## Rapport de stage individuel

4ème année

# The influence of topsoil as an amendment on agricultural mineral soil

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2024-2025

# Aknowledgements

First, I would like to express my gratitude to **Sabine Greulich**, my academic tutor at Polytech Tours, for her valuable guidance and supervision.

I am particularly thankful to **Joachim Audet** for offering me the opportunity to carry out this internship within the Department of Ecoscience. His supervision, constructive feedback, availability, and insightful advice were essential to the successful completion of this project.

I would also like to thank my scientific tutor for their assistance throughout the internship. I am grateful to **Dominik Zak** for his availability, advice, clear explanations, coordination of the fieldwork and laboratory expertise. I would like to thank **Nichlas Hermansen** for his guidance in processing greenhouse gas data and for his support with the use of R software. Furthermore, I also express my appreciation to **Rasmus J. Petersen** for his availability and expertise.

My gratitude extends to the entire **Department of Ecoscience** for their warm welcome and for providing a collaborative and stimulating research environment.

I would also like to thank the **Polytech Tours administrative team** for their support with the administrative procedures for the scholarship that made this internship possible.

Finally, I would like to thank my fellow interns : **Claire Delandre, Noémie Gay, Florian Tillon and Camille Blanchais**, for their help in the laboratory, fieldwork and support with RStudio. I would also like to thank them for the complementary nature of their research topics, which enriched my experience.

# Summary

# I. Introduction

## A. The host organization : Department of Ecoscience at Aarhus University

Aarhus University, established in 1928, is now among the top 100 universities worldwide and is attended by more than 38,000 students. It is composed of five faculties : Arts, Business, Health, Natural science and Technical science. This internship took part in Ecoscience department in faculty of technical science (Aarhus University, n.d.). This department employs around 300 people, including researchers, technicians, students, PhD students, administrative staff, consultants, professors and interns. The main themes of this department are Biodiversity, Green transition, Environmentally hazardous substances, innovative monitoring, climate impacts on nature and environment and modeling. Research on these topics is carried out within four main thematic areas (Aarhus University, n.d.) :

- **Terrestrial ecology**

This section of research focuses on green transition and sustainable production in farming and forestry, using nature-based solutions. It develops tools for nature conservation and handles conflicts between nature and human activities. The section also creates methods to monitor biodiversity and works with the citizens, the public sector, and research institutions to plan sustainable species management.

- **Marine ecology**

This area of research focuses on the structure and function of marine ecosystems, from the coastal zone to the open area, covering different systems like Arctic, temperate, and tropical zones. The marine ecology team focuses on identifying changes in the ocean due to natural variation or human impact. They develop tools and models to assess marine health, using methods like remote sensing, habitat mapping, and experimental work. They also explore nature-based solutions to support carbon storage and biodiversity in marine ecosystems.

- **The Arctic**

The department plays a leading role in Arctic research, especially in Greenland, focusing on the region's nature and environment. It works closely with local authorities and the Greenland Institute of Natural Resources, offering advice on environmental issues like mining and nature protection. The research covers various ecosystems, studying the effects of climate change, pollution, and ecosystem health, with a focus on marine mammals and human health. They also study the effects of climate change on the Arctic’s ecosystem and environment.

- **Fresh water ecology**

This section of research covers the biology and ecology of streams, lakes, ponds, natural and constructed wetlands and more generally, the catchments of the surrounding rural areas. It studies biological and chemical processes in freshwater ecosystems, focusing on nutrient dynamics, pollution, and biodiversity. Research topics include lake and stream restoration, greenhouse gases, and the link between catchments and freshwater areas. It also develops models to calculate nitrogen and phosphorus leaching from fields to streams and the marine environment. My internship took place in this section, including focusing on peatlands.

# B. The internship mission

## 1. Context of the mission

### 1.1 Peatland dynamics

Peatlands are a type of terrestrial wetland consisting of accumulated organic matter derived from plant detritus. Indeed, the saturated soil leads to anaerobic conditions, which slow down decomposition, resulting in the accumulation of peat (IPS, 2025). Although this particular type of ecosystem covers only 3% of the land surface, it provides many ecosystem services, like storing water, enhancing, purifying water quality, and mitigating both floods and droughts. They act as significant nutrient sinks due to the slow decomposition rates of organic matter and denitrification. Peatlands also have high biodiversity value, as their unique environmental conditions support rare and specific biota.

