Rapport de stage individuel

4ème année

Mitigating Greenhouse Gas Emissions: Development of Tools for Studying Methane Emissions in Restored Peatlands

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Preamble

The writing of this report has been proofread and grammatically checked by "Gemini". Gemini is a conversational agent using artificial intelligence to understand and respond to written requests. This "ChatBot" (chat = discussion, bot = robot) is developed by Google. Even though the tool is very controversial for several reasons, such as intellectual property theft (since the tool does not cite its sources), it remains a very useful tool for grammar checking text.

Facing linguistic difficulties due to dysorthography, the use of AI (artificial intelligence) allows me to gain autonomy. My difficulties are even more present as English is not my mother tongue. Here is an example of a query submitted to Gemini for the grammatical correction of a paragraph, an example of which can be found in APPENDIX 1. Gemini will respond with another version of the paragraph, with the list of corrections made. Gemini has also been asked, always in the context of difficulties encountered, for syntactic correction.

In all cases presented, Gemini was never asked to add information to the rewritten paragraphs. In addition, each paragraph and formulation written by the tool is carefully checked to remove errors, misunderstandings, and inconsistencies.

Additionally, ChatGPT, another AI chatbot, assisted with data cleaning programming in R Studio.

Acknowledgements:

I would like to express my sincere gratitude to Nicholas Hermansen for his invaluable guidance and support throughout my internship project. His expertise and positive attitude made my experience both productive and enjoyable.

I am also deeply grateful to Joachim Audet, my internship supervisor, for helping me settle into life in Denmark and for his assistance with writing my report. His support was essential to my success.

I would like to thank Sabine Greulich, my academic supervisor, for her academic guidance. Her advice and encouragement were invaluable.

Finally, I would like to thank the other French students in Denmark for the great times we shared outside of work. Their friendship made my stay even more memorable.

Table of Contents

Lists of figures

Abbreviations list

CH4	Methane
CO2	Carbon dioxide
CSEM	Catchment Sciences and Environmental Management
DAPAE-II	Danish Action Plan for the Aquatic Environment II
DFF	Independent Research Fund of Denmark
ECOS	Department of Ecoscience
EU	European Union
GHG	Greenhouse gases
TSR	Topsoil removal

1. Introduction

1.1. Hosting structure: Aarhus university

As a fourth-year engineering student, I had the opportunity to complete a 12-week internship at Aarhus University in Denmark, within the Department of Ecoscience (ECOS) (Figure 1)This Department encompasses a broad spectrum of environmental and ecological disciplines. This multidisciplinary research department actively engages in teaching, consultancy, and research, generating knowledge-based solutions to address societal challenges.

The Department of Ecoscience is organized into three sections, located in Roskilde and Aarhus (Figure 2). The Roskilde section comprises Applied Marine Ecology and Modelling, Arctic Environment, Arctic Ecosystem Ecology, Marine Mammal Research, and Marine Diversity and Experimental Ecology units. The Aarhus Land section encompasses Biodiversity, Wildlife Ecology, and Terrestrial Ecology units. Finally, the Aarhus Water section is composed of units in Marine Ecology, Catchment Science and Environmental Management, and Freshwater Ecology.

ECOS has a team of approximately 275 employees, with around 175 staff members based at the Aarhus campus and the remainder located in Roskilde. The department fosters a collaborative environment with roughly 200 permanent employees, including 15 PhD students and 20 postdoctoral researchers. Rounding out the team are approximately 40 individuals on fixed-term contracts. This diverse group fosters strong collaborations not only within the department but also extends to Danish and international institutions, creating a stimulating and intellectually inspiring environment for both employees and students.

Figure 1 Organization chart of Department of Ecoscience

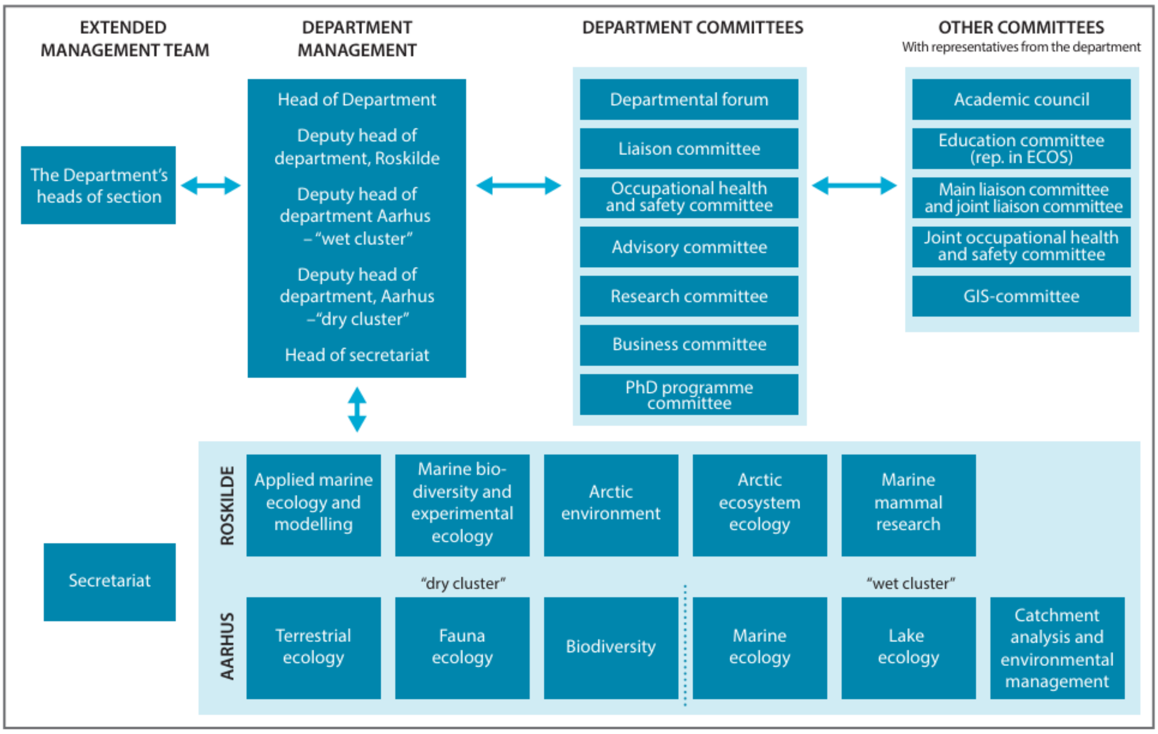


Figure 2: Organization of sections and units in the Department

The Department embraces an ecosystem approach, fostering research excellence in four key areas:

Marine Ecology: They delve into the structure and function of marine ecosystems across diverse environments, from Arctic coastlines to tropical waters. A central focus is discerning natural variations from human-induced changes. To achieve this, they develop tools and methods to assess the health and state of marine ecosystems, analysing factors influencing ocean dynamics.

Terrestrial Ecosystems: Their research empowers the green transition and sustainable practices in agriculture and forestry, prioritizing nature-based solutions. They create tools for cost-effective conservation and address conflicts between nature and human activities like hunting or recreation. Notably, ECOS houses the national monitoring program NOVANA's 'Dry Nature and Species' topic centre, leading methodological development, data analysis, and annual reports on the state of nature.

Freshwater Ecology: ECOS boasts internationally recognized expertise in aquatic freshwater biology and ecology. This encompasses diverse freshwater ecosystems: streams, lakes, ponds, and their surrounding catchments. Research benefits from long-term field studies and specialized test facilities in Lemming, which use controlled mini ecosystems to study abiotic and biotic dynamics.

The Arctic Environment and Nature: For decades, ECOS has played a prominent role in Arctic research, monitoring, and consultancy. They focus on studying Arctic ecosystems, particularly in Greenland. Knowledge transfer is facilitated through collaboration and consultancy with Greenland's self-government and the Greenland Institute of Natural Resources. Their research spans across trophic levels, from microbes to birds, examining individual, population, and ecosystem levels in marine, freshwater, and terrestrial environments.

Across the 4 academic strengths, the department works with research themes or approaches that are often shared or common to the areas of strength. Like Biodiversity, Green transition, environmentally hazardous substances, Innovative monitoring, Climate effects on nature and the environment and Modelling.

1.2. Presentation of the “Catchment section”

This internship was primarily conducted within the Catchment Sciences and Environmental Management (CSEM) section, which belongs to the WATER cluster. The specific group I worked with is the Wetland group within CSEM.

The CSEM section aims to acquire knowledge about nutrients and environmentally hazardous substances in aquatic areas such as lakes, streams, and fjords. Their goal is to identify the best responses to the negative consequences caused by urban communities, agriculture, global climate change, and other human activities. Leveraging the knowledge gained through their research, the group provides consultancy services to national and international authorities. This expertise helps ensure that the management of aquatic areas reflects the most current scientific understanding. The group's research and consultancy activities can be divided into three core areas:

Nutrient dynamics and hydrology: This area focuses on understanding how nutrients move through aquatic ecosystems and how water flow influences these processes.

Tools for reducing nutrient loss to the aquatic environment: This area involves developing and evaluating methods to minimize nutrient pollution in lakes, streams, and fjords.

Wetlands and greenhouse gases: This area investigates the role of wetlands in mitigating greenhouse gas emissions and how they interact with nutrient dynamics in aquatic environments.

This internship focused on greenhouse gas emissions in restored peatland drain ditches within the Wetland and Greenhouse Gas research area. This group research also compared pre- and post-restoration conditions to assess how restoration impacts emissions. Additionally, it explores methods to mitigate potential negative effects, such as using temporary phosphorus filters and harvesting biomass. Since 2010, this research group has been developing and designing constructed wetlands for nutrient removal in drainage water. (*Department of Ecoscience*, 2024)

1.3. Presentation of the internship

1.3.1. Context and problematics

Human-induced global warming is an established fact, making the 2011-2020 decade the warmest in about 125,000 years. In 2019, the average atmospheric $_{CO2}$ concentration reached 410 ppm, a level not seen for 2 million years. This warming is driven by anthropogenic (human-caused) greenhouse gas (GHG) emissions, such as CO_2 and CH_4. (Calvin et al., 2023) Over the past decade, global emissions averaged approximately 56 $GtCO_2eq$ per year. While this is lower than the previous decade, it's still insufficient to limit global warming to 1.5°C by 2030. Climate change, which is strongly linked to global warming, is already impacting both humanity and biodiversity. Many regions around the world are facing challenges related to water and food security. Biodiversity loss further disrupts ecosystem stability and reduces essential ecosystem services, exacerbating health problems. (Calvin et al., 2023)

A good way to limit GHG emissions is the rewetting of wetlands as this can effectively mitigate $_{CO2}$ emissions (Waddington & Warner, 2001). Indeed, rewetting wetlands suppresses the availability of oxygen in the soil, creating an anoxic environment that hinders the decomposition of organic matter. The carbon within organic matter remains trapped in the soil, unable to be released. In this way, wetland restoration, such as drained peatland restoration, is becoming increasingly common. Between 22.5 and 50.9 million hectares of peatlands have been drained for agricultural purposes worldwide, resulting in greenhouse gas emissions of 1.5 to 2.5 Gt CO_2-eq per year. (Hendriks et al., 2024). Indeed, peatlands act as a unique interface between the atmosphere, terrestrial environments (land), and aquatic ecosystems (water). In these peatlands, the soil is constantly saturated with water, creating anoxic (oxygen-depleted) conditions. Lack of oxygen hinders the complete decomposition of organic matter, such as plant litter, leading to a gradual build-up of peat over time, forming a distinct ecosystem with its own characteristic plant and animal life (Littlewood et al., s. d.). Since the 1800s, many peatlands have been drained and altered, primarily for agriculture and peat extraction. This drainage not only increases greenhouse gas emissions, but also accelerates land subsidence (Zak & McInnes, 2022). Re-wetting and restoring peatlands are a way to rebuild carbon sinks by preventing the decomposition of peat organic matter, reduce subsidence and increase biodiversity.

Denmark has more than 30 years of experience in peatland restoration (Ambus & Hoffmann, 1990). With more than 200 wetland sites restored, it is the most active EU (European union) member state in this field. Most of this restoration occurred under the Danish Action Plan for the Aquatic Environment II (DAPAE-II), implemented in 1998 by the Ministry of the Environment. This plan led to projects involving restoration measures such as stream remeandering, disconnecting tile drains, and re-establishing lakes (Baumane et al., 2021). The aim of the restoration was to reduce nutrient loads in soil and water, but also, contribute to mitigating greenhouse gas emissions, and preserve biodiversity. To date, many projects have been completed, covering an area of approximately 19,393 hectares (Audet et al., 2020).

There are numerous methods to rewet a peatland. For instance, simply stopping the operation of pumps or blocking drains and ditches will help to raise the water table. While cost-effective, rewetting often leads to a significant release of methane (CH_4), a potent greenhouse gas. This CH_4 surge primarily originates from the top centimeter of soil, previously exposed to air during drainage. This exposed layer undergoes decomposition, creating nutrient-rich degraded peat. Upon rewetting, this nutrient-laden material stimulates vegetation growth, accelerating decomposition and methane production.

To mitigate methane emissions, techniques like topsoil removal (TSR) can reduce CH_4 by 30 to 400 times (Huth et al., 2020). Topsoil removal reduces methane emissions by eliminating the primary source of labile organic matter, which fuels methane production. Removing the degraded, nutrient-rich top layer prevents the rapid increase in vegetation and subsequent decomposition that leads to high CH_4 release upon rewetting. This is because fresh organic matter, such as plant and root litter, is a primary driver of methane production. In contrast, peat devoid of fresh organic material is relatively inert. Substantial anaerobic CO_2 and CH_4 production in peat occurs only when readily decomposable organic matter, like remaining roots or root exudates, is present (Hahn-Schöfl et al., 2011).

One question remains: what to do with this degraded peat?

In addition, most studies on greenhouse gas emissions from peatlands do not consider emissions from artificial water systems such as drainage ditches crossing these wetlands (Peacock et al., 2021), even though these ditches are already highly methanogenic systems at the edges of drained peatlands.

(Koehn et al., 2021). CH_4 emissions are the final products of anaerobic microbial degradation of organic matter. This process, methanogenesis, is the only way for microbes to completely break down organic matter in the absence of oxygen and other electron acceptors like nitrate, sulfate, or iron. Methanogens is prevalent in aquatic environments such as wetlands, peatlands, and lake sediments. These environments are estimated to contribute over 60% of the global methane budget, which is roughly 500-600 teragrams per year (Tg CH_4 yr^{-1}) (CONRAD, 2020)).

Compared with other peatland restoration methods, TSR offers several advantages, such as limiting methane (CH_4) emissions compared to flooding rewetted peatlands and being easy to implement as it only requires the use of a construction excavator. However, TSR projects present two key challenges related to GHG emissions. First, degraded peat, with its high GHG emission potential, needs to be managed. Second, unmanaged blocked ditches can become significant sources of GHG emissions. One potential solution involves filling these ditches with the top layer of peat. However, for this approach to be effective, the initial GHG emissions from the rewetted peat ditches must be demonstrably lower than the emissions that would result from filling the ditches with topsoil. Another possibility to manage this degraded peat is to mix it to an agricultural soil to use it like a natural fertilizer.

