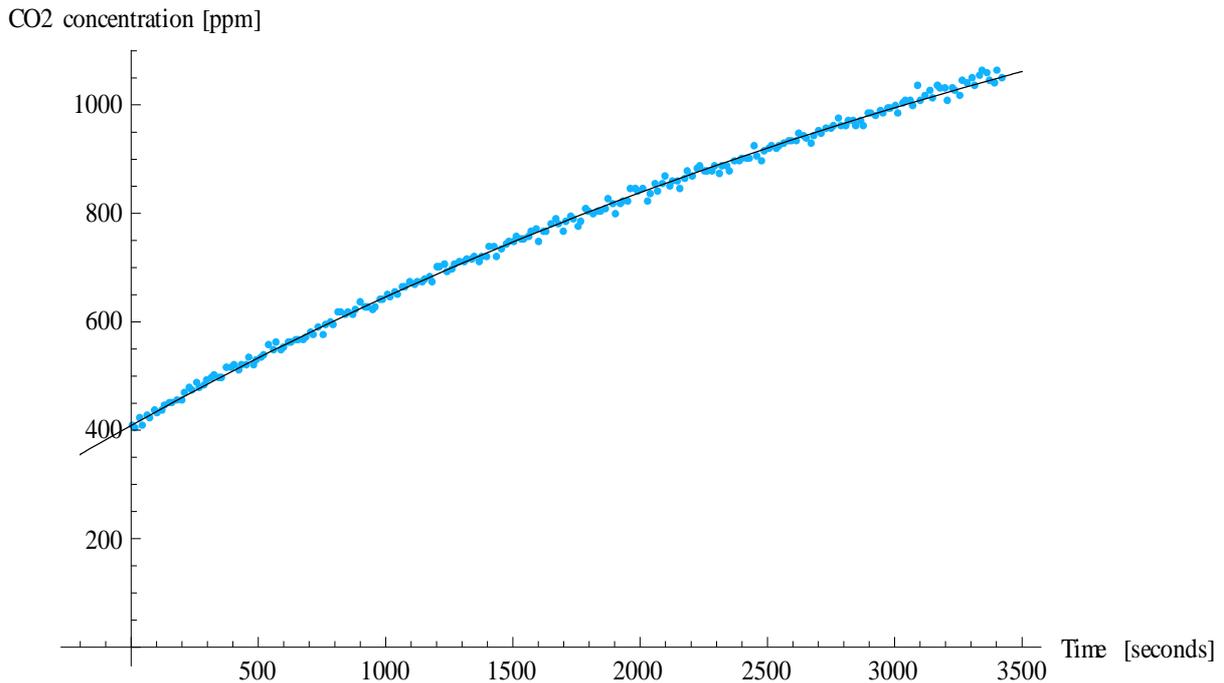


Figure 9: fit to the corrected CO₂ concentration data of sample D ($\sigma_{n-1} = 8.1$ ppm).

The data from the CO₂ detector did not always show a nice exponential curvature. Especially in the first minutes, probably due to getting the cup into place. To make a good fit to the data only the part of the data that showed a fit-able exponential behavior was used. To find the curvature at the start of the sampling procedure, the fit was extrapolated to $t=0$.

5.2 Methane

Because there was not an-easy-to use measuring device that could measure the methane concentration in situ in the field, only a sample at the beginning and at the end of the sampling process are taken. Therefore only the start (C_i) and end (C_f) concentrations are known. Now you could make a linear estimation of the methane flux, just by dividing the differences in concentration at the start and end of the sampling process by the time it took to collect the sample ($t_f - t_i$):

$$F = \frac{(C_f - C_i) V}{(t_f - t_i) S} \quad (5)$$

But at the same time and spot the CO₂ measurements where done. So there is some information of the diffusivity of this specific spot in these specific conditions. According to Fick's first law

$$F = -D \frac{\partial C}{\partial x} \quad (6)$$

the flux is proportional to the diffusion coefficient D and the concentration gradient. The diffusion coefficient of a gas in another gas is proportional to the square root of their reduced mass. Since methane and carbon dioxide both diffuse through the same gas, air, the ratio of their diffusion coefficients is proportional to the square root of the inverse ratio of their reduced masses with air (Zeebe and Wolf-Gladrow, 2001):

$$\alpha = \sqrt{\frac{M_{CO_2} * M_{air}}{M_{CO_2} + M_{air}} * \frac{M_{CH_4} + M_{air}}{M_{CH_4} * M_{air}}} = \sqrt{\frac{44.01 * 28.97}{44.01 + 28.97} * \frac{16.04 + 28.97}{16.04 * 28.97}} = 1.30 \quad (7)$$