Above all, peatlands play a crucial role in the **greenhouse gas** (GHG) **and nutrient cycle** (Reddy et al., 2023). Firstly, they store 600 Gt of **carbon**, which represents 25% of the world soil's carbon (Yu et al., 2011 ; Parish et al., 2020). The photosynthesis process is more important than the decomposition process, which allows peatlands to store such a large amount of carbon. Peatland carbon is stored in two main forms, organic and inorganic, within interconnected reservoirs that together drive the carbon cycle in these ecosystems (figure 1) (Reddy et al., 2023):

- **Plant Biomass Carbon (PBC) :** This carbon is fixed by plants through photosynthesis, converting inorganic carbon ($CO_2$) into organic carbon in the form of biomass. Plants transform inorganic carbon into organic carbon, forming the base of the carbon pool in peatlands.

- **Particulate Organic Carbon (POC) :** POC consists of dead organic matter undergoing decomposition. In peatlands, decomposition is greatly slowed by anaerobic conditions, leading to significant accumulation of this carbon reservoir. This stored carbon serves as an important energy source for the ecosystem and is gradually released through microbial activity.

- **Microbial Biomass Carbon (MBC) :** this reservoir refers to carbon contained within microbial biomass that processes plant detritus during decomposition. Although microbial biomass represents only about 3% to 5% of the total organic carbon in peatlands, it plays a crucial role in recycling carbon and nutrients within the ecosystem.

- **Dissolved Organic Carbon (DOC) in Dissolved Organic Matter (DOM) :** DOC originates mainly from the decomposition and leaching of plant detritus in soils and sediments. In soils, DOC accounts for less than 1% of total organic matter, but in surface waters, it can represent up to 90% of total organic carbon. However, only a small fraction of DOC is bioavailable to microbes.

- **Gaseous Carbon Forms (GCF) :** Carbon is also present as gases, primarily carbon dioxide ($CO_2$) and methane ($CH_4$), which are end-products of anaerobic decomposition of organic matter in peatland. $CO_2$ readily dissolves in water and exists in various chemical forms depending on pH, whereas methane, being sparingly soluble and flammable, escapes easily into the atmosphere. These gaseous forms are dynamic reservoirs controlled by biological and chemical conditions in the wetland.