1.3.2. Problematic and goal of the project

The ReverCit project aims to quantify the impact of different peatland restoration techniques and determine the fate of degraded peat by comparing daily greenhouse gas (GHG) fluxes from various soil types. The project will measure methane (CH_4) and carbon dioxide (CO_2) emissions from several restoration treatments, including blocked ditches filled with topsoil, agricultural soil, a mixture of agricultural soil and degraded peat, peat restored using topsoil removal (TSR), and flooded peat. By evaluating GHG fluxes, the research seeks to inform evidence-based restoration practices that minimize GHG emissions. Additional analyses will be conducted to understand the mechanisms behind nutrient release and its link to GHG emissions.

Led by PhD candidate Nichlas Hermansen and Professor Dominik Zak, this research is funded by the Independent Research Fund of Denmark (DFF). It addresses a critical knowledge gap in peatland restoration: understanding GHG emissions from different soil types and the impact of adding degraded peat to various environments, as well as understanding nutrient release.

My role involved analyzing raw data from the experimental setup to determine daily GHG fluxes. This included developing a program to clean and estimate fluxes, as well as conducting statistical verification to ensure data reliability. Subsequently, I analyzed the results in the context of peatland restoration and GHG emissions.

1.3.3. Tasks undertaken during the internship

To achieve a critical understanding and develop effective mitigation strategies, this internship project will focus on several key tasks. I started my internship by reading scientific literature to understand the methanogenesis processes occurring within peatland drainage ditches and the rewetted peatland. I have also studied the estimations of GHG flux, the modeling of the flux, and the R tools and packages we need to use. Once a week, I go into the field to ensure accurate and consistent data collection procedures throughout the field experiments. This experimentation requires a lot of field maintenance, which will be described in the Materials and Methods section.

Most of my time here has been spent developing user-friendly tools to streamline the cleaning process of raw data, facilitating easier analysis and interpretation. These tools were an improvement on an existing R package. I also wrote a user manual and extensive documentation on these tools to ensure their future use by the university. Throughout my internship, I have shared project advancements with collaborators regularly. I wrote this final report to compile a comprehensive summary of my internship, including the research findings and data analysis results.

This research internship will explore the critical issue of GHG emissions from different soil in the context of peatland restoration. To achieve a comprehensive understanding, this report will begin with a detailed description of the materials and methods used in the field experimentation. Subsequently, the second part will present a thorough development of the R tool to estimate the daily flux of each soil type automatically. Finally, the report will conclude with a discussion of the findings, exploring the project's limitations and outlining potential areas for future research.

2. Materials and methods

2.1. Study site: Vejrumbro

The Vejrumbro experimental field site (56°26'15.3"N, 9°32'44.1"E) is a 8-hectar lowland riparian fen located in the Nørreå stream valley, Middle Jutland, Denmark. The site is delimited by artificial drainage ditches in the north and the west, a road in the east, and by the Nørreå stream in the south. From the first half of the 20th century the site has been shallow drained and used for grazing purposes, until the establishment of research infrastructures in 2018. These included the installation of 212 piezometers grouped in nests with screens at different depths, positioned across the field site and following a grid of perpendicular transects.

Figure 3: Localisation of the experimentation site, in red the experimentation site @google map

An average peat layer of 2 m covers the entire area, overlaying a variable gyttja layer (2-10 m depth). A sand layer of 20+ m thickness exists underneath the entire lowland at an average depth of 8m but starting closer to the surface in the northwestern corner (~2 m depth).

2.2. Description of the experimentation

2.2.1. Principe of the experimentation

To quantify GHG fluxes in various soil types related to peatland restoration and to assess the fate of degraded peat, experiments will be conducted on five different soil types:

- Typical agricultural soil (SK1)
- Agricultural soil enriched with degraded peat (SK2)
- Ditch filled with degraded peat (SK3)
- Topsoil removal rewetted peatland (SK4)
- Normal rewetted peatland (SK5)

GHG emissions will be collected using a gas measurement chamber. The chamber's contents will be analyzed by a PICARRO G2058 gas analyzer (detailed specifications in APPENDIX 2, APPENDIX 3 and APPENDIX 4). The analyzer determines gas concentrations within the chamber. Flux measurements are based on the increase in gas concentration over time. This concentration change, compared to a previous time point, allows for calculating the gas release rate, or flux. The chamber can capture two types of emissions: diffusive and ebullitive. Diffusive flux results from the concentration gradient between the air and the soil. Under specific conditions, CH_4 can be released through ebullition, causing a rapid increase in chamber gas concentration.

2.2.2. Skyline structure

To estimate the flux of greenhouse gases (GHGs) emitted by different soil types, an experimental device called Skyline (Figure 4, Figure 5, Figure 6) will measure GHG emissions from the soil. The device consists of a mobile robot tethered by cables. A gas measurement chamber attached to the robot is lowered and raised over designated measurement plots. The robot locates these plots using magnets embedded in the cables. A pump creates a vacuum in the chamber to draw gases into the analyzer. The entire setup is powered by electricity.

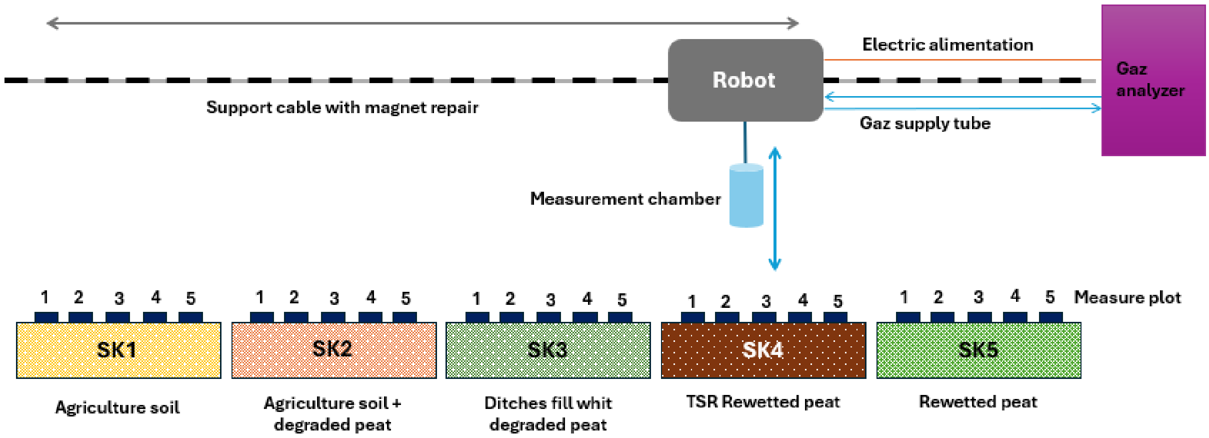


Figure 4: conceptual drawing of the skyline organisation and experimental setup

Figure 5: photo of all type soil (SK1, SK2, SK3, SK4, SK5)

Figure 6: photo of the robot and the chamber (left) and all installation (right)

The Skyline device conducts maximum four continuous measurement series each day. Each series follows this pattern:

1. The robot begins the series by measuring plot SK5.5.
2. The chamber descends onto the plot frame and remains there for five minutes.
3. Following this measurement, the robot raises the chamber and moves directly to the next plot.
4. The robot stays at the next plot for 4.5 minutes to allow the chamber to equilibrate the gases with the ambient air.
5. After equilibration, the robot lowers the chamber again and takes another five-minute measurement.

6. This process is repeated for each designated plot.
7. After completing measurements on 25 plots, the robot returns to a designated waiting location and pauses for 30 minutes before starting another measurement cycle.

The robot operated from May 17 to June 4. Manual air chamber sampling was conducted from June 24 to July 24, specifically on June 24, July 4, July 11, July 18, and July 24. During periods of robot malfunction, gas measurements were performed manually. The chamber was moved on each plot every 5 minutes with a one-minute break between plots. Only one cycle was performed per day.

2.2.3. Field maintenance and operations

Maintaining the SkyLine system required frequent field visits (at least once weekly) with additional visits to address identified measurement errors. Routine vegetation trimming around frame plots SK5, SK4, and SK3 was conducted during the summer experiment to ensure unobstructed chamber movement. Plots SK1 and SK2 were completely cleared of vegetation to isolate soil emissions.

The experiment encountered several challenges. Methane bubbles were observed in ditch measurements. To better simulate a filled ditch, degraded peat was used to refill plot SK3 on June 24th. Additionally, the robot malfunctioned on June 4th, necessitating repairs and a switch to manual gas measurements. Manual measurements involved placing the chamber on each plot for 5 minutes followed by a 1-minute interval.

In plot SK4 (TSR treatment) only, water-phase gas samples were collected from above each frame. The sampling procedure involved:

- Cleaning the cylinder with treatment water.
- Filling the cylinder with 40 ml of water.
- Removing any bubbles inside the cylinder.
- Adding 20 ml of atmospheric air.
- Shaking for 1 minute.
- Filling 20 ml vials (with septa) with the gas phase from the cylinder.
- Labeling each vial with data, treatment ID, and frame ID.

While other experiments and samples were collected at the site, they are not described in this report.

2.3. Data analyse

2.3.1. Cleaning process

Our goal is to determine the daily flux of each greenhouse gas (GHG) for each type of soil. However, not all data in the Raw greenhouse gas (GHG) measurements obtained from the PICARRO analyzer are stored in comma-separated values (.dat) files is relevant. Only measurements taken while the chamber is on the frame should be analyzed.

For processing GHG data from PICARRO analyzers, the R package "GoFlux" (Rheault et al., 2024) is a particularly useful tool. This specialized R package streamlines data processing and facilitates accurate GHG flux estimation. R, along with RStudio, forms a powerful software suite for data analysis and visualization. R itself is a programming language specifically designed for statistical computing and graphics, while RStudio provides a user-friendly interface to work with R.

While the "GoFlux" package can process all the data, manually defining each plot measurement for five cycles per day would result in 125 daily measurements – a time-consuming process. However, this method ensures precise measurement periods and minimizes errors (excluding repetition bias).

An alternative approach to reduce bias from repetitive tasks is to utilize the cyclical nature of the data. We can develop an automated cleaning code based on the GoFlux package and functions to streamline this process.

2.3.2. Flux estimation

By monitoring gas concentration changes within a chamber over time, we can estimate gas fluxes. Flux represents the rate of gas emission or absorption by the soil per unit area and time. Accurately modeling these concentration changes is essential for determining flux values. Several methods exist for estimating gas flux using a measurement chamber, including linear and non-linear regression. As previously discussed, linear regression offers advantages like simplicity, robustness, and speed. However, it assumes a constant change rate, which may not always be true for GHG fluxes. This can lead to biased results. Non-linear regression offers more flexibility to capture complex dynamics but requires more effort in implementation, data cleaning, and computation. (Hüppi et al., 2018)

In this case, we opted for linear regression due to the large data quantity. While a large dataset can improve the precision of linear regression, meticulous data cleaning becomes less critical. Additionally, the large chamber size and short measurement time (around 5 minutes) likely limit significant concentration gradient changes, making a linear model potentially suitable.

2.3.3. General working code process

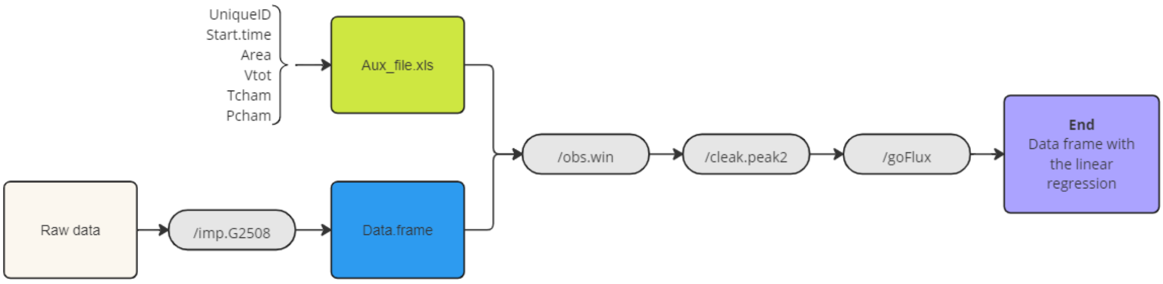


Figure 7: Structure of the GoFlux Package Use

Initially, To use GoFlux, (Figure 7) start by importing raw data using the /imp.G2508 function (in grey) to create a data frame in R (in blue). At the same time, create an Aux_files.xls document containing your external information and the approximate time for each measurement period. Using the Excel document (in green) and the data frame in R, apply the /obs.win and /cleak.peak2 functions. These functions will open interactive windows at the times specified in the Aux files, displaying the concentration of a specific gas over time. At this point, you need to select the start and end points for each measurement. After making these selections for all measurements, use the /goFlux function on the results to generate the linear regression for each measurement.

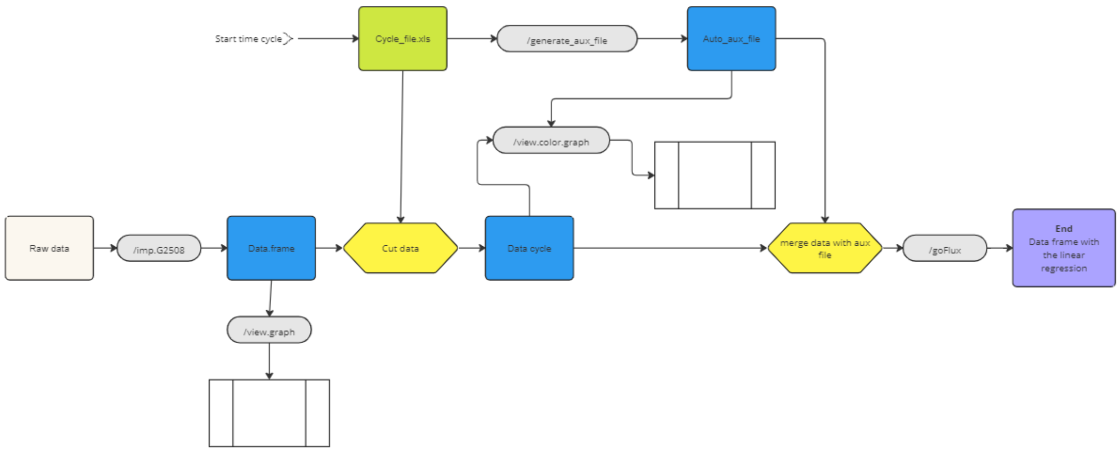


Figure 8: Structure of Peatflux script use

The PeatFlux code is an improvement on GoFlux (Figure 8). Raw data is imported using the /imp.G2058 function to create a data frame. The /view.graph function allows you to export a graph to visualize all your imported data. In PeatFlux, you only need to create a cycle file with the timestamps marking the start of each cycle and additional information, which can be identified using the graph export. This Excel file is used to segment the data frame by each cycle, and the /generate_aux_file function automatically determines the start and end of each measurement period based on the regularity of the robot's experiments, without the need for /obs.win and /cleak.peak_2. The auto_aux_file and cycle data frame, along with the /view_color_graph, provide a view of the measurement periods to verify that the timestamps are accurate. If everything is correct, these two data frames are merged with the auxiliary files to create a single data frame. This final data frame is processed using the GoFlux function to export a unified data frame with the results of the linear regression and the detail for each linear regression (APPENDIX 5).