So at the same pressure and temperature the diffusion coefficient of methane in air is 1.30 times higher than for carbon dioxide. By assuming that the concentration gradient is linear over the short distance from just above the soil surface until just below the soil surface (first order Taylor representation), Fick's first law becomes:

$$F = -D \frac{\Delta C}{\Delta x} \quad (8)$$

Now by fitting the linear function

$$y(x) = a x + b \quad (9)$$

through the two data points $(C_{CO_2i}, C_{CH_4i}), (C_{CO_2f}, C_{CH_4f})$, a linear transformation is found between the CO_2 and CH_4 concentration scale. $C_{CO_2i}, C_{CH_4i}, C_{CO_2f}$ and C_{CH_4f} are respectively the initial and final concentrations of carbon dioxide and methane of one sampling action. By using equation 7 and 9 it is possible to calculate the methane flux from the known carbon dioxide flux:

$$F_{CH_4} = \alpha * F_{CO_2} * a \quad (10)$$

F_{CH_4} and F_{CO_2} are respectively the methane and carbon dioxide fluxes, α the diffusion coefficient ratio of CO_2 and CH_4 and a the transformation factor that can be found by using equation 9. Note that the fluxes need to be expressed in units of number of particles per unit of area per unit of time, otherwise also a correction for the molecular mass needs to be made. Also note that the concentration gradient is unknown.

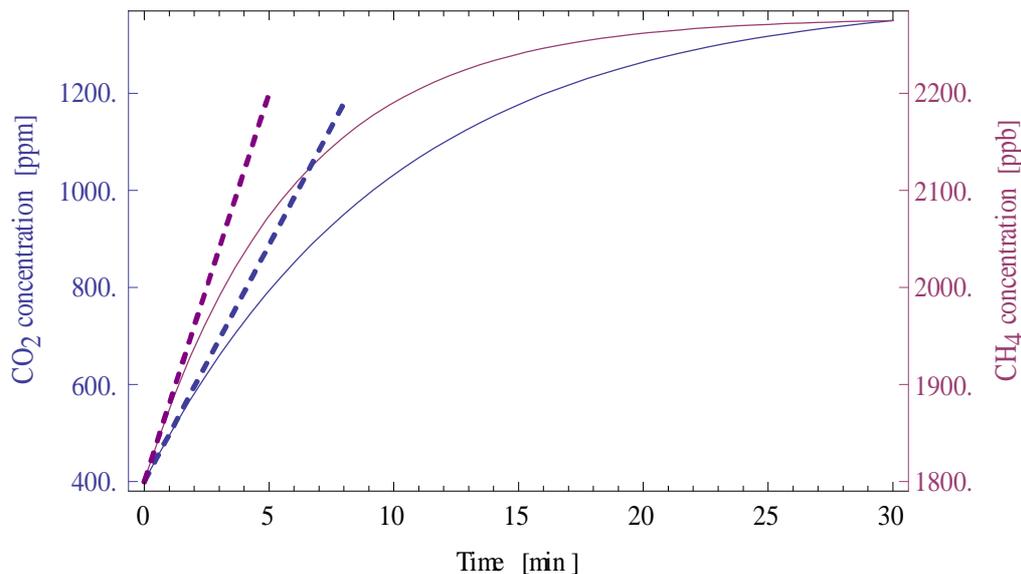


Figure 10: fictitious CO_2 and CH_4 concentration increase.

To illustrate how we got equation 10, figure 10 is made. In figure 10 the course of the CO₂ and CH₄ concentration during a fictitious sampling process are shown. Methane has a α times higher diffusion coefficient D . This means that CH₄ flux would be α times higher than the CO₂ flux if the their concentration gradients would be the same. This is illustrated in figure 10. The dashed lines represent the concentration increase at time zero. The slope of the purple dashed line is α times steeper than the blue dashed line. The methane concentration in the cup increases faster, but will reach its final concentration much earlier. Since methane does not have the same concentration gradient as carbon dioxide (as can be seen on the right scale of the y-axes), a linear correction in the calculations need to be made. This is done by using equation 9.

6. Results and discussion

6.1 Uptake and release

The calculated methane fluxes from the soil into the atmosphere can be found in table 4. These fluxes are arranged to their sample location and sample dates. A negative flux means that a net flux from the atmosphere into the soil was present. A positive flux means that methane was produced in the soil and released to the atmosphere.