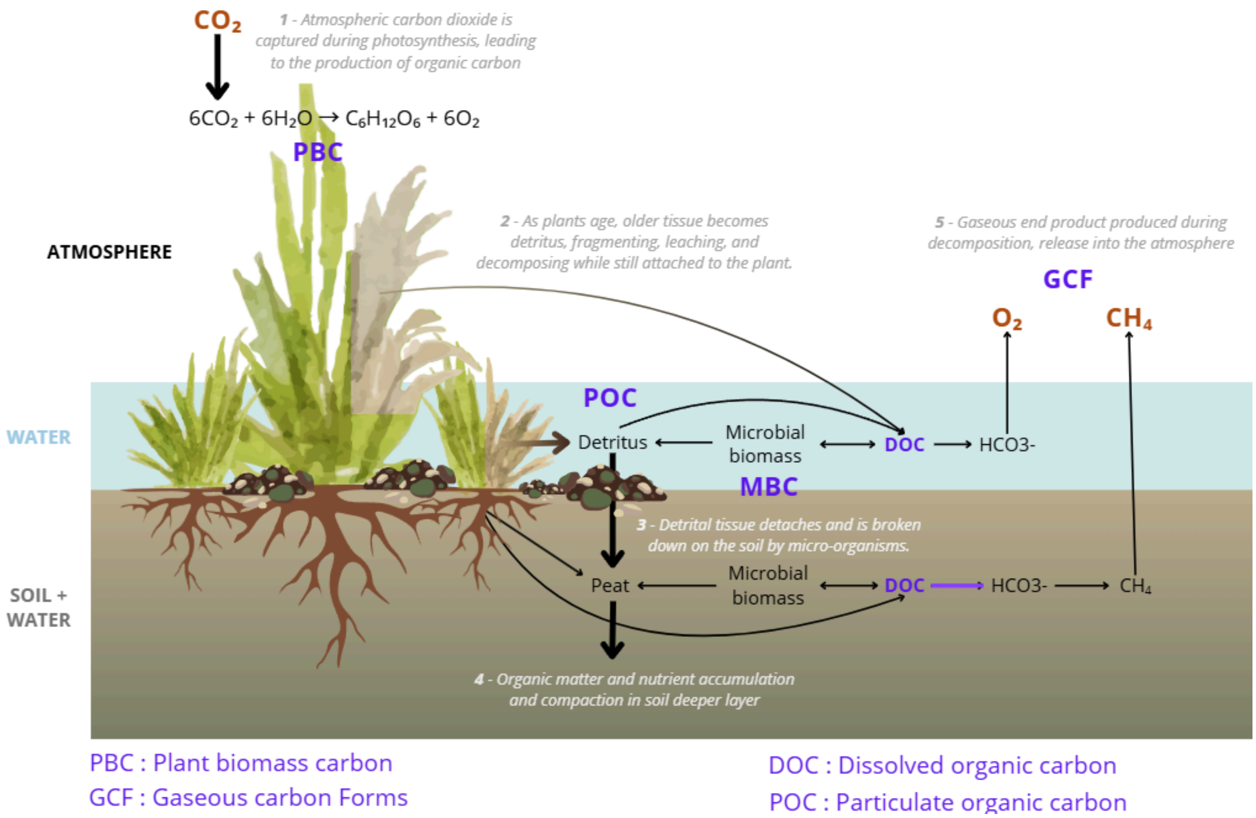


Figure 1 : Schematic carbon cycle, showing major storage pools and stages of organic matter decomposition and accumulation in peatlands

Adapted from Reddy et al., 2023 (Mathilde Sandron, 2025)

Peatlands are also involved in the $N_2O$ (nitrous oxide) cycle, a GHG that has a global warming potential approximately 300 times greater than that of $CO_2$. (Zak and McInnes, 2022 ; Liu et al., 2019). This greenhouse gas cycle in peatlands is part of the **nitrogen** (N) cycle (Figure 2).

Nitrogen enters peatland ecosystems through various pathways, such as biological $N_2$ fixation, dry and wet atmospheric deposition, non-point sources, and wastewater inputs. In peatland ecosystems, nitrogen exists in two forms, organic and inorganic, just like carbon. It is distributed among several major, interconnected pools, which can act either as sources or sinks (figure 2) (Reddy et al., 2023):

- **Plant biomass nitrogen** (PBN) : This nitrogen is found in living plants and serves as an essential nutrient. Alongside carbon, it is one of the key elements that can limit biomass production. Wetland plants are capable of absorbing nitrogen in the form of ammonium, nitrate, and, in some cases, certain soluble organic compounds.

- **Particulate organic nitrogen** (PON) : This refers to the nitrogen contained in the detrital pool, where the decomposition and mineralization of organic nitrogen take place.

- **Microbial biomass nitrogen** (MBN) : This pool consists of nitrogen contained in living microorganisms, which use both organic and inorganic nitrogen for cell growth. Although this pool represents only 0.5 to 3% of total nitrogen, it is the most active one and plays a key role in regulating the amount of bioavailable nitrogen. Microorganisms utilize detrital organic material for energy and convert organic nitrogen into ammonium during decomposition.

- **Dissolved organic nitrogen** (DON) : The dissolved organic nitrogen pool consists of small organic compounds from various sources, such as leachates from litter, detritus, and even single-celled microorganisms.

- **Inorganic forms of nitrogen** (IFN) : They include dissolved gases ($N_2$, $NH_3$, $N_2O$) and inorganic forms of nitrogen such as ammonium, nitrate, and nitrite.

- **Gaseous end product** (GEP) : Gaseous nitrogen forms, such as ammonia, nitrous oxide, and dinitrogen, make up less than 1% of total nitrogen in wetlands and are easily released into the atmosphere. In addition to nitrogen released into the atmosphere through gaseous losses, other outputs include volatilization, outflow, and plant harvesting.

Pristine peatlands act in part as a nutrient (such as N) sink because anoxic conditions are more favorable to a complete denitrification. Under anaerobic conditions, bacteria use $NO_3^-$ as an electron acceptor and convert it into $N_2$. Moreover, although wetland plants and denitrifying microbes both require nitrate, denitrification tends to prevail due to anaerobic conditions that favor high electron availability and the plants' tendency to absorb ammonium rather than nitrate. In addition, nutrients stored in dead organic matter accumulate due to the slow decomposition processes typical of peatlands.