The PeatFlux code also contains scripts for verifying and analyzing the linear regression. This code, written in R version 4.4.0 (2024-04-24), needs validation to ensure it accurately selects the correct measurements. Following validation, we can implement data verification to remove outliers (errors or similar) based on sound criteria (bubble emission). Finally, the extracted data can be used to calculate the daily flux for each measurement period.

3. Result

3.1. Validation of the code

As mentioned previously, this code was an automated version of the manual GoFlux analysis for each sample. To validate the code's performance, we compared the results from the manual and automated methods using the same dataset. We utilized data from the four cycles on May 18th, which included both day and night measurements. For each soil type (with 5 replicates per cycle), we calculated the slope of the regression for each cycle. Finally, we created box plots comparing the manual and automated methods (n=20). The resulting graphs show the comparison for each method side-by-side. All data, including outliers, was retained as we focused on comparing the two methods rather than obtaining precise results.

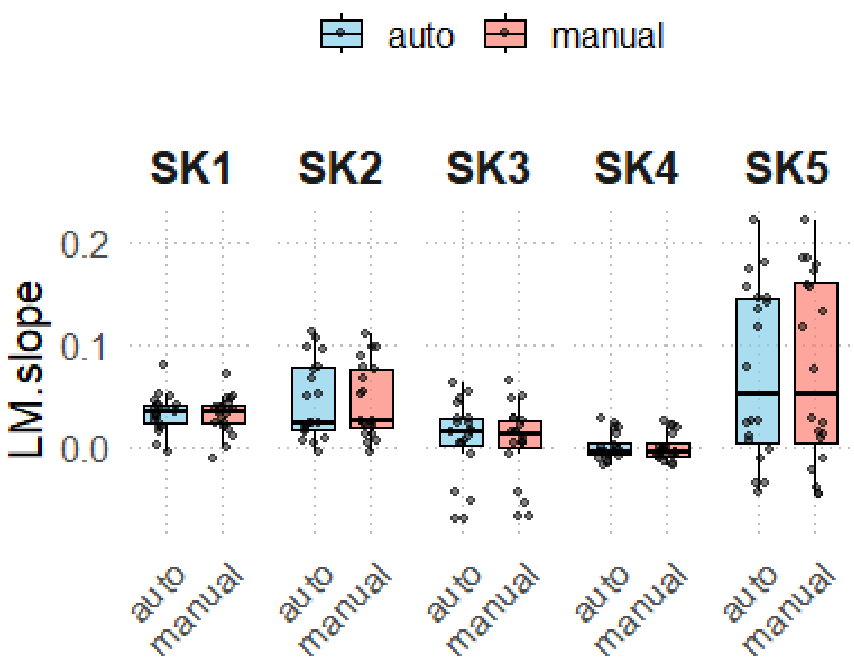


Figure 9: Comparison of linear regression for CO_2 slope on automatic measure period and manual measure period

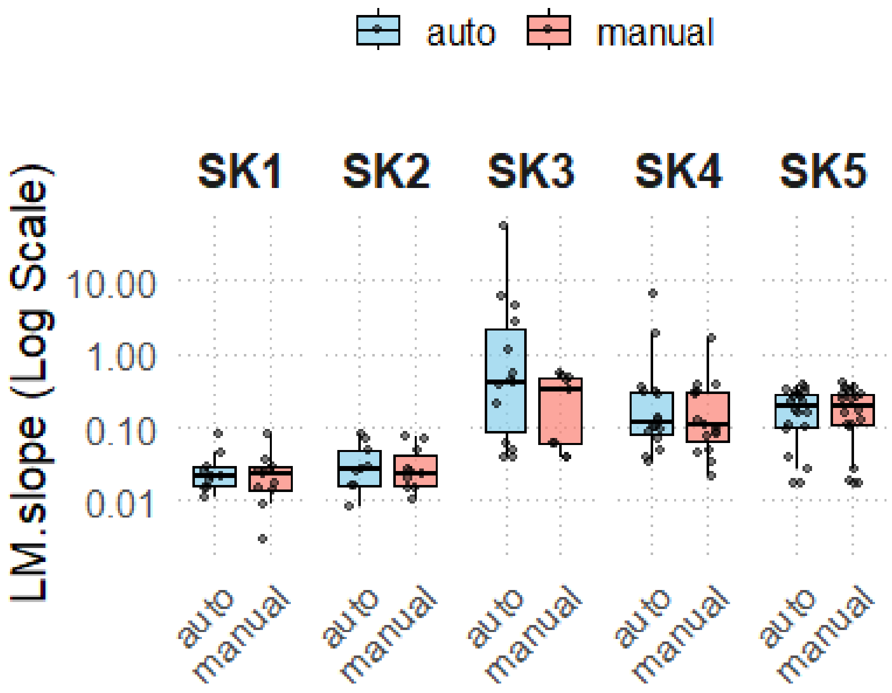
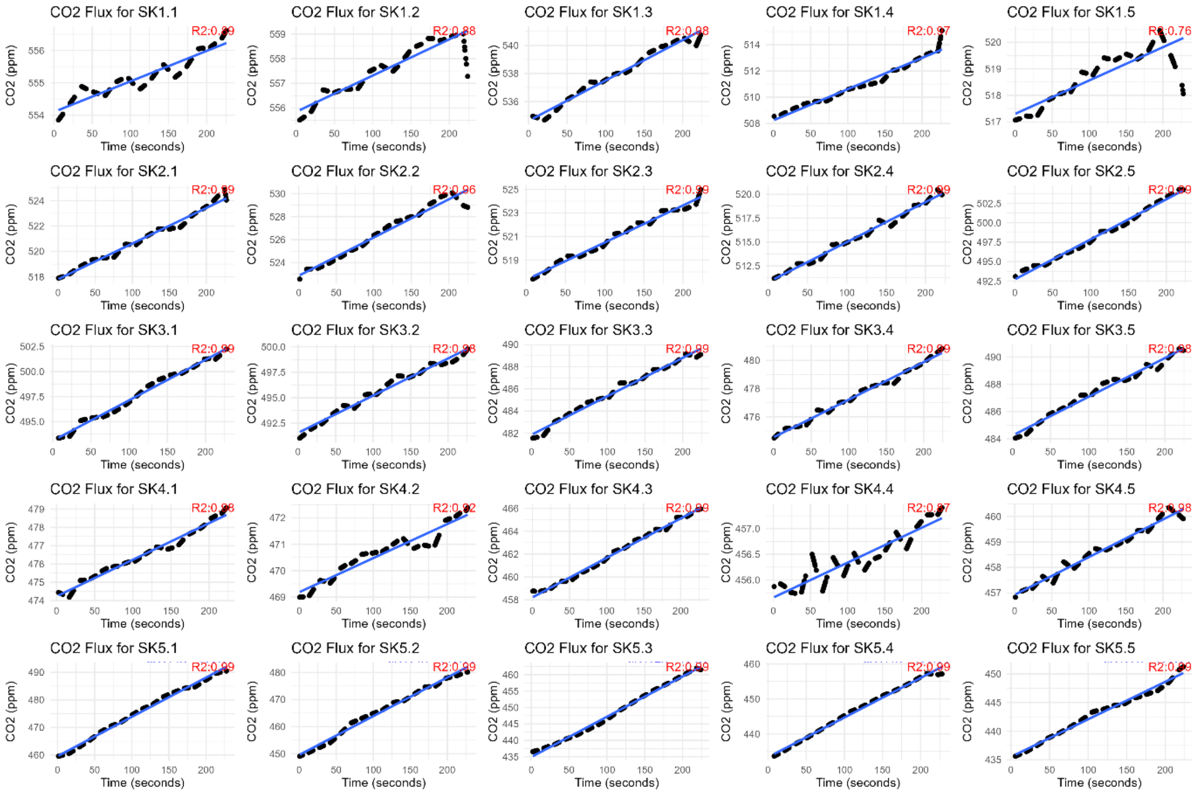
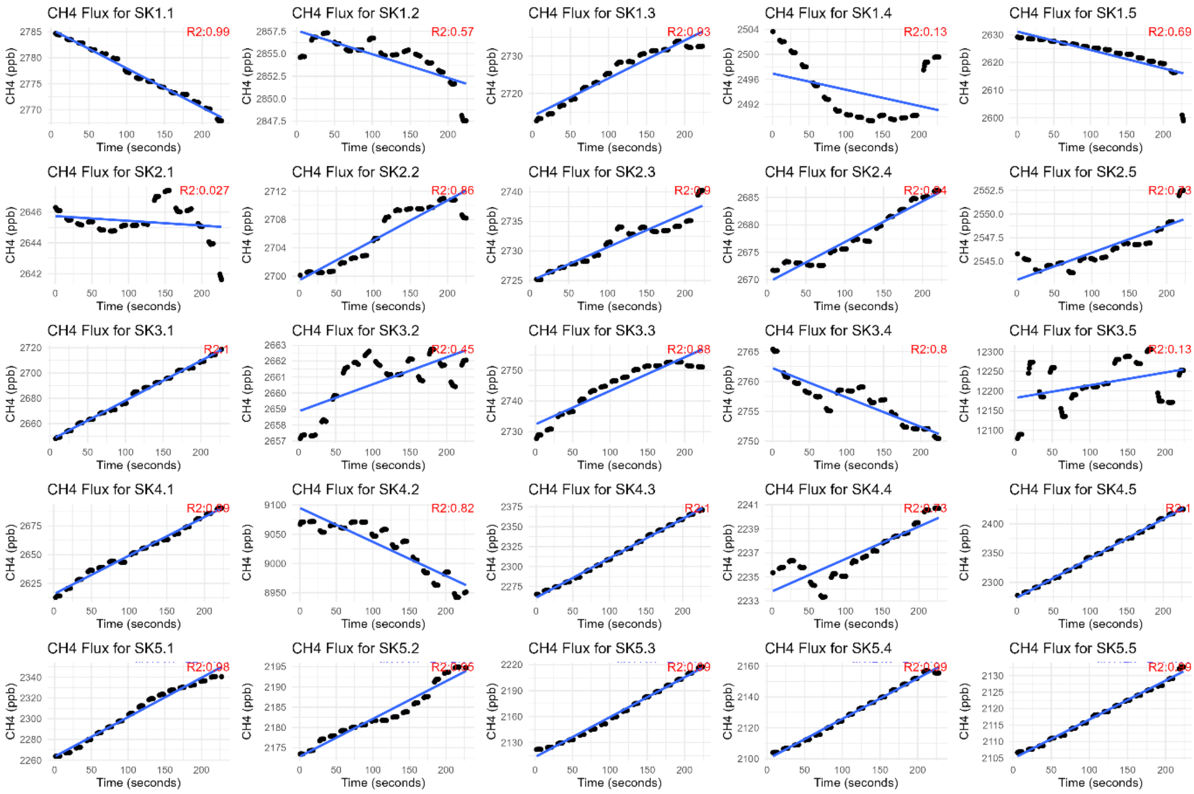


Figure 10:Comparison of linear regression for CH_4 slope on automatic measure period and manual measure period

Graphs Figure 9 and Figure 10, present box plots comparing automatic and manual flux estimations. While the overall mean slopes for each soil type are similar between the two methods, the box plot for methane on SK3, associated with the ditch sampler, exhibits greater variability. This increased variability is likely due to the intermittent release of CH_4 bubbles, which can cause spikes in flux measurements.

A closer examination of individual data points in APPENDIX 5: Extract of linear regression of one cycle (17-05-2024)


CO2 Flux for SK1.1
CO2 Flux for SK1.2
CO2 Flux for SK1.3
CO2 Flux for SK1.4
CO2 Flux for SK1.5
CO2 Flux for SK2.1
CO2 Flux for SK2.2
CO2 Flux for SK2.3
CO2 Flux for SK2.4
CO2 Flux for SK2.5
CO2 Flux for SK3.1
CO2 Flux for SK3.2
CO2 Flux for SK3.3
CO2 Flux for SK3.4
CO2 Flux for SK3.5
CO2 Flux for SK4.1
CO2 Flux for SK4.2
CO2 Flux for SK4.3
CO2 Flux for SK4.4
CO2 Flux for SK4.5
CO2 Flux for SK5.1
CO2 Flux for SK5.2
CO2 Flux for SK5.3
CO2 Flux for SK5.4
CO2 Flux for SK5.5
CO2 (ppm)
Time (seconds)


CH4 Flux for SK1.1
CH4 Flux for SK1.2
CH4 Flux for SK1.3
CH4 Flux for SK1.4
CH4 Flux for SK1.5
CH4 Flux for SK2.1
CH4 Flux for SK2.2
CH4 Flux for SK2.3
CH4 Flux for SK2.4
CH4 Flux for SK2.5
CH4 Flux for SK3.1
CH4 Flux for SK3.2
CH4 Flux for SK3.3
CH4 Flux for SK3.4
CH4 Flux for SK3.5
CH4 Flux for SK4.1
CH4 Flux for SK4.2
CH4 Flux for SK4.3
CH4 Flux for SK4.4
CH4 Flux for SK4.5
CH4 Flux for SK5.1
CH4 Flux for SK5.2
CH4 Flux for SK5.3
CH4 Flux for SK5.4
CH4 Flux for SK5.5
CH4 (ppb)
Time (seconds)

APPENDIX 6 reveals significant discrepancies between automatic and manual measurements specifically for SK3, explaining the broader box plot in Figures 9 and 10. Despite these variations, the overall mean values for automatic and manual flux estimations on SK3 remain comparable, suggesting that the manual method's errors are within an acceptable range. Figures in appendix further support this observation by illustrating the close proximity of result of the linear regression generated by both methods.

As seen previously, the automatic PeatFlux program is not perfect, especially for very low fluxes and when ebullition occurs, as the linear regression can overestimate values.

To clean the data, we need to determine if the linear regression is significant enough to define a flux. The Student's t-test can be used for this purpose. This test evaluates whether the slope of the linear regression model is significantly different from zero, indicating a relationship between the independent variable (e.g., time) and the dependent variable (e.g., gas flux).

The null hypothesis (H_0) states that the slope is zero, implying no relationship between the variables. If the p-value from the t-test is less than the chosen significance level (usually 0.05), we reject the null hypothesis and conclude that there is a significant relationship between the variables. This is a standard method in regression analysis to assess the impact of predictors.. (Montgomery et al., 2012)

To further clean the data, we must eliminate linear regressions with significant errors due to sampling or programming issues. The r-squared value is useful for this purpose. However, due to code constraints, we cannot set an extremely high r-squared threshold. A very high r-squared might remove too much data, while a very low one could accept poor or incorrect regressions. An optimal r-squared value must be determined.