Table 4: methane fluxes in g/m²/yr arranged to data and location.

Date	In land	Polder 1	Polder 2	Wetland	Mudflat
02-07-2010	D: -0.33±0.02	C: 0.15±0.02	A: -0.06±0.02 B: -0.27±0.06		
07-07-2010		E: -0.30±0.02	F: -0.00 G: -.037±.006		
15-07-2010			J: -.079±.005	H: 0.015±0.01 I: 0.20±0.04	
20-07-2010		K: 0.12±0.01	L: -.048±.003		M: 10±3
21-07-2010	N: -0.7±0.1	P: -.041±.003	O: -.086±.005	Q: 0.42±0.04	
03-08-2010					R: 0.2±5 S: 0.03±0.4

As expected there is a net methane production in the wet areas. The fluxes of all samples taken in the wetland and mudflat are positive. In those areas the water table is near the soil surface, creating oxygen-poor conditions. The aerated soils on land and in the polders are expected to act as a net methane sink. This is in accordance with the measurements. However, in polder 1 two samples were taken with a positive methane flux. These two samples are C and K. Why these two samples read a positive methane flux is not clear. However, 13 days earlier sample E was taken at the same site as sample K which gave a negative methane flux. In the time between the samples the soil conditions changed. When sample E was taken, the soil was hard, dry and cracks were present. Later the soil was humid and soft when sample K was taken. This could explain the positive flux for sample K. Probably anaerobic conditions were created due to the wet soil (see table 3 for the total precipitation of the previous week). However, when sample C was taken the soil was not very humid at all. Furthermore, the samples taken at land sites on the same days as C and K did not result in a positive flux.

The mean of the negative methane fluxes is -0.15 g/m²/yr, ranging from -0.7±0.1 up to -0.000 g/m²/yr. This is a bit higher compared to some fluxes on clay in the literature: -0.07 ± 0.04 g/m²/yr (Dörr et al., 1993), -0.4 g/m²/yr on average (and as low as -0.09 g/m²/yr) (Born et al., 1990) and -0.18 g/m²/yr between March and December (Mosier et al., 1991).

Lof (2011) has measured the fluxes of a number of gasses from the soil air, among which methane. He determined 50 fluxes on a fixed spot next to Lutjewad in the period from March up to the end of May 2011. These fluxes are measured in the same area but almost one year later.

His sampling time was 4 hours. He determined the fluxes by fitting a linear function through the begin and end concentration. In this way the flux is underestimated. Of the 50 methane fluxes, 49 read a negative value. The average of these 49 methane fluxes is -0.05 ± 0.02 g CH₄/m²/yr, varying between -0.008 ± 0.02 and -0.19 ± 0.02 g CH₄/m²/yr. (Lof, 2011).

The first sample taken at the mudflat (sample M) gave a high methane emission of 10 ± 3 g/m²/yr. This suggested that the Wadden Sea could be a major source for this greenhouse gas. However, the two extra measurements in the same area (sample R and S) could not confirm this presumption.

6.2 Measurement uncertainties

The measurement uncertainties in the CH₄ flux are determined using the uncertainty in the CO₂ flux. The uncertainty in the CO₂ flux is based on the uncertainties in: the fit parameters C_{soil} and k , C_{atm} , the time the cup is placed over the soil t_i with respect to the first data point used for the fit, volume of the cup V , surface covered by the cup S , CO₂ concentration measured with the CO₂ detector and the gauging parameters $a1$ and $b1$ (from $C_{GC} = a1 * C_{vaisala} + b1$). These uncertainties are summarized in table 5 with their relative values.

Table 5: uncertainties in different variables used to determine σ_{CH_4Flux} .

Uncertainty	Value
σ_k	Dependent on quality of fit. (Sample D: $4.5 \cdot 10^{-6} \text{ s}^{-1}$ (2.2%))
$\sigma_{C_{soil}}$	Dependent on quality of fit. (Sample D: 22 ppm (1.3%))
$\sigma_{C_{atm}}$	2.5% of C_{atm}
σ_{t_i}	60 s (120% for Sample D)
σ_V	$5.0 \cdot 10^{-4} \text{ m}^3$ (3.5%)
σ_S	$2.0 \cdot 10^{-3} \text{ m}^2$ (4.0%)
$\sigma_{[CO_2]}$	2.5% of $[CO_2]$
σ_{a1}	0.012 (1.2%)
σ_{b1}	6.6 ppm (38%)