Regarding $N_2O$, peatlands can act as a sink when microbial communities reduce $N_2O$ to $N_2$ under highly anoxic and nitrogen-poor conditions (Behrendt et al., 2022). They can also act as a source when incomplete denitrification or nitrification occurs due to the presence of nitrate ($NO_3^-$) or ammonium ($NH_4^+$) and fluctuating oxygen levels, like in drained peatland (Lin et al., 2022).

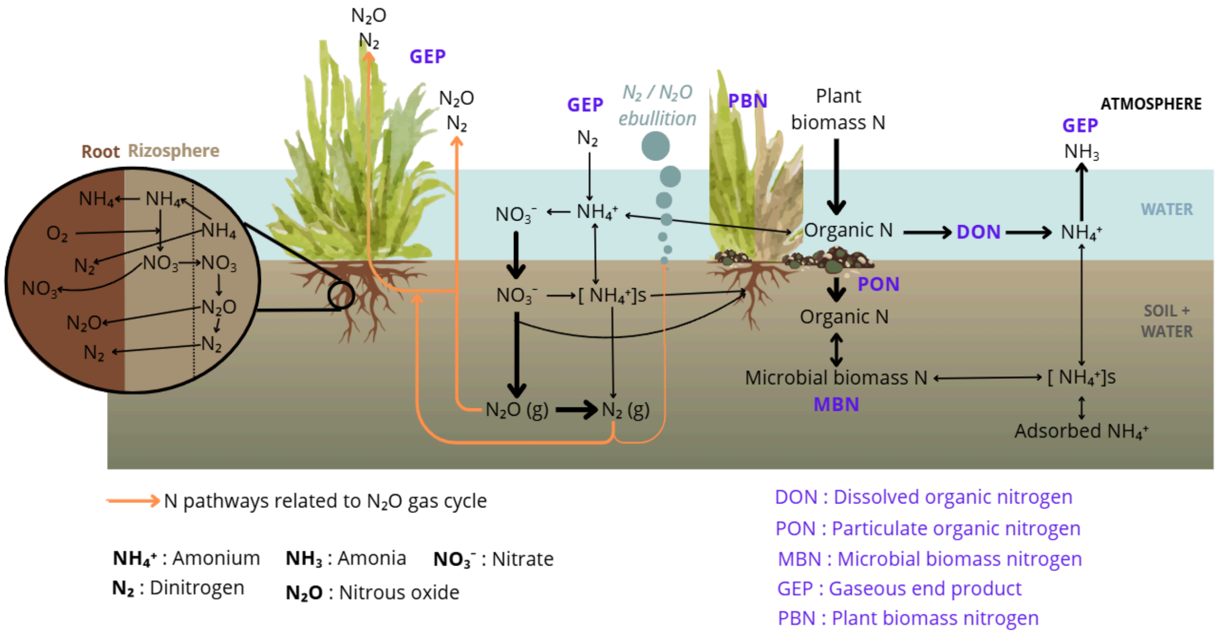


Figure 2 : Schematic Nitrogen and Nitrous oxide cycle showing major storage pools in peatlands
Adapted from Reddy et al., 2023 (Mathilde Sandron, 2025)

The **phosphorus (P)** cycle is another important nutrient dynamic in peatlands (Reddy et al., 2023). Phosphorus exists in several forms within peatlands (figure 3) in different interconnected storage : soil, water columns, and plant biomass. P can be stored in inorganic or organic forms. The form that is bioavailable to plants is dissolved inorganic phosphorus (DIP) (figure 3), also referred to as dissolved or soluble reactive phosphorus (DRP or SRP, respectively). DIP mainly occurs as orthophosphate ions ($H_2PO_4^-$, $HPO_4^{2-}$, or $PO_4^{3-}$), depending on the pH.