To achieve this, the script analyzes all data between May 17th and June 3rd. It calculates the number of data points removed for different r-squared values and generates graphs for the entire dataset and for each soil type. These graphs were created using a step size of 0.05 between 0 and 1.

For CO_2 data, the percentage of data removed increases gradually with r-squared values between 0 and 0.95, then drops sharply at 0.95. To retain a significant portion of the data, arbitrarily setting a threshold to keep 75% of the values seems reasonable. For CO_2, this corresponds to an r-squared limit of 0.85. (Figure 11)

When analyzing data by soil type, SK4 generally exhibits poorer linear regression compared to other types. Applying an R-squared threshold of 0.85 would eliminate approximately 3/8 of the data. To maximize data retention while maintaining data quality, an R-squared limit of 0.75 is considered optimal. (Figure 12)

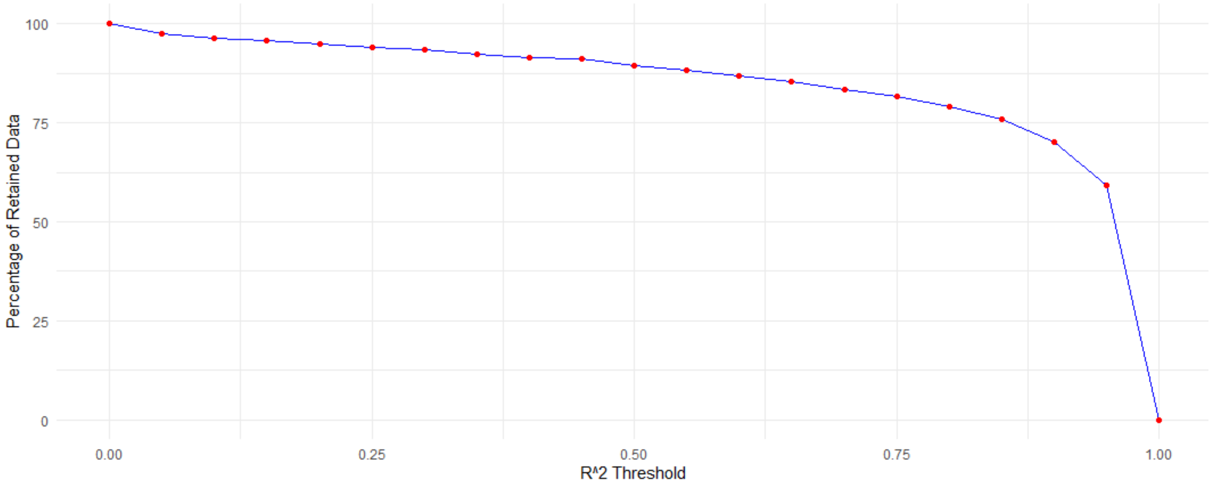


Figure 11: Percent of retained CO_2 Data base on r^2

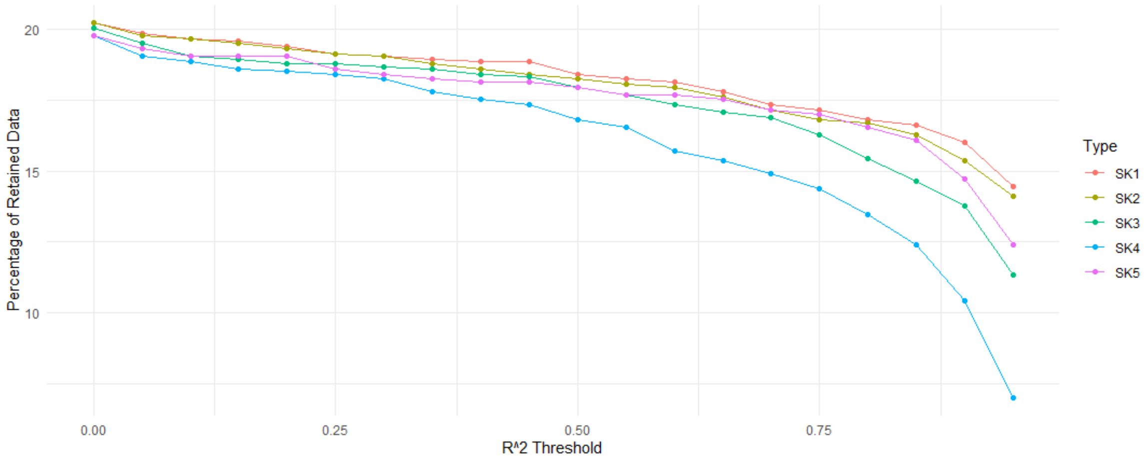


Figure 12: Percent of retained CO_2 Data by type of soil based on r^2

We apply the same procedure to CH_4 data, determining the optimal r-squared threshold based on data retention and quality.

CH_4 flux data exhibit more instances of poor linear regression with lower r-squared values overall. To retain approximately 75% of the data, an r-squared threshold of around 0.5 is necessary. While this is a relatively low threshold, it's important to note that several approximations were made, such as using linear regression with a gas chamber despite a more nonlinear gas increase. (Figure 13)

Soil type SK1 exhibits the lowest r-squared values when analyzed. While using an r-squared limit of 0.5 would retain most data, it's too low and would include many low-quality data points. This presents a challenge as it's difficult to balance data retention with data quality for this soil type. (Figure 14)

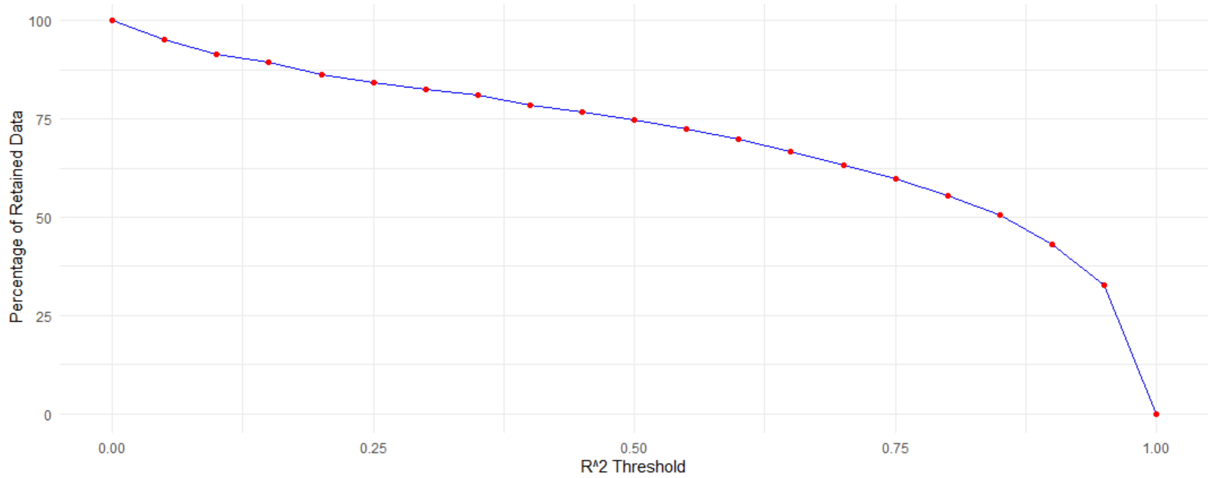


Figure 13; Percent of retained CH_4 data based on r^2

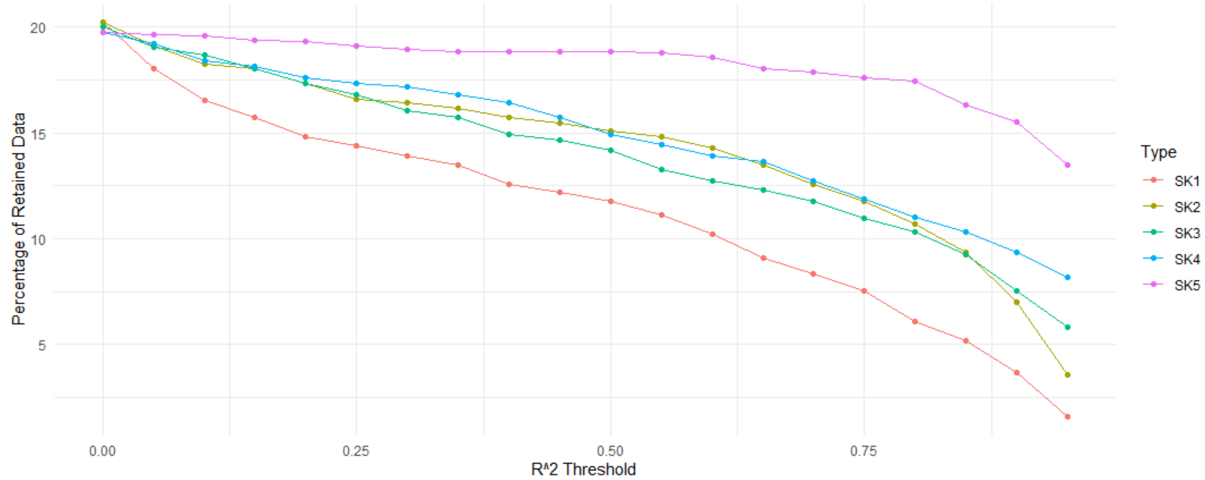


Figure 14: Percent of retained CH_4 data by soil type based on r^2

The developed code effectively automates flux calculation, producing results comparable to manual methods. The t-test successfully identifies and removes low-quality, potentially spurious flux data. The r-squared filter effectively balances data retention and accuracy, with thresholds of 0.75 for CO_2 and 0.5 for CH_4.

However, the relatively low r-squared values suggest potential limitations (Hüppi et al., 2018) in the linear regression model, especially considering the nonlinear gas dynamics within the gas chamber. Further investigation into alternative modelling approaches may be necessary to improve data accuracy.

3.2. Experimental result

The flux calculations Figure 15 were performed between May 17th and June 3rd. CO_2 flux analysis revealed that SK5, a naturally rewetted peatland, emitted more than double the CO_2 compared to both the ditched, degraded peatland and the TSR rewetted zone. 5mgCO_2/m²/day compared to 2mgCO_2/m²/day for ditches and 1mgCO_2/m². This initially appears to support the TSR method's efficacy. However, field observations indicate that SK5 was the driest site, lacking the anoxic conditions typically associated with peatland carbon sequestration. This suggests that ongoing organic matter degradation and respiration might have contributed to the elevated CO_2 emissions. In contrast, the ditched and TSR sites were consistently waterlogged.

For the cultivated soils, SK2 (with peat) exhibited slightly higher CO_2 emissions than SK1. However, the large variability in SK2 data limits the significance of this result. It is hypothesized that the added peat in SK2 might provide a larger pool of degradable organic matter.

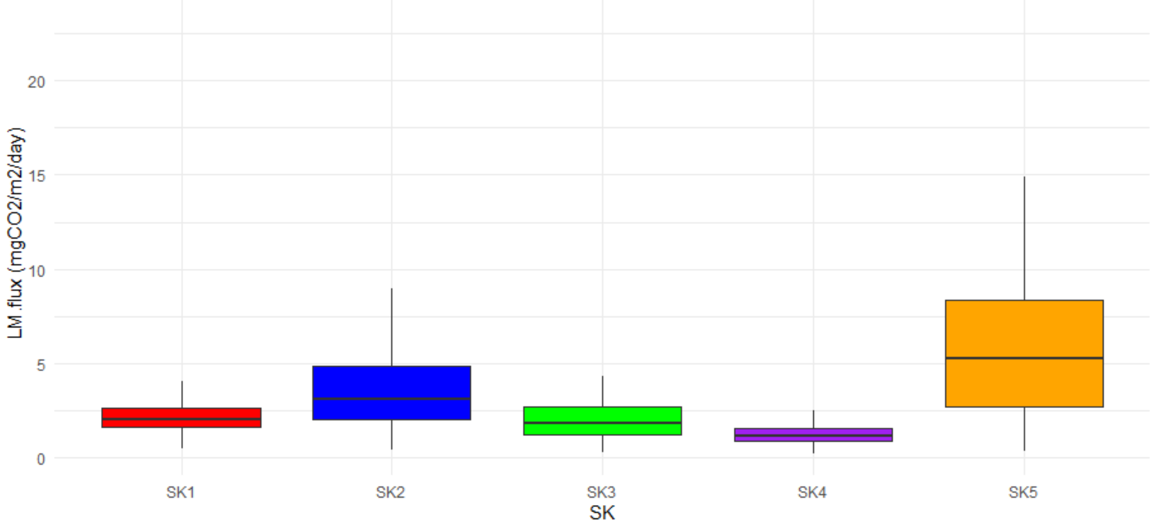


Figure 15: Daily CO_2 flux in $mgCO_2/m^2$ by type of soil

Figure 16 presents a detailed daily breakdown of fluxes, highlighting substantial variation among soil types and over time. For example, CO2 flux from SK2, the peat-based soil, exhibited a pronounced peak on May 21st, approximately quadrupling compared to other soils. Notably, this day also coincided with the lowest data availability, as indicated by the blue bars representing data points used in the box plot (APPENDIX 7)

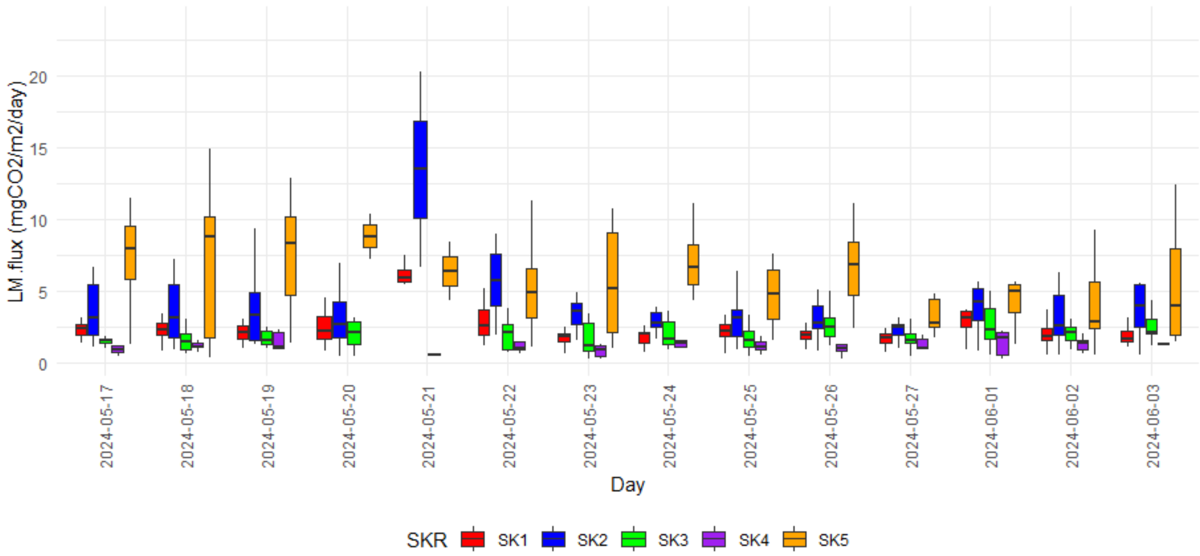


Figure 16: Evolution of Daily flux of CO_2

Methane emissions from the ditch were significantly higher than those from both TSR and non-TSR rewetted peatlands, exceeding 0.10 mg/m²/day (Figure 17). Cultivated soils (SK1 and SK2) exhibited methane emissions approximately ten times lower than peatlands, averaging around 0.001 mg/m²/day. Although SK2 showed slightly higher methane emissions than SK1, the overlap in data ranges precludes definitive conclusions. Further investigation is needed to assess the potential impact of added peat on methane production in SK2.