The parameter t_i is not mentioned before and its relative uncertainty of 120% in sample D looks quite dramatic. That is why a brief explanation is given here. As mentioned in section 5.1, the CO₂ is fitted to equation 1. Only the first part of these data is not used for this fit (compare figure 8 and 9). In order to find the flux at the moment that the cup is put into place, the derivative of the fit to the CO₂ data is taken at t is zero (equation 2). In practice this is not strictly true. Since the fitted function starts ($t=0$) at the first data point used for the fit, which is not the moment the cup was put into the soil. Therefore we do not want to know the flux at $t=0$, but at $t=-t_i$, the time difference between the first data point used for the fit and the actual start of the measurement.

$$\frac{dc}{dt} \Big|_{t=t_i} = (C_{soil} - C_{atm})k e^{(-k)(-t_i)} \quad (11)$$

The uncertainty in the initial time t_i is put at 60 seconds, because placing the cup on the soil is not an instant process, but takes some time. This σ_{t_i} could also have been 30 seconds, but it is not of a significant influence in the final uncertainty of σ_{CH_4Flux} . Most of the CO₂ data of sample D could be used and therefore t_i is only 50 seconds, which makes σ_{t_i}/t_i look large.

The uncertainties in the fit parameters (C_{soil} and k) were most of the time the dominant parameters. This explains the relative high uncertainty in sample R and S, because it was not possible to find a neat fit to the CO₂ concentrations. It must be noticed that the determined measurement error in the methane flux is only the error in the measured methane flux out of the soil into the cup. A difference could exist between the measured flux and the real flux from the

soil. This is due to the fact that one always influences the surroundings slightly by placing the cup. For example, near the rim of the cup the structure of the soil is a bit altered by placing the cup into the soil. In this way trapped pockets of methane could come free or free flow paths could get blocked. In this research it is assumed that only vertical methane fluxes exist, but also horizontal concentration gradients exist. Therefore it is possible that not only the soil air immediately below the cup is interacting with the air in the cup, but also some soil air just besides the cup. In extreme cases it is even possible that the surrounding atmospheric air has some influence by diffusing into the soil next to the cup and ends up under the cup itself. This small effect could be realistic if you realize that the methane concentration (gradient) in the soil is influenced during a sampling action.

6.3 Influence of environmental conditions

At Lutjewad measurements of the atmospheric temperature at different heights, the water table depth, the soil moisture content and air pressure are taken. At each sample location the soil temperature at 5 cm and 10 cm below the soil-atmosphere interface and the surrounding atmospheric temperature is measured. These measurements are used to investigate if any correlation exists between the methane flux and these parameters. Also the change in some physical conditions could have influenced the fluxes, like the water table and the atmospheric pressure. If the water table would rise, it pushes the soil air up into the atmosphere increasing the flux. On the other hand if the water table is decreasing, atmospheric air is sucked into the soil and will flow through the soil under the cup. During these conditions you would measure atmospheric air and the flux will be low.

In order to find the correlation between one of (or change in one of) these parameters and the methane flux, all conditions should be kept constant except for the one that is under investigation. This was not the original setup of this research. That is why no effort is put in 'creating' similar conditions except for one environmental parameter. Since there are only 19 fluxes available it is not possible to select the results in such a way that the influence of one parameter could be investigated. Especially if you realize that a number of parameters are of influence, originating from atmospheric (pressure, temperature) and soil conditions (moisture, water table, temperature, permeability, tortuosity).

The initial idea was to have the automatic soil-chamber system, as described by Lof (2011), set up and running by the time the samples for this research project have been taken. This would have given information about the flux variations in time at one single place, due to frequently monitored environmental variables. Unfortunately the system was not yet functional in time.

However, the fluxes have been plotted against a number of different physical parameters. Often no clear correlation was visible in the small amount of data points available. Correlations that were present could also have been a coincidence. Therefore it is hard to say anything conclusive. To give an indication of the results some of the plots are shown below.