Phosphorus accumulates in the soils of undisturbed peatlands : it consists of both short-term and long-term storage. In the short term, phosphorus is temporarily held within living biomass such as plants and periphyton, and is subsequently transferred into detrital matter as these organisms die and decompose (figure 3).
Over longer timescales, phosphorus becomes more permanently retained through its association with accumulating organic and mineral materials in the soil. This long-term sequestration is guaranteed by the anaerobic conditions in peatlands, which slow down decomposition processes and promote the gradual build-up of peat layers.
This storage process is further influenced by hydrological inputs, which transport phosphorus into the system. Concentrations are typically higher near inflow areas and decrease along the flow path, reflecting the peatland's capacity to retain phosphorus as it moves through the soil matrix . Because phosphorus has no stable gaseous form, it must be either stored or transformed within the system. Its distribution and long-term accumulation are monitored by water dynamics, soil characteristics, and redox conditions (Reddy et al., 2023).

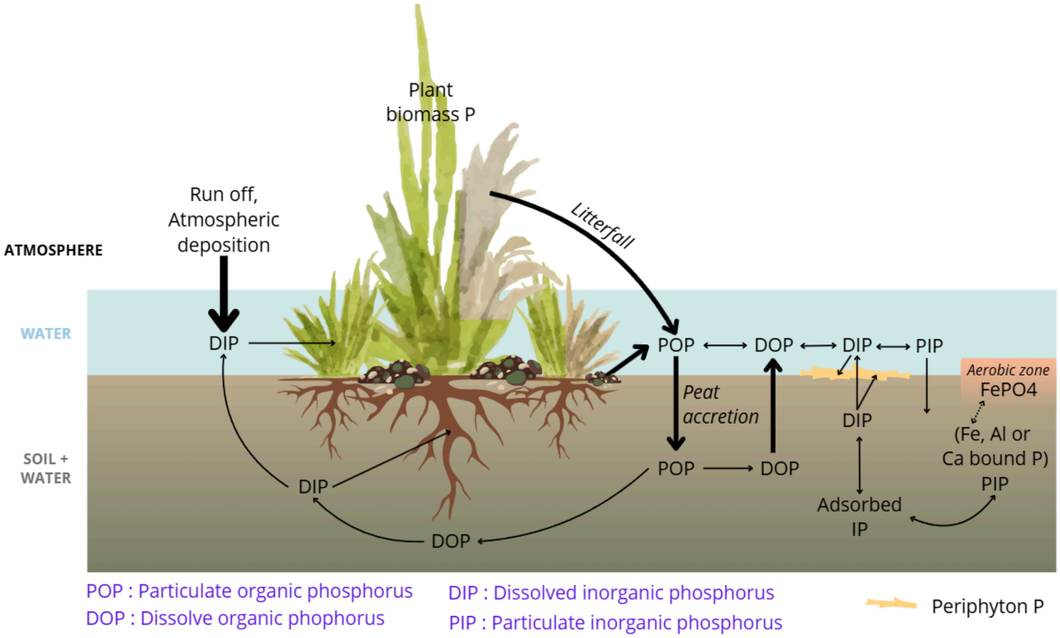


Figure 3 : Schematic phosphorus cycle in peatlands
Adapted from Reddy et al., 2023 (Mathilde Sandron, 2025)

On the other hand, peatlands are a source of methane, which is part of the carbon cycle (figure 1). This gas is responsible for approximately 17% of radiative forcing (Le Bodelier and Steenbergh, 2014) and has a global warming potential 28 times higher than that of $CO_2$. Wetlands account for 33% of methane emissions to the atmosphere (Lyu et al., 2018).

In peatlands, methane is produced by archaea, a group of microorganisms known as methanogens. The process of methane production is called methanogenesis. It is a form of anaerobic respiration that generates methane as the final product of microbial metabolism. Methanogenic archaea require substrates to produce methane : acetate or hydrogen and carbon dioxide. These substrates are converted into methane through a complex enzymatic process (Lyu et al., 2018; Kotsyurbenko et al., 2019) (Figure 4 (A)). Another way to produce methane for microorganisms is using methyl groups (Weil et al., 2023).