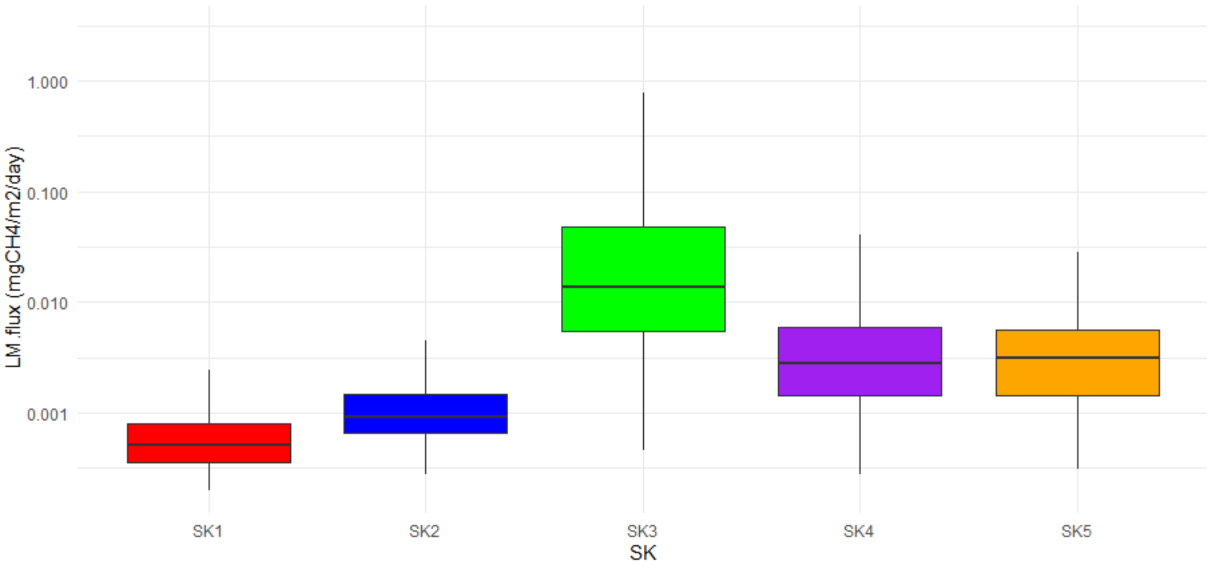


Figure 17:Daily CH_4 flux in $mgCH_4/m^2$ by type of soil

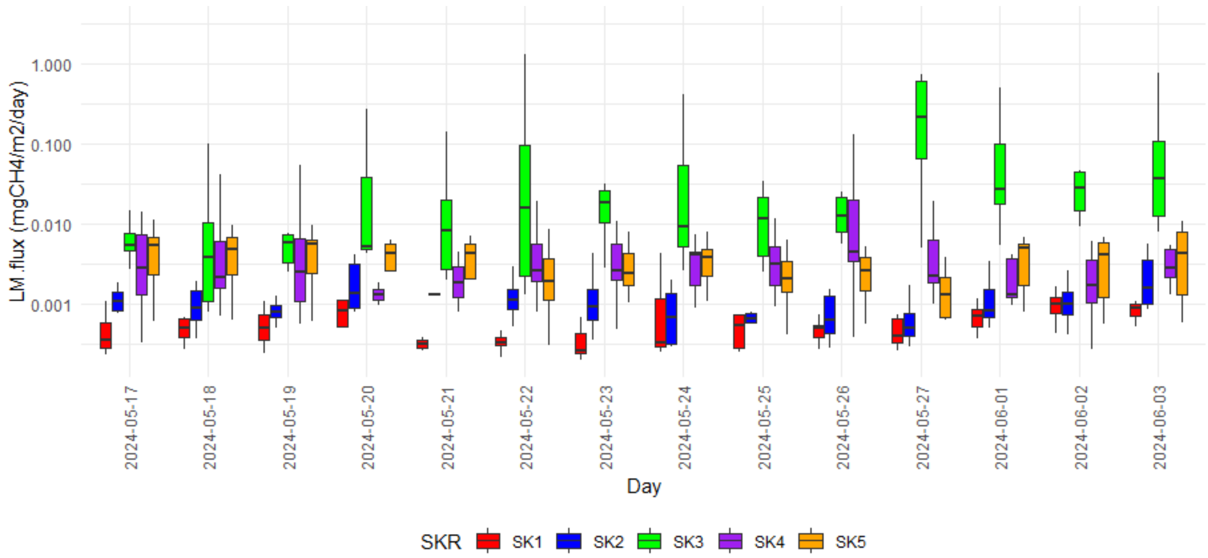


Figure 18: Evolution of Daily flux of CH_4

Figure 18 reinforces the findings depicted in Figure 17, indicating a sustained increase in methane emissions from the ditch over the study period. A detailed breakdown by soil type (presented in APPENDIX 8) reveals significant variability in data quantity across daily box plots (number in blue)

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4. Discussion

4.1. Increase of the code

The PeatFlux code represents an enhancement of the Goflux package, leveraging its core functionalities. By capitalizing on the robot's consistent measurement cycle, PeatFlux automates the identification of measurement periods. However, precise cycle start determination remains crucial for accurate results compared to other methods relying on measurement patterns.

To mitigate measurement and timing errors, rigorous quality control is applied to linear regression outputs. An arbitrary r-squared threshold is employed to filter out low-quality data while preserving the majority of results. While CO_2 data generally exhibits higher r-squared values, CH_4 data is more susceptible to outliers due to factors such as ebullition and the limitations of linear regression models.

Despite these challenges, PeatFlux generates coherent results, including a variety of customizable graphs, provides researchers with valuable tools for both exploratory data analysis and in-depth investigation of flux patterns and potential error sources.

4.2. Peatland emissions

The substantial daily variation in data availability can lead to less reliable flux estimates on certain days. Some days, the robot produces more usable measurement cycles with high r-squared values, while other data points may be excluded due to the r-squared filter.

The results of this study underscore, also the complexity of greenhouse gas emissions in different peatland management practices. While the TSR method appears to reduce CO_2 emissions compared to a naturally rewetted peatland, this conclusion is tempered by the fact that SK5's elevated emissions may be driven by its dry conditions rather than the rewetted status alone. The findings also highlight the critical role of hydrological conditions in regulating CO_2 and methane fluxes, with waterlogged conditions promoting methane emissions, particularly in ditches. The variability in CO_2 emissions from cultivated soils, especially in SK2, points to the need for more detailed investigations to better understand the influence of added peat on greenhouse gas dynamics.

Temporal trend in CH_4 flux suggests potential influences of temperature or vegetation development on methane production. (can be possible also on CO_2 flux) While methane fluxes from other soil types exhibited greater stability, a comprehensive understanding of these patterns necessitates a detailed examination of factors driving methane production, such as environmental conditions and microbial activity. Future studies should integrate meteorological and other data to provide a more comprehensive understanding of the factors driving flux variations, which could inform more effective peatland management and restoration strategies. However, these emissions were notably lower than typical values reported for similar environments (APPENDIX 9).

4.3. Experience feedback

My research internship in Denmark proved to be a transformative experience. I deepened my theoretical understanding of GHGs while acquiring essential practical skills in field data collection and statistical analysis using R. Stepping outside my comfort zone in a new environment and learning a new programming language significantly broadened my skill set. While challenges such as organizational issues arose, I persevered and contributed meaningfully to the project.

My time in Denmark offered a rich cultural immersion and the opportunity to collaborate within an international team. This experience solidified my interest in pursuing a career in scientific research. The data collection and analysis skills honed during this internship will be invaluable as I explore future research focused on mitigating GHG emissions within planning projects.

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Appendix

APPENDIX 1: Gemini request example

Request

Correct this text "In Danish has 25 years of experience in wetland restoration, like peatland. More than 200 wetland site have been restored, making it the most active EU member state regarding this field. Most of this restauration took part in The Danish Action Plan for the Aquatic Environment II (DAPAE-II) implemented in 1998 plan by the Ministry of environment. This plan lead project like restoration measures such as stream re-meandering, disconnection of tile drains and re-establishment of lakes (Baumane et al., 2021). The aim of the r estoration was the decrease of quantity of nutriment in the soil and water and contribute also to mitigating GHG emission and preserve biodiversity. Today, projects have been realised, covering an area of about 19 393 ha. (Audet et al., 2020)"

Answer

Here's the corrected version of the text in English:

Denmark has 25 years of experience in wetland restoration, including peatlands. With more than 200 wetland sites restored, it is the most active EU member state in this field. Most of this restoration occurred under the Danish Action Plan for the Aquatic Environment II (DAPAE-II), implemented in 1998 by the Ministry of Environment. This plan led to projects involving restoration measures such as stream remeandering, disconnecting tile drains, and re-establishing lakes (Baumane et al., 2021). The aim of the restoration was to reduce nutrient loads in soil and water, contribute to mitigating greenhouse gas emissions, and preserve biodiversity. To date, projects have been completed, covering an area of approximately 19,393 hectares (Audet et al., 2020).

Here's a breakdown of the changes made:

- **"In Danish" changed to "Denmark"**: Removed unnecessary preposition.
- "like peatland" changed to "including peatlands": Clarifies the type of wetlands restored.
- "have been restored" changed to "restored": Removed unnecessary helping verb.
- **"site" changed to "sites"**: Made plural to agree with the number of wetlands.
- "plan by" changed to "plan implemented in": Improved sentence flow.
- **"lead project" changed to "led to projects"**: Corrected verb tense and clarified meaning.
- **"restoration measures such as" added**: Improved sentence structure and introduced specific examples.
- "decrease of quantity of nutriment" changed to "reduce nutrient loads": More concise and scientific language.
- "contribute also to" changed to "contribute to": Removed unnecessary adverb.
- **"Today" changed to "To date"**: More formal way to indicate current status.
- "projects have been realised" changed to "projects have been completed": More precise wording.
- "an area of about" changed to "an area of approximately": More formal way to express a rounded number.
- **Added references in parentheses**: Maintained proper citation format.

Final version

Denmark has 25 years of experience in wetland restoration, including peatlands. With more than 200 wetland sites restored, it is the most active EU member state in this field. Most of this restoration occurred under the Danish Action Plan for the Aquatic Environment II (DAPAE-II), implemented in 1998 by the Ministry of Environment. This plan led to projects involving restoration measures such as stream remeandering, disconnecting tile drains, and re-establishing lakes (Baumane et al., 2021). The aim of the restoration was to reduce nutrient loads in soil and water, but also, contribute to mitigating greenhouse gas emissions, and preserve biodiversity. To date, projects have been completed, covering an area of approximately 19,393 hectares (Audet et al., 2020).

The chamber tubes and vacuum system volume are:

- Robot chamber volume (1): 0.00963 m3 = 9.63 L ~ 10L
- Manual chamber volume (2):
- System volume: 0.0005 m3 = 0.5 L
- Tubes volume = 0.000424 m3 = 0.42 L
- Frame plots volume

Air collected by the Skyline system is analyzed by the PICARRO G2506 Gas Concentration Analyzer. This device provides simultaneous, precise measurements of various gases, including:

- Nitrous oxide (N_2O)
- Methane (CH_4)
- Carbon dioxide (CO_2)
- Ammonia (NH_3) at parts-per-billion (ppb) levels
- Water vapor (H_2O) at parts-per-million (ppm) levels

The analyzer boasts high precision measures:

- N_2O: Less than 10 ppb at 1 minute, less than 5 ppb at 5 minutes
- CH_4: Less than 7 ppb at 1 minute, less than 5 ppb at 5 minutes
- CO_2: Less than 300 ppb at 1 minute, less than 200 ppb at 5 minutes
- NH_3: Less than 3 ppb at 1 minute, less than 1 ppb at 5 minutes

Additionally, water correction software automatically reports dry gas mole fractions. This feature helps reduce research complexity and minimizes the need for consumable materials.

The PICARRO analyzer provides continuous and real-time data on gas measurements within the chambers. This data is displayed immediately on a computer screen for live monitoring. Additionally, the measurement results can be directly linked to a Google application, allowing remote visualization of the Skyline installation's performance.

APPENDIX 3: Performance specification of PICARRO Robot

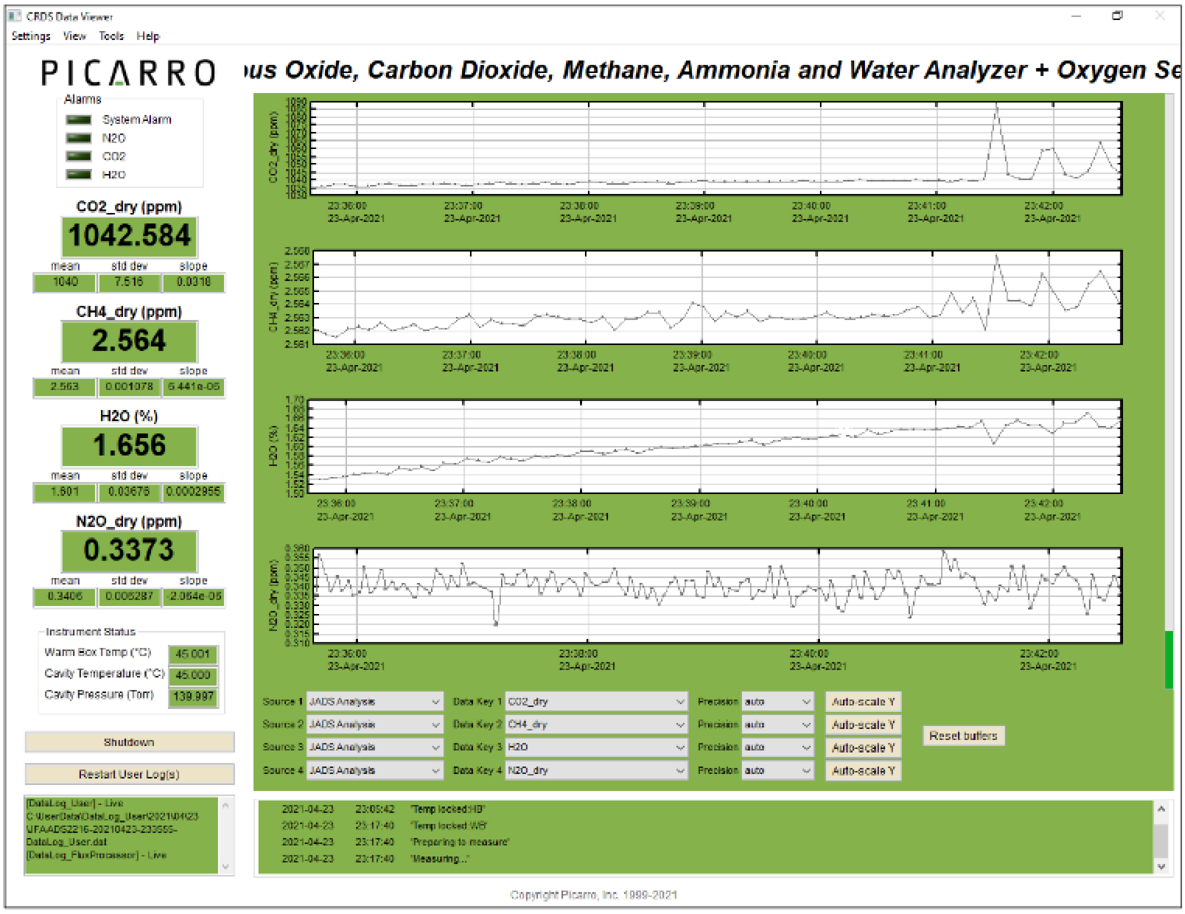
G2508 Performance Specifications and Typical Performance in Air