6.4 Temperature

In figure 11 are the fluxes in the polders and inland sites plotted against the soil temperature at 5 cm (green) and 10 cm (red) below the soil surface plotted together with their linear trend lines. Despite that the temperature is one of the main parameters influencing the methane flux, no clear correlation is present. The belonging linear regressions and their sample standard deviations are $F_{CH_4} = 0.11 - 0.011 T$, $\sqrt{S_{n-1}} = 0.22 \text{ g m}^{-2} \text{ yr}^{-1}$ and $F_{CH_4} = 0.26 - 0.020 T$, $\sqrt{S_{n-1}} = 0.21 \text{ g m}^{-2} \text{ yr}^{-1}$ for the temperature at respectively 5 cm and 10 cm below the soil surface. Even if we take only the samples taken at the reference location in polder 2 (samples: A, G, J, L and O), there is still no clear correlation between temperature and the methane flux. The resulting linear fits to the data and the sample standard deviations for the temperature at 5 cm

and 10 cm below the soil surface are respectively: $F_{CH_4} = -0.055 - 0.0031 T$, $\sqrt{S_{n-1}} = 0.23 \text{ g m}^{-2} \text{ yr}^{-1}$ and $F_{CH_4} = 0.25 - 0.016 T$, $\sqrt{S_{n-1}} = 0.23 \text{ g m}^{-2} \text{ yr}^{-1}$.

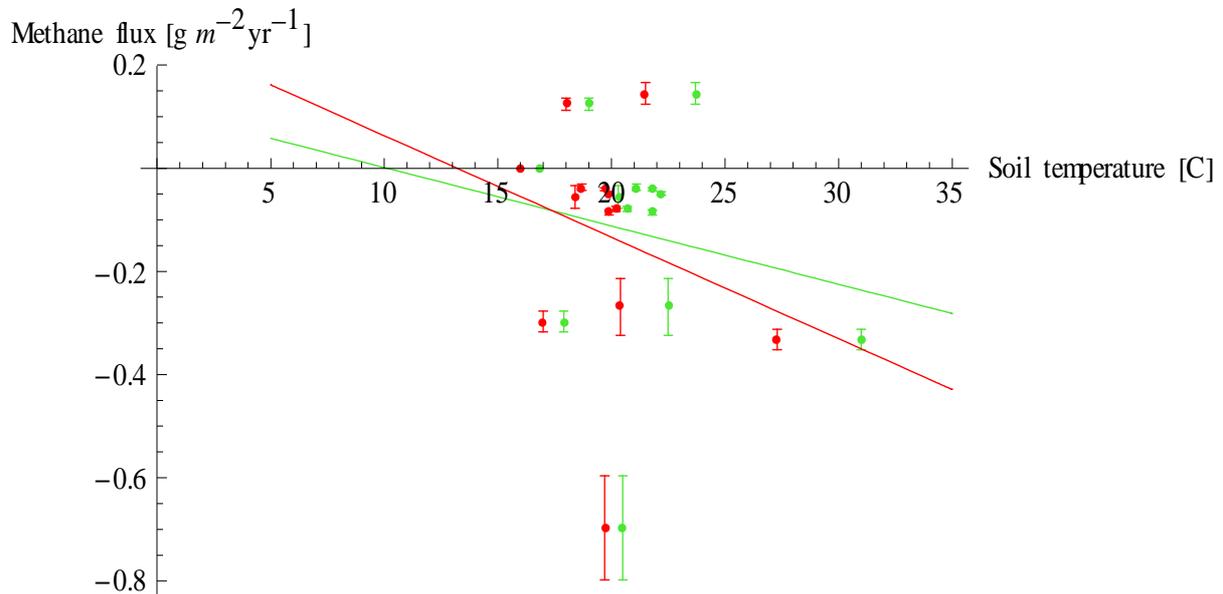


Figure 11: Methane fluxes of all agricultural sites plotted against the soil temperature at 5 cm (green) and 10 cm (red) below the soil surface.

Born et al. (1990) concluded that the methane flux into the soil is mainly controlled by the transport resistance in the soil. They only found a slight soil temperature dependency on the methane flux. But Dörr et al. (1993) did not find a strong correlation between the soil temperature and the methane flux.

6.5 Water table

Water is responsible for creating anaerobic conditions. Water can also fill up pore spaces influencing diffusivity. Some gasses like CO_2 can dissolve in water. Those effects all influence the fluxes of the gasses in the soil air. That is why a correlation between the water table and/of the soil moisture is present. Like the previous example with the soil temperature, no clear correlation has been found between the methane flux and the water table or soil moisture. The R^2 values of the fits with the methane fluxes measured on all land locations with the water table and soil moisture are respectively $R^2=0.019$ and $R^2=0.003$.

It is expected that the change in water table has more influence on the methane flux than the absolute water table itself. If for example the water table drops, it sucks atmospheric air into the soil. In this situation the soil air near the surface is mixed with atmospheric air, making the gas concentrations in this region of the soil closer to atmospheric concentrations. On the other hand, if the water table rises, soil air is pushed up out of the soil. Now soil air influenced by organisms in lower layers is present in the top layer. To give an impression, the water table on July 2, 2012 is plotted in figure 12.