The peatland vegetation plays a key role in regulating methane transport from the anaerobic soil layers to the atmosphere, primarily through the aerenchyma tissues of roots, stems, and leaves of herbaceous plants. Indeed, to enable gas transport under anaerobic and aquatic conditions, wetland plants have developed specialized systems. The fundamental adaptation is the aerenchyma, a plant tissue characterized by interconnected air spaces that facilitate gas exchange between the atmosphere and sediment (Figure 4 (B)).
The $CH_4$ flux through plants is driven by several physical mechanisms, including diffusion and mass flow. Diffusion is a slower process where gas moves in response to concentration gradients, and mass flow is a faster process where gas moves due to physical pressure differences (Reddy et al., 2023). Another process releases methane into the atmosphere in the form of gas bubbles : ebullition (figure 4 (C)). This is not a plant-mediated process, but rather a physical one : when the total partial pressure of dissolved gases exceeds the hydrostatic pressure in the peat, gas bubbles are formed (Lai, 2009).

Some of the methane generated in peatland soils undergoes oxidation within the root zones prior to its release into the atmosphere (figure 4 (D)). Due to methane's limited solubility in water, its diffusion through saturated soils is restricted, resulting in the majority being converted to carbon dioxide (figure 4 (E)) (Reddy et al., 2023).

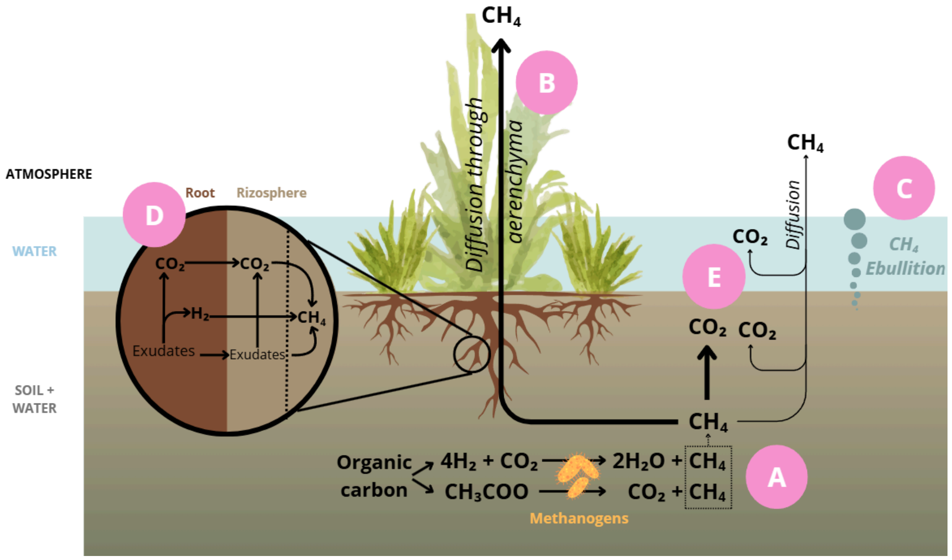


Figure 4 : Schematic methane cycle in peatlands
Adapted from Reddy et al., 2023 & Lai, 2009 (Mathilde Sandron, 2025)

***A*** *: Methanogenesis ;* ***B :*** *Diffusion of $CH_4$ through aerenchyma to the atmosphere ;* ***C****: Release of $CH_4$ in atmosphere by ebullition ;* ***D*** *: Production and oxidation in the rhizosphere/roots zone*

To summarize the GHGs cycles in peatlands: the carbon sink function still outweighs other GHG emissions, such as methane, under undisturbed peatland conditions.

### 1.2 Peatland restoration issue

Peatlands have been drained for agricultural purposes, creating more oxygenated conditions by lowering the water table, promoting the aerobic decomposition of organic matter, and consequently the degradation of peat. This drainage turns peatland from carbon sinks into carbon sources. The decomposition process becomes more important than the carbon uptake by assimilation or plant growth. It also stimulates $N_2O$ emissions due to disruptions in nitrogen cycling, where an imbalance between ammonification and nitrification promotes $N_2O$ production (Landry and Rochefort, 2012).

Moreover, the acceleration of organic matter decomposition increases nutrient availability in the soil, such as nitrogen and phosphorus, which were previously stored in dead organic material and associated with carbon.

Phosphorus mineralization is enhanced and promotes the formation of another important inorganic form of phosphorus in the soil : ferric phosphate ($FePO_4$) (Figure 3). In addition, peatlands that have been used for agriculture are often heavily fertilized, contributing to a nutrient-rich topsoil.