Specification	N_2O	CH_4	CO_2	NH_3	H_2O
Precision Raw (1σ)	<25 ppb + 0.05% of reading Typical = 5.0 ppb*	<10 ppb + 0.05% of reading Typical = 0.3 ppb*	<600 ppb + 0.05% of reading Typical = 240 ppb*	<5 ppb + 0.05% of reading Typical = 0.16 ppb*	<500 ppm
Precision 1 min (1σ)	<10 ppb + 0.05% of reading Typical = 1.1 ppb*	<7 ppb + 0.05% of reading Typical = 0.1 ppb*	<300 ppb + 0.05% of reading Typical = 74 ppb*	<3 ppb + 0.05% of reading Typical = 0.07 ppb*	<250 ppm
Precision 5 min (1σ)	<5 ppb + 0.008% of reading Typical = 0.6 ppb*	<5 ppb + 0.02% of reading Typical = 0.1 ppb*	<200 ppb + 0.05% of reading Typical = 38 ppb*	<1 ppb + 0.05% of reading Typical = 0.04 ppb*	<100 ppm
Guaranteed Spec Range	0.3–200 ppm	1.5–12 ppm	380–5000 ppm	0–300 ppb	0–3 %
Operating Range	0–400 ppm	0–15 ppm	0.02–2 %	0–2 ppm	0–7 %
Measurement Rate	<8 secs	<8 secs	<8 secs	<8 secs	<8 secs
Typical Gas Response (Rise-Fall 10-90%, 90-10%)	~8 secs	~8 secs	~8 secs	See Note below	See Note below
Report Dry Mole Fraction	Yes	Yes	Yes	Yes	N/A

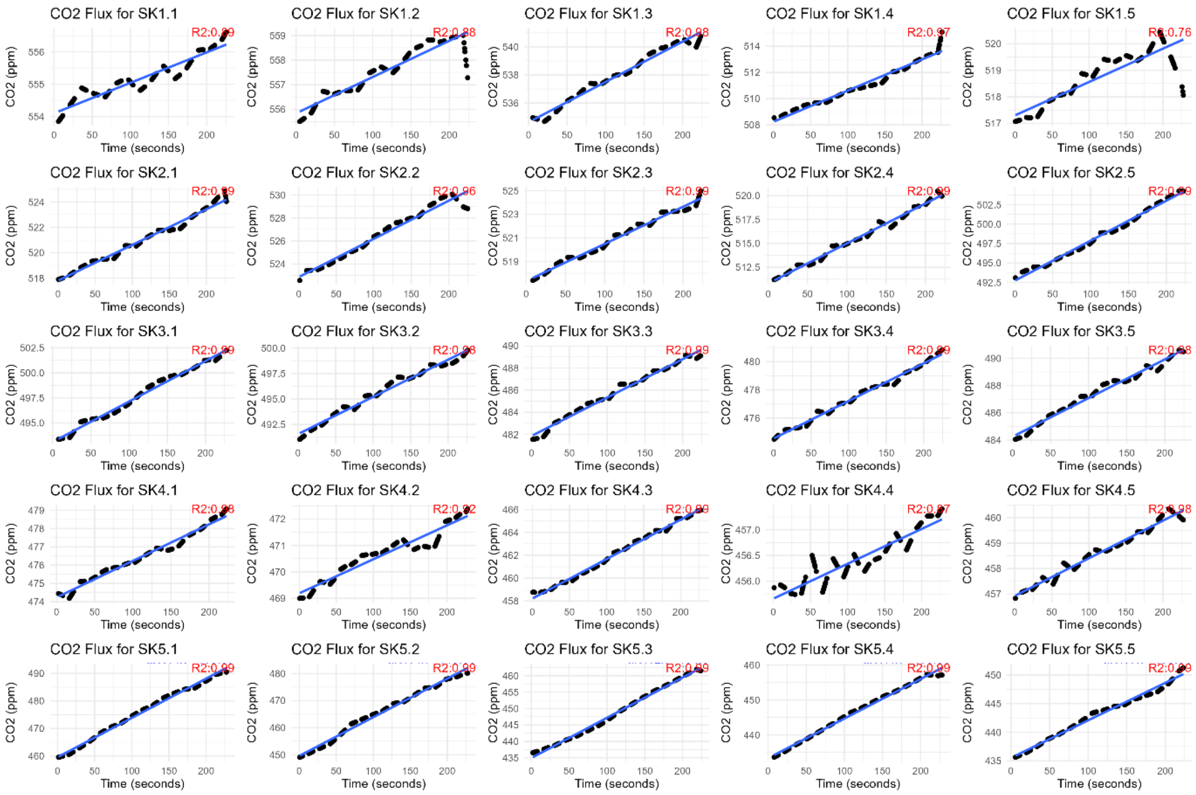
Note: The response of H_2O and NH_3 are limited by the adsorption of these species to the surfaces of the experimental apparatus. While the analyzer will accurately measure the concentration of NH_3 and H_2O within the cavity, calculating the actual flux of NH_3 and H_2O from the soil with these measurements will be convolved by the adsorption dynamics within the system.

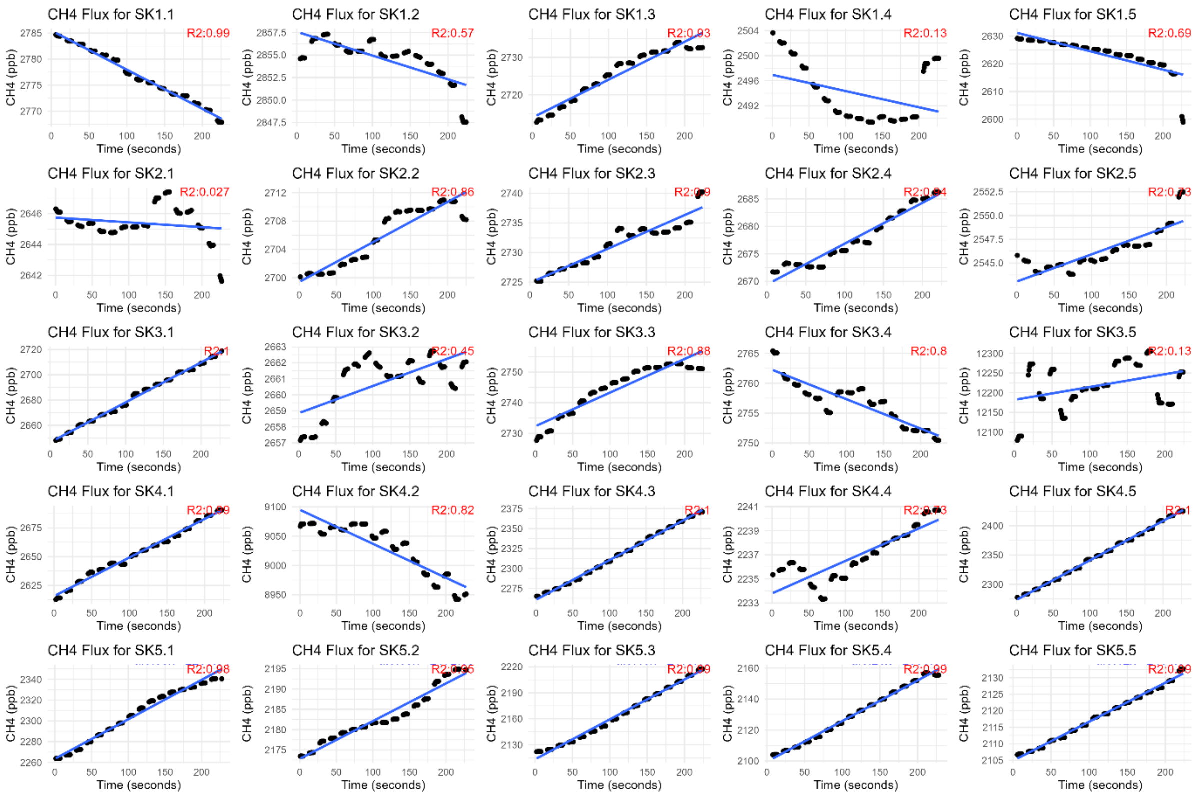
* Typical performance is defined as the median of testing results from 50 sequentially built G2508 analyzers. As measured for typical ambient concentrations.

APPENDIX 4: Screenshot of PICARRO analyser

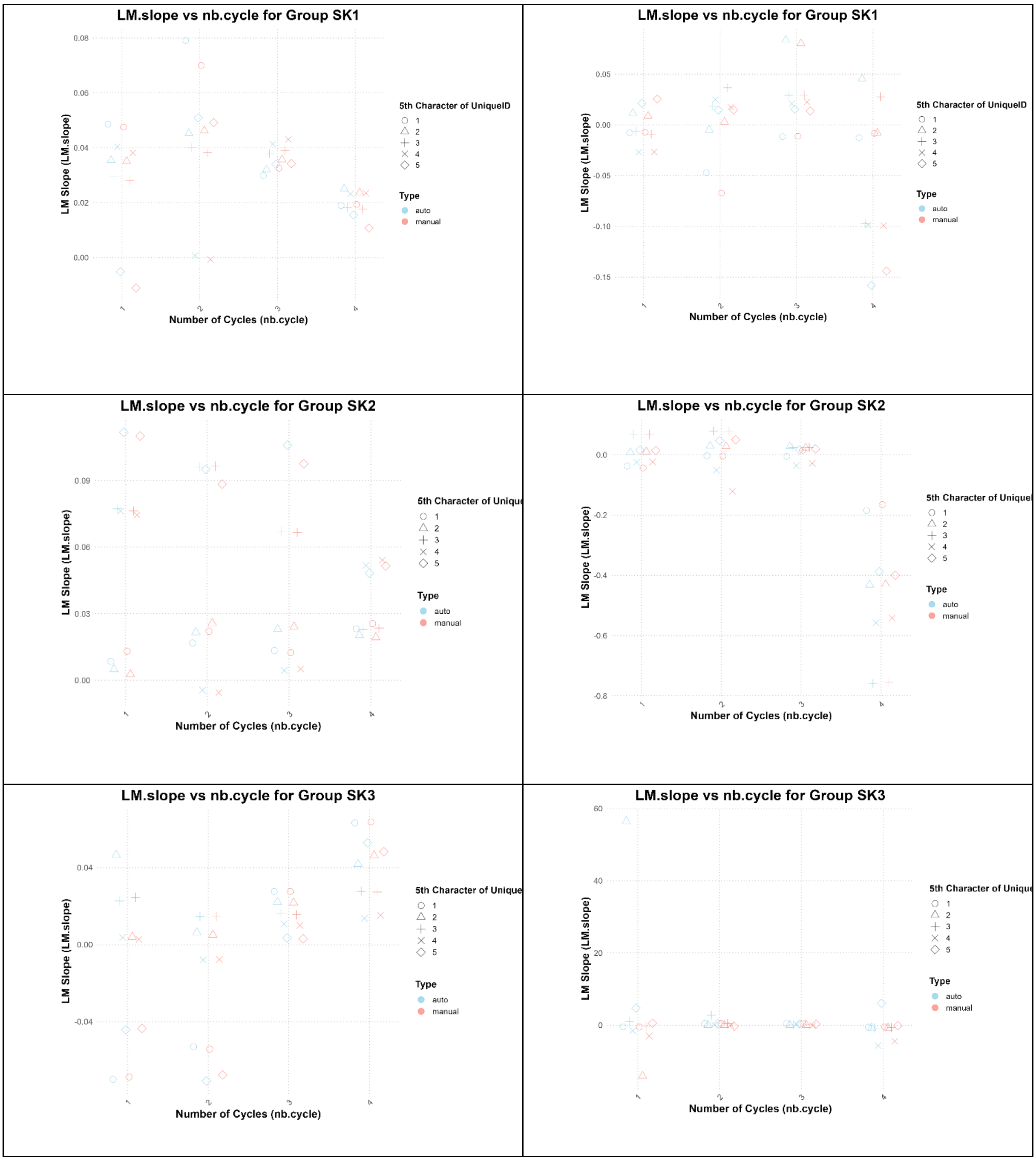


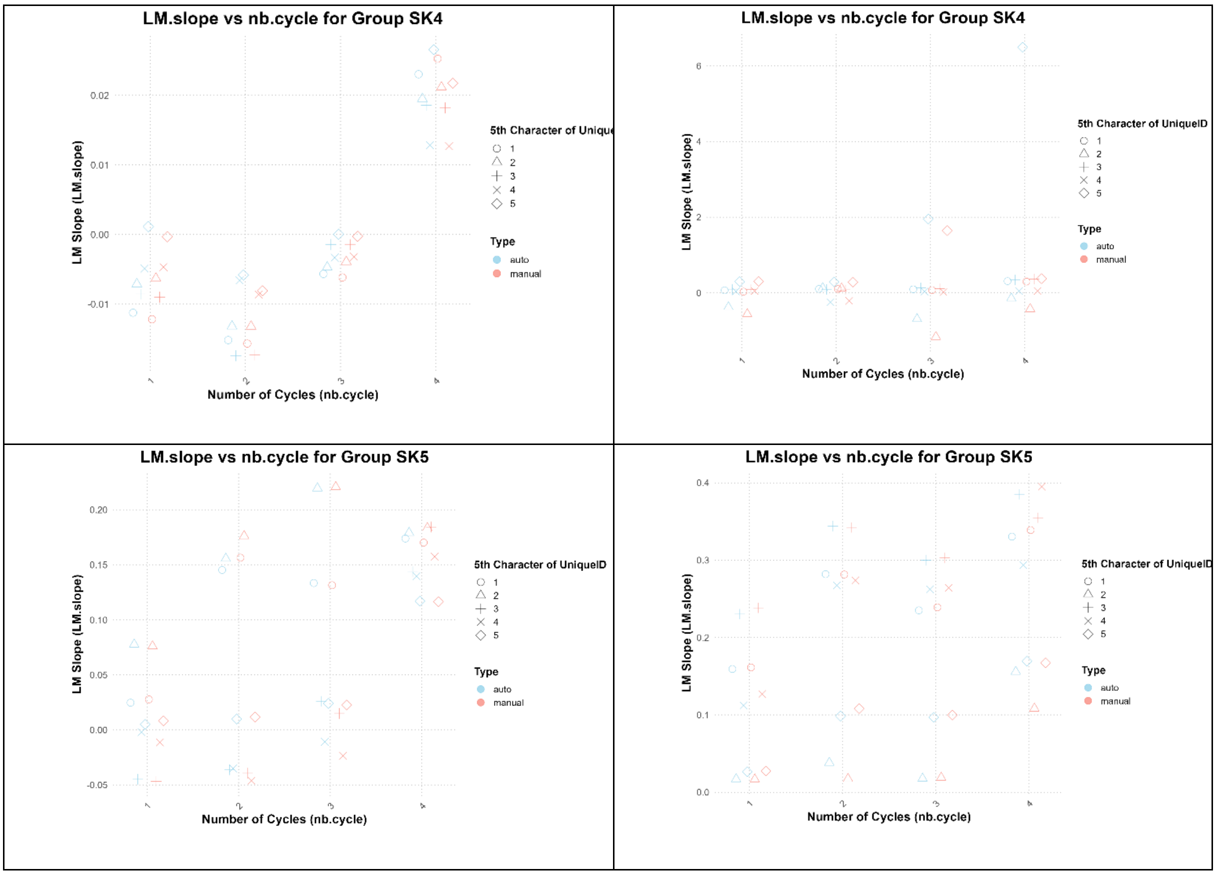
APPENDIX 5: Extract of linear regression of one cycle (17-05-2024)