The dashed lines in figure 12 indicate the moment when the sampling started of the four samples taken this day. During sampling sample A and B, the water table was dropping. When sample C and D were taken, the water table was rising. There is probably some lag between the change in water table and soil air movement at the soil/atmosphere interface. Therefore it could be possible that during sampling sample C the effects of a dropping water table are still present.

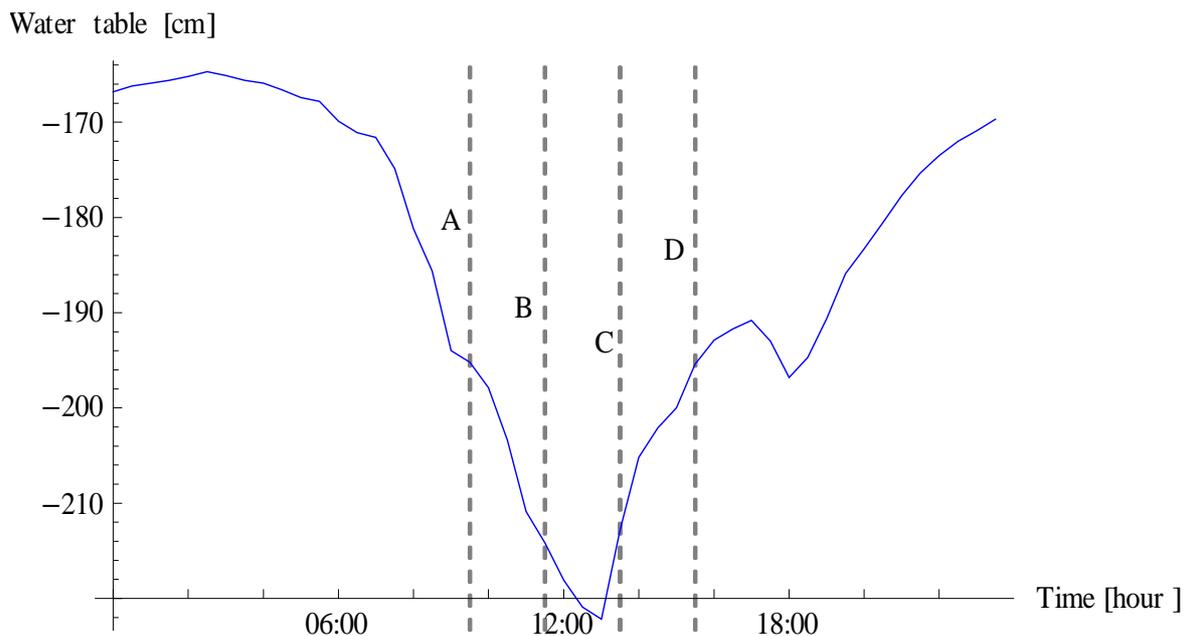


Figure 12: the water table in cm below the soil/atmosphere interface on 2 July 2010.

As you can see in table 4 the methane fluxes measured on 02-07-2010 are -0.06 ± 0.02 , -0.27 ± 0.06 , 0.15 ± 0.02 and -0.33 ± 0.02 g CH₄ m⁻² yr⁻¹ for respectively sample A, B, C and D. In figure 2 you can see that they were all taken on land. For sample A, B (and C) a relatively small flux is expected, but only sample A shows a relative small flux compared to the other samples on this day. Sample D does not have a big methane flux compared to for example sample B, while the water table is rising. The methane flux of sample C is even positive (i.e.: release of methane). This indicates that specific circumstances of the spot on which the methane flux is measured (like soil structure), have more influence on the methane flux than, in this case, the water table. The water table is measured near the atmospheric monitoring and sampling station Lutjewad and it is assumed that this is representative for the water table in the near area. However, this is not necessarily the case and could also be the cause why the methane fluxes do not show their expected behavior.

6.6 Pressure

The atmospheric pressure has a similar influence on the fluxes from the soil as the water table. When the pressure increases it forces atmospheric air into the soil and the other way around. However, this is only a small effect. Especially during the period the samples were taken, since the fluctuations in atmospheric pressure were only small. The average pressure during the 19 sampling sessions is 1011.5 hPa. The minimal and maximal pressure was 1004.3 and 1021 hPa. The pressure during a sampling session only fluctuated by a few hPa (~2‰). That is probably why no clear relation between the atmospheric pressure and the measured methane flux could be found.

6.7 The same sample locations

Besides the five measurements on the reference location (A, G, J, L and O), three other locations are measured twice at different days to investigate if they would give the same fluxes. These measurements are from sample E and K in polder 1, D and N at the inland area and I and Q on the wetland. The measured fluxes at these same locations are not the same and no clear correlation between the differences and the soil moisture content, water table or temperature is found. Therefore the data from this research cannot give a clear explanation for the measured differences in these fluxes. This is also a reason why the deviations in the measurements at the

reference location are not used to 'correct' the other measurements for the daily variation in environmental conditions.

6.8 Comparison to the linear flux

The CO₂ flux is used to determine the CH₄ flux. Since this is not a common used method, we want to know how good it actually works. Since the begin and end time and initial and final concentration of CO₂ and CH₄ are known, we know the flux based on a linear estimate. Therefore we will look at the difference between the determined fluxes and their linear approaches and compare this to literature values.

Since the inverted cup method influences the concentration gradients, a linear approach using equation 5 will give an under estimation of the real flux. Dörr et al. (1993) used parallel measurements of the ²²²Radon flux to estimate the methane flux from concentration measurements in the soil air. This resulted in a 30% higher methane flux than from a linear estimation from an inverted cup experiment. This deviation is of course depending on the sampling time duration (45 minutes in Dörr et al., (1993)) and the cup height (Stolk et al, 2009). The reason for these dependencies is that the concentration in the cup is exponentially decreasing or increasing until a stabilization limit is reached. In my experiment the average deviation in the linear approach compared to the exponential approach in the CO₂ flux is 33%, varying between -2% and 91%. For methane the flux calculated with equation 10 is on average 72% higher compared to the linear approach, varying between 47% and 149%.

No corrections have been introduced to compensate for the different conditions in this research and that of Dörr et al. (1993). Therefore you cannot compare these percentages one on one. However, the difference in the deviation in the methane flux from linear seems to be high (72% compared to 30%). Maybe a seasonal effect could explain the difference, since the measurement from this report are only taken during the summer months. However, according to the findings of Dörr et al. (1993) methane does not show a pronounced seasonal cycle, unlike CO₂ which does (Dörr and Münnich, 1987). This means that the results should be independent on the time of year that the samples are taken. The CO₂ flux is highest in the summer months during which the samples were taken. The methane fluxes are calculated on the basis of the CO₂ fluxes, however the height of the CO₂ flux should not be of an influence. The correction factor a in equation 10 compensates for the height of the CO₂ flux. Therefore the fact that the samples are taken in the summer months does not explain why the difference in linear and not linear determination of the methane flux is higher than in the literature.

Kroon et. al. (2008) found a difference up to 60% and Anthony et al. (1995) an average of 54% between linear and exponential calculated N₂O fluxes. It could be possible that the difference is different for different gasses.

6.9 Possible disturbing effects

Pressure effects and leaking effects can cause an under estimation of the flux (Kroon et al., 2008). If the pressure in the cup increases, air can be forced into the soil hindering the soil air flux. A pressure increase could be caused by a temperature rise in the system when heat from the sunshine is absorbed by the system or due a decrease in volume of the system when the cup is pushed into the soil. To minimize these effects the system was shielded from the sunshine with an umbrella on sunny days. Also the rim of the cup is only placed 2 to 3 cm into the soil, corresponding to a 6.5% to 9.5% volume decrease of the system, to minimize the volume change effect. The rim needs to be placed into the soil to prevent leakage of gasses. Stolk et al. (2009) mention an insertion depth in combination with the sampling time of at least 12 cm h⁻¹ to prevent leakage. But for this study only ~2 cm h⁻¹ is used. Especially in dry clay soils shrinkage cracks can arise, through which gasses can escape the cup. This causes an under estimation of

the measured flux (Stolk et al., 2009). As mentioned earlier it is even possible without those (shrinkage) cracks that the flux is influenced by gasses in the surroundings of the cup, by vertical diffusion.

An improvement to the sampling system to minimize the effect of volume decrease during the placement of the cup is possible. This can be done by providing a kind of valve that can be opened when the cup is put in place. With such a valve the pressure inside the cup will stay the same during the placement of the cup into the soil. In this research the hose(s) (from the flow meter to the cup) was(ere) connected to the cup, while placing the cup. Even if this was not the case it would not make a difference. The reason is that the connectors used to connect the hoses to the cup, would close automatically when a hose was disconnected.

Conclusion

The inverted cup method has been used to successfully determine 19 times the methane flux in the area around the atmospheric monitoring and sampling station Lutjewad.