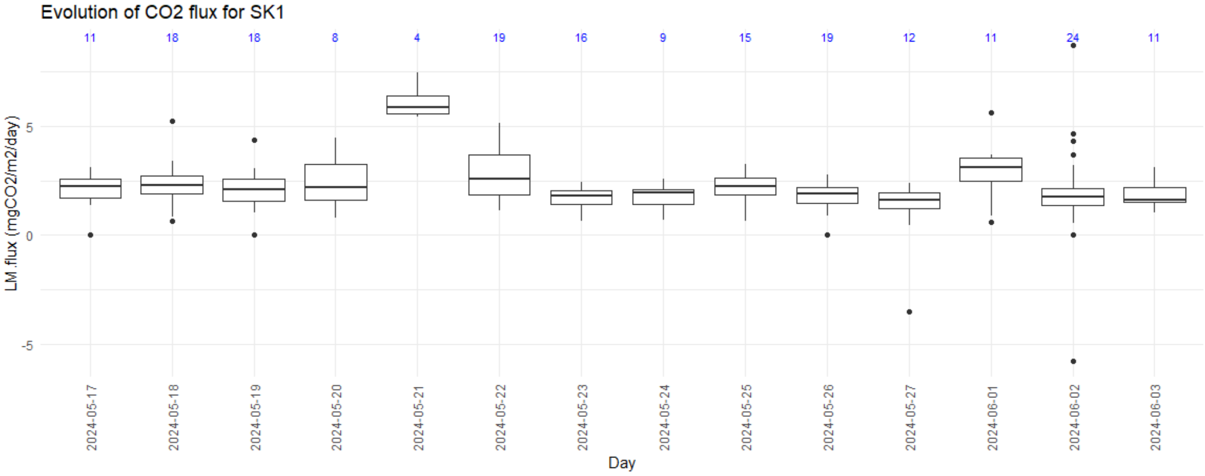


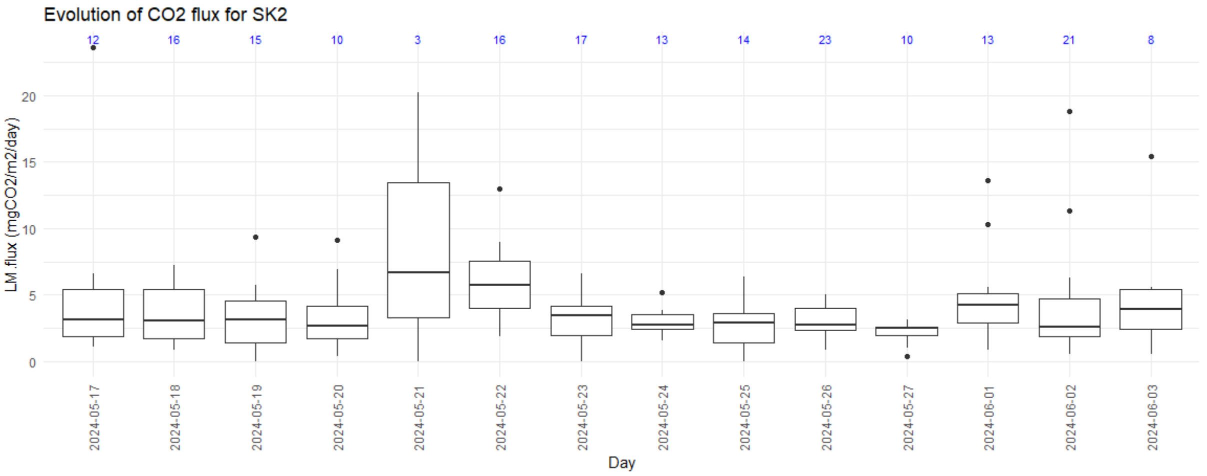
APPENDIX 6: Detail of comparison of automatic and manual linear regression

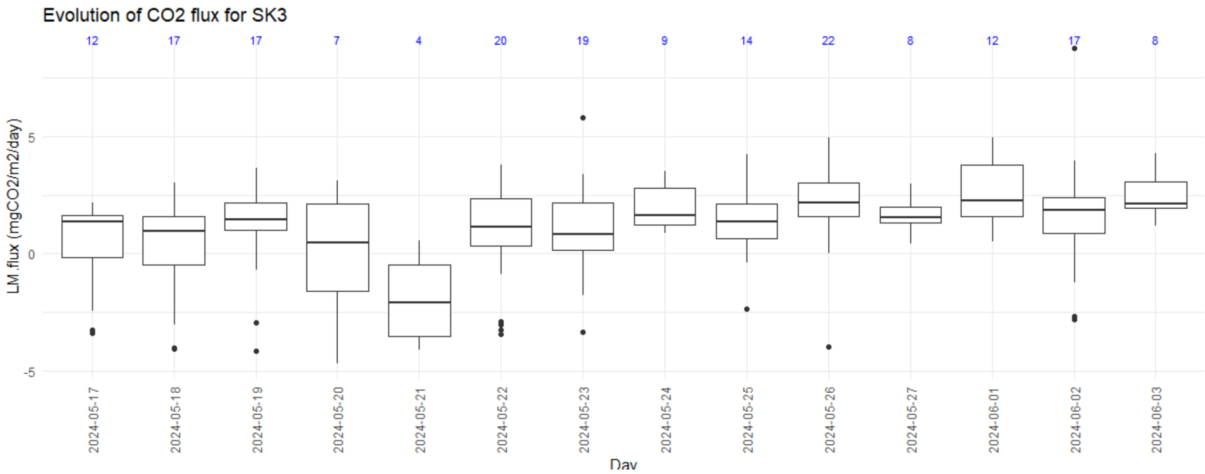


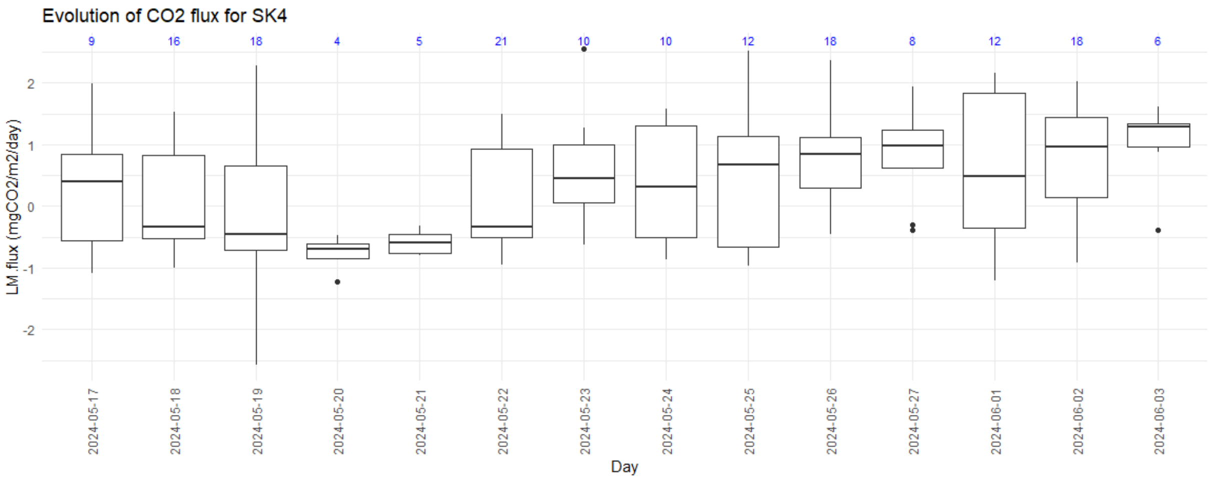

LM.slope vs nb.cycle for Group SK4
LM Slope (LM.slope)
Number of Cycles (nb.cycle)
5th Character of UniqueID
1
2
3
4
5
Type
auto
manual
LM.slope vs nb.cycle for Group SK4
LM.slope vs nb.cycle for Group SK5
LM.slope vs nb.cycle for Group SK5

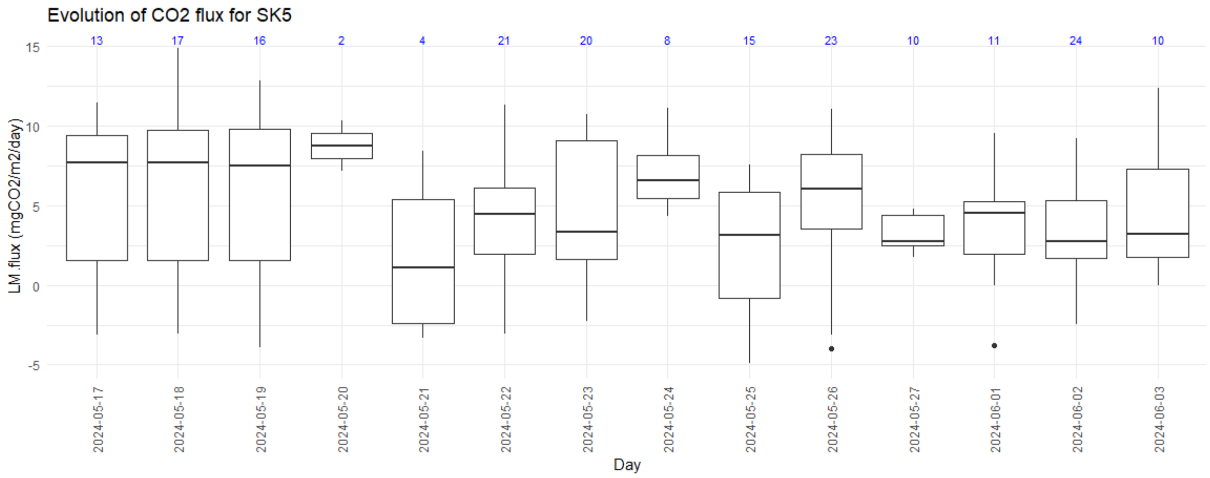
APPENDIX 7: CO_2 flux evolution for each type of soil