It can be concluded that outside the sea dike methane is produced and released from the soil. All measurements on the wetland and mudflat resulted in a methane release. This is due to the anaerobe conditions created by the high water table on these locations.

On the other hand, on the land side of the sea dike, a net methane uptake is revealed by the measurements performed in this area. From the 13 measurements on the land sides, 11 of them showed a methane uptake by the soil. Both measured methane releases were in polder 1. The largest methane fluxes into the soil were measured on the land area, on the landside of the old sea dike.

This research was too short to collect a sufficient amount of data to come to firm conclusions over the methane fluxes in the different sections around Lutjewad. Nor could it give a clear relation between certain parameters and the methane flux. The conditions that have been compared to the methane flux are: atmospheric temperature, soil temperature, moisture content, depth of the water table and atmospheric pressure. None of them could be fitted with enough accuracy to the methane fluxes. This indicates that multiple parameters are important for the size of the methane flux, which can vary from spot to spot and from day to day.

The main reason for this research was to give an indication of the methane fluxes around Lutjewad. This is what has been accomplished and following research should collect more data, in parallel to a quasi-continuous measurement series at the station, to give more detailed results.

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Appendix

Table 6: all measured fluxes and their environmental conditions*.

Sample	CH ₄ flux g/m ² /yr	CO ₂ flux kg/m ² /yr	Temp. air (°C)	Temp. 10cm (°C)	Temp. 5cm (°C)	Soil Temp Lutjewad (°C)	Soil Moisture	Water table below soil surface (m)	Atmospheric pressure (hPa)	Soil conditions
A	-0.06 ±0.02	0.4 ±0.2	27.6	18.4	20.3	18.82	0.291	209.5	1011.9	Dry, loose clay
B	-0.27 ±0.06	3.1 ±0.6	31.3	20.4	22.5	18.92	0.290	218.6	1012.1	Short grass
C	0.15 ±0.02	3.3 ±0.5	35.3	21.5	23.7	19.17	0.289	199.2	1012.2	Dry, loose clay
D	-0.33 ±0.02	1.17 ±0.07	31.5	27.3	31.0	19.50	0.288	191.8	1012.5	Dry clay
E	-0.30 ±0.02	1.17 ±0.008	23.4	17.0	17.9	18.33	0.285	218.9	1021	Hard, compact, cracked
F	0.000	0.23 ±0.08	26.7	16.0	16.9	18.38	0.285	215.4	1020.6	Hard, dry
G	-0.037 ±0.006	0.7 ±0.1	25.5	18.7	21.1	18.53	0.284	197.8	1019.5	Top clay layer is loose/brittle
H	0.015 ±0.001	2.1 ±0.2	20.4	18.9	18.8	19.78	0.284	169.9	1006.8	Long grass, wet clay
I	0.20 ±0.04	4.5 ±0.8	20.5	18.3	18.5	19.71	0.283	174.8	1008.1	Between plants, wet clay
J	-0.079 ±0.005	2.2 ±0.1	22.0	20.2	20.7	19.65	0.283	171.2	1009.1	Humid, fictile clay
K	0.12 ±0.01	1.8 ±0.2	30.4	18.0	19.0	18.32	0.284	206.9	1014.6	Humid
L	-0.048 ±0.003	1.8 ±0.1	27.2	19.9	22.2	18.42	0.283	214.3	1012.7	Humid
M	10±3	0.8 ±0.3	28.1	24.1	26.0	18.72	0.282	206.6	1011.6	Low tide mudflat
N	-0.7±0.1	7±1	24.6	19.7	20.5	19.13	0.281	213.4	1004.4	Humid, soft, sandy
O	-0.086 ±0.005	2.0 ±0.1	28.7	19.9	21.8	19.16	0.280	221.7	1004.3	Just next to ref. location
P	-0.041 ±0.003	1.4 ±0.1	28.0	19.7	21.8	19.26	0.279	208.0	1004.9	Cracked
Q	0.42 ±0.04	4.3 ±0.4	26.0	19.1	24.0	19.44	0.279	201.5	1006	Between plants, wet clay
R	0.2±5	0.5±1	18.5	17.5	18.2	17.17	0.271	195.6	1013.5	Low tide mudflat
S	0.03 ±0.4	0.3±3	19.6	19.4	20.7	17.22	0.270	193.3	1013.3	Low tide mudflat

* Some of the environmental parameters measured at Lutjewad are not relevant for the samples taken at the mudflat and wetland, like the water table, soil moisture and soil temperature Lutjewad.