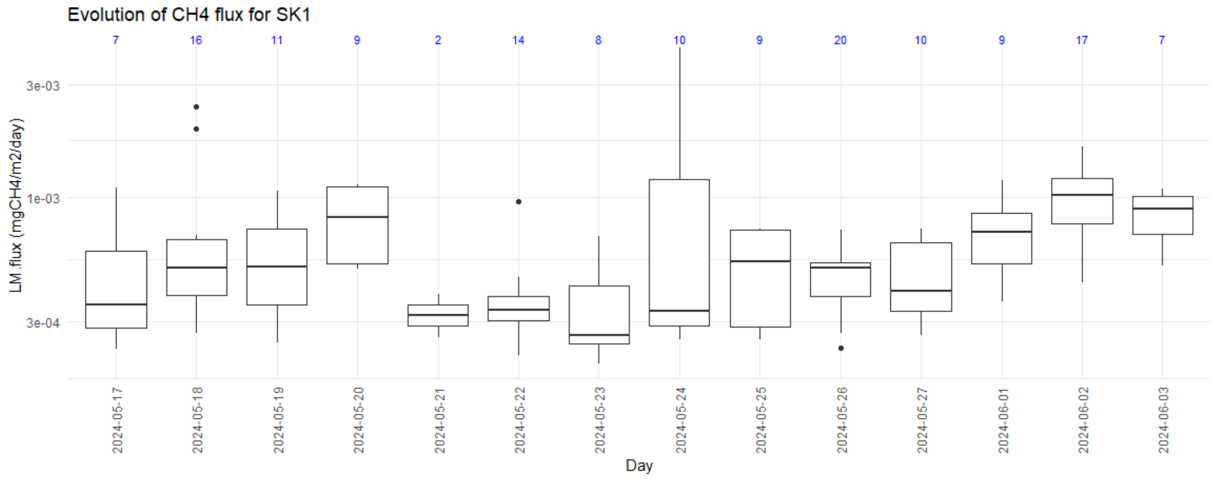


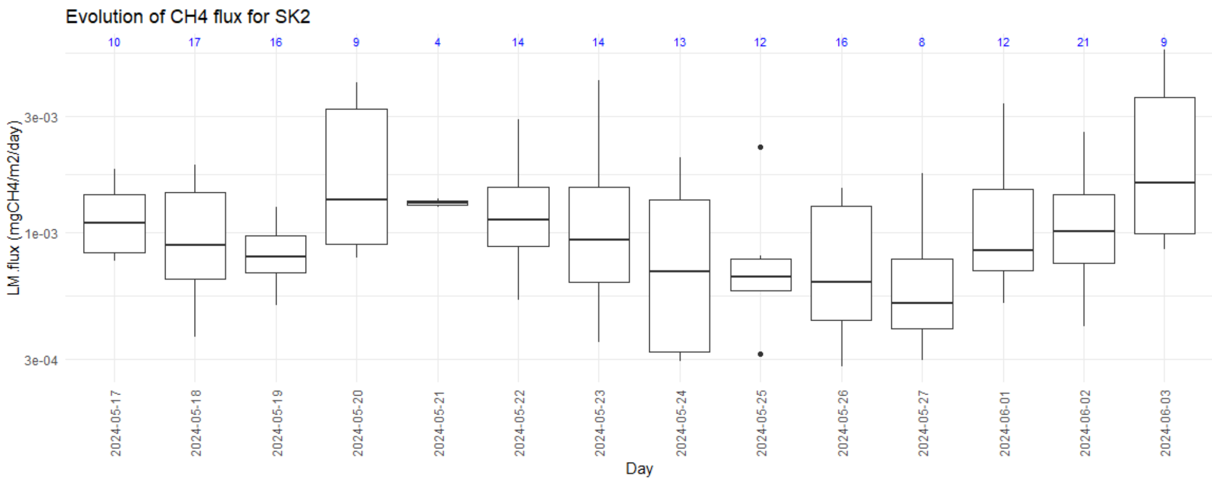


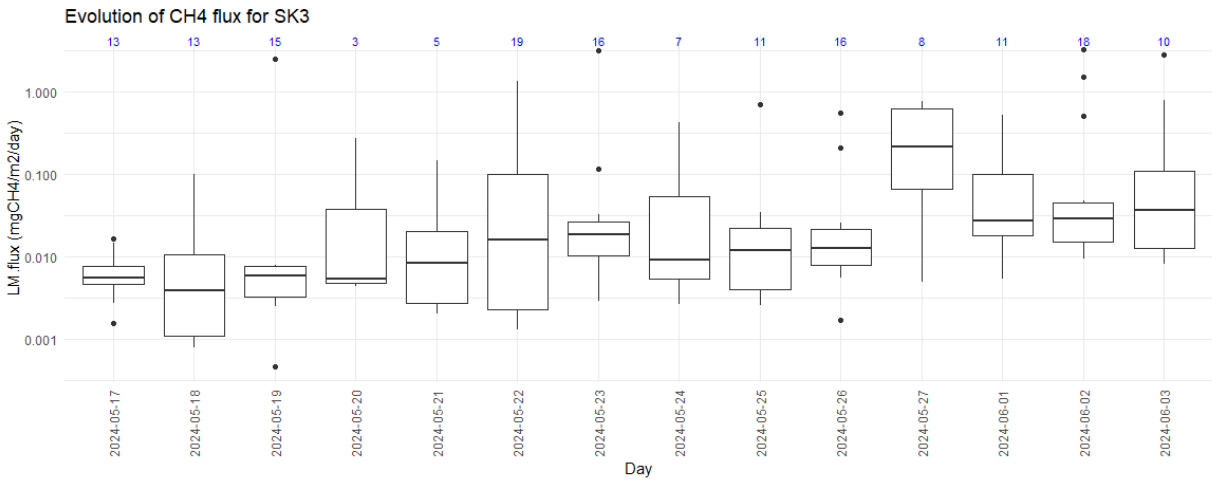

Evolution of CO2 flux for SK4
LM flux (mgCO2/m2/day)
Day

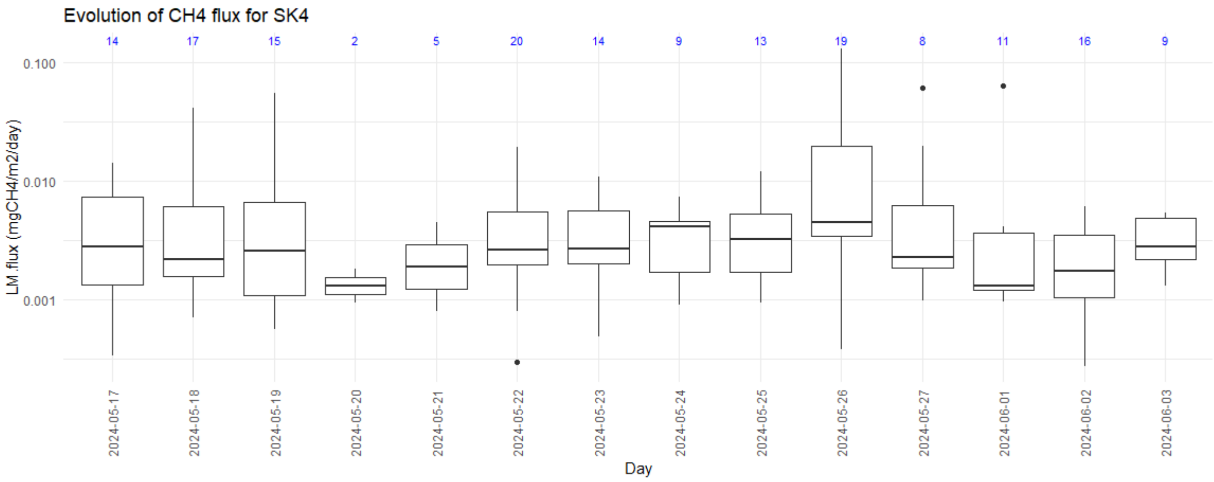

Evolution of CO2 flux for SK5
LM flux (mgCO2/m2/day)
Day

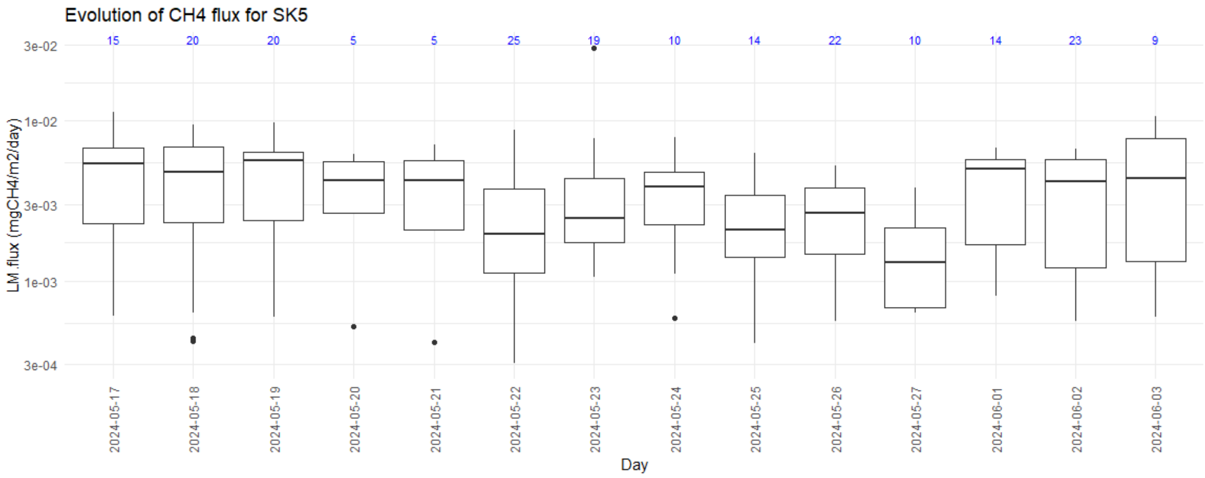
APPENDIX 8: CH_4 flux evolution for each type of soil








Evolution of CH4 flux for SK4
LM.flux (mgCH4/m2/day)
Day
14 17 15 2 5 20 14 9 13 19 8 11 16 9
0.100
0.010
0.001
2024-05-17 2024-05-18 2024-05-19 2024-05-20 2024-05-21 2024-05-22 2024-05-23 2024-05-24 2024-05-25 2024-05-26 2024-05-27 2024-06-01 2024-06-02 2024-06-03


Evolution of CH4 flux for SK5
LM.flux (mgCH4/m2/day)
Day
15 20 20 5 5 25 19 10 14 22 10 14 23 9
3e-02
1e-02
3e-03
1e-03
3e-04
2024-05-17 2024-05-18 2024-05-19 2024-05-20 2024-05-21 2024-05-22 2024-05-23 2024-05-24 2024-05-25 2024-05-26 2024-05-27 2024-06-01 2024-06-02 2024-06-03

APPENDIX 9: Review of studies on CH_4 emissions from restored peatland ditches

Source	Mesurement technique	Place	Max	Min	Average	Place type	Peat layers (m)	Ditche type	Cleanning	Water table (cm)	Mean water depht (cm)
M. D. A. Cooper and other (2014)	Ward et al. (2007)	North Wales, UK, Llyn Sern)	12,2	-1,2	5,6	Drained	2	Blanket bog unslope		5,5	
M. D. A. Cooper and other (2014)	+ chromatographe e	North Wales, UK, Llyn Sern)	12,2	-1,2	5,6	Drained	2	Within ditch		At surface	
M. D. A. Cooper and other (2014)		North Wales, UK, Llyn Sern)	12,2	-1,2	5,6	Drained	2	Blanket bog downslope		14,7	
M. D. A. Cooper and other (2014)		North Wales, UK, Llyn Sern)	12,2	-1,2	5,6	Rewetted	2	Blanket bog, unslope		3	
M. D. A. Cooper and other (2014)		North Wales, UK, Llyn Sern)	12,2	-1,2	5,6	Rewetted	2	Within ditch unvegetated		At surface	
M. D. A. Cooper and other (2014)		North Wales, UK, Llyn Sern)	12,2	-1,2	5,6	Rewetted	2	Within ditch vegetated		At surface	
M. D. A. Cooper and other (2014)		North Wales, UK, Llyn Sern)	12,2	-1,2	5,6	Rewetted	2	Blanket bog, downslope		2,7	
M. D. A. Cooper and other (2014)		North Wales, UK, Nant y Brwyn	12,2	-1,2	5,6	Undrained	2	Blanket bog		1	
M. D. A. Cooper and other (2014)		North Wales, UK, Nant y Brwyn	12,2	-1,2	5,6	Undrained	2	Withing ditch		1,2	
Hendrick (2023)	Floatting chamber w	North Netherlands, Site A	21	0	10,5	Drained	2	Ditche			43
Hendrick (2023)		North Netherlands, Site A	21	0	10,5	Drained	2	Ditche			39
Hendrick (2023)		North Netherlands, Site A	21	0	10,5	Drained	2	Ditche			22
Hendrick (2023)		North Netherlands, Site K	21	0	10,5	Drained	2	Ditche			46
Hendrick (2023)		North Netherlands, Site K	21	0	10,5	Drained	2	Ditche			52
Hendrick (2023)		North Netherlands, Site S	21	0	10,5	Drained	2	Ditche			24
Hendrick (2023)		North Netherlands, Site S	21	0	10,5	Drained	2	Ditche			64
Hendrick (2023)		North Netherlands, Site S	21	0	10,5	Drained	2	Ditche			10
Hendrick (2023)		North Netherlands, Site V	21	0	10,5	Drained	2	Ditche			34
Hendrick (2023)		North Netherlands, Site V	21	0	10,5	Drained	2	Ditche			24
Kohn (2021)	Floatting chamber w	North Germany			9,1	Drained	5	Ditche orthogonal	yes		40,00
Kohn (2021)		North Germany			9,1	Drained	5	Ditche paralelle	yes		40,00
Kohn (2021)		North Germany			9,1	Rewetted	6	Ditche orthogonal	No		104,00
Kohn (2021)		North Germany			9,1	Rewetted	6	Ditche paralelle	No		38,00
Kari Minkkinen and al. (1995)	Floatting static chan	Lakkasuo mire, Central Finland				Drained	1,4	Old ditch static water		50	40
Kari Minkkinen and al. (1995)		Lakkasuo mire, Central Finland				Drained	1,5	New ditch moving water		60	14
Kari Minkkinen and al. (1995)		Lakkasuo mire, Central Finland				Drained	1	Old ditch static water		40	0
Kari Minkkinen and al. (1995)		Lakkasuo mire, Central Finland				Drained	2,4	Old ditch static water		39	0
Kari Minkkinen and al. (1995)		Lakkasuo mire, Central Finland				Drained	2,4	Old ditch static water		22	0
Kari Minkkinen and al. (1995)		Lakkasuo mire, Central Finland				Drained	2,8	New ditch moving water		30	0

Width (m)	Flow	Sediment thickness (cm)	pH	Red/Ox potential (mV)	DOC (mg/l)	SO4 (mg/l)	NH4+(umol/l) surface water	NH4+ pore water	NO3- surface water	NO3- pore water	NO2-	(PO4)3- surface water	(PO4)3- pore water	F-	mgCH4/m2/day (dif)	mgCH4/m2/day (eb)	mgCH4/m²/day (tot)	Nb sample	Nb mesure spot	Nb of chamber test
			4,91		71,4	1											**15,1**	28	6	111
			4,81		30,3	0,64											**16,3**	10	4	24
			4,84		77	1,86											**8,8**	21	6	108
			4,94		80,7	0,9											**23,7**	30	6	102
			4,88		35,3	0,38											**10,3**	10	4	17
			4,92		52,1	0,97											**197**	10	4	28
			4,9		48,8	0,54											**16,3**	30	6	98
			4,67		44,1	1,91											**16,7**	17	8	89
			4,59		27,6	0,86											**13,9**	18	4	39
2,5	Low	103	6,7				52,6	390,2	48,5	152,7		2,4	11,2		**0,0**	**535,7**	**535,7**			
5	Low	85	6,3				50,1	651,6	46,5	26,7		3,6	51,1		**107,1**	**71,4**	**178,6**			
3,6	High	100	6,8				39,3	940,7	62	188,5		4,7	78,4		**71,4**	**178,6**	**250,0**			
2,8	High	78	6,1				68,1	432,8	11	5,1		2,5	5,5		**357,1**	**71,4**	**428,6**			
4,3	High	75	6,4				66,2	234,6	21,5	14,1		2,5	7,2		**0,0**	**71,4**	**71,4**			
1,1	Low	40	5,3				80,6	431,4	15,5	23,7		1,6	0,3		**357,1**	**1607,1**	**1964,3**			
3,8	High	65	6,6				86,2	657,1	28,4	34		1,7	3,4		**35,7**	**35,7**	**71,4**			
1,8	No	60	6,2				496,3	628,4	17,4	10,6		4,6	1,5		**535,7**	**178,6**	**714,3**			
3,8	Hign	46	6,1				71,9	1080,1	15	26,8		6,3	119,5		**178,6**	**1250,0**	**1428,6**			
2	No	75	5,9				76,3	1070,7	12,5	14,5		3,7	17,6		**160,7**	**267,9**	**428,6**			
2			6,9	-62	12	79,8	400		6800		500	100		300					5	300
2			7,1	-33	7,7	120	100		21300		1200	100		200	340,4	11,34361	351,8		5	300
4			7,3	-53	24,4	41,3	100		500		0	500		300					5	246
2			7,1	-53	11,4	123,7	100		200		100	200		300	1576,0	25,3304	1601,3		5	246
															210	**30**	**240**			
															250	**10**	**260**			
															95	**0**	**95**			
															60	**0**	**60**			
															60	**0**	**60**			
															50	**0**	**50**			

POLYTECH TOURS
35 ALLÉE FERDINAND DE LESSEPS
37200 TOURS

Julie
MOINDREAU

2023-2024

Titre: mitigating greenhouse gas emissions: development of tools for studying methane emissions in restored peatlands

Résumé : This internship focused on developing tools to quantify greenhouse gas emissions, specifically CH_4 and CO_2, from restored peatlands. Fieldwork, literature review, and data analysis were conducted. An R package was improved to streamline data processing. The report details methodology, tool development and first results

Mots Clés : greenhouse gas emissions, ,restored peatlands, tool development, data analysis

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