It has been estimated that degraded peatlands account for 5% of anthropogenic greenhouse gas emissions, highlighting the need to restore these damaged ecosystems (Strack and al., 2022).

The solution is to rewet previously drained peatlands to restore their carbon storage function and contribute to climate change mitigation. In Denmark, the goal of rewetting is to restore the natural hydraulic functions of peatlands and consequently reestablish their natural functions and ecosystem services by maintaining anaerobic conditions (Zak et al., 2017). To achieve this goal, several methods can be used, such as blocking the drainage system, using dams to stop water flowing into drainage ditches, or stopping the implemented pumping. (Landry and Rochefort, 2012).

However, degraded peatlands with a high content of easily decomposable organic matter and nutrients may respond negatively to rewetting. The process can trigger the release of a bigger amount of methane in the atmosphere and a bigger concentration of DOC in pore water than in undisturbed peatland (Harpenslager et al., 2015).

Furthermore, the nutrient-rich topsoil promotes the mobilization and leaching of excess phosphorus into downstream aquatic systems. The release of phosphorus, bound to iron in soil, back into the water column is a key process. Indeed, ferric iron ($Fe^{3+}$) is reduced to ferrous iron ($Fe^{2+}$), which dissolves $FePO_4$ complexes, releasing dissolved inorganic phosphorus into the pore water (interstitial water) :

$$\mathbf{FePO_4 \rightarrow Fe^{2+} + PO_4^{3-}}$$ (Reddy et al., 2023).

This release can cause a peak in orthophosphate ion concentration in the water, a form that is readily assimilated and bioavailable to aquatic plants. It has been estimated that, following peatland rewetting, phosphorus concentrations in pore water can increase by up to three orders of magnitude compared to undisturbed conditions (Zak et al., 2004 & 2008). This nutrient influx often leads to eutrophication, characterized by excessive algal blooms that degrade water quality. (Harpenslager et al., 2015 ; Zak et al., 2017).

To mitigate these risks, the uppermost 30-60 cm of soil (topsoil) can be removed before rewetting (Huth et al., 2020 ; Zak et al., 2017). The topsoil corresponds to the uppermost layer of degraded peat, which has lost its physical properties and has become enriched in nutrients. The aim of topsoil removal (TSR) is to restore conditions similar to those of pristine peatlands, so that the peat present at the soil surface is less degraded and more similar to that found in undisturbed peatlands, with its original physical properties preserved. However, this procedure raises a key question: what should we do with this removed topsoil, and how can it be repurposed ? **One possible solution could be to use this degraded peat, which is rich in nutrients and carbon, as a soil fertilizer on mineral soils intended for agriculture.**

## 2. Purpose of the mission

In Denmark, 61% of the land area is under cultivation, and the majority of surface soils have a **sandy texture** (Adhikari et al., 2013). Some studies have shown that adding peat can increase water holding capacity as well as nutrient availability by enhancing soil microbial activity in both cultivated and mineral soils. (Moskal et al., 2001 ; Witkowska-Walczak et al., 2002 ; Vepsäläinen et al, 2003). One amendment that has received considerable attention in recent years is biochar, a carbonaceous material produced from biomass incineration under oxygen-limited conditions. More recent discussions focus on how it can increase soil fertility by adding carbon and organic matter (Munoz et al., 2016; Yuan et al., 2025). However, unlike biochar, which requires energy to produce, degraded peat, also rich in carbon and organic matter, is already present in disturbed peatlands.

The goal of this study is to understand the **effects of mixing degraded peat with mineral soil on various soil properties, such as moisture, temperature, conductivity, phosphorus, carbon and nitrogen content, dissolved organic carbon, and GHG gas fluxes.** We want to know how adding this topsoil can change these properties in a mineral soil and how it could help in agriculture.

**It is hypothesized that incorporating degraded peat into mineral soils will enhance soil water retention and stimulate plant productivity as a result of the increased organic matter and nutrient availability provided by the peat.**

**Another statement that can be made in this study concerns carbon dioxide emissions.** Indeed, topsoil removal can be costly. The use of topsoil, and thus its removal, will partly depend on the carbon footprint generated by its new application (Zak and McInnes, 2022). In this study, we will also focus on the carbon footprint associated with reusing this topsoil as an amendment **: Despite the fact that degraded peat can release $CO_2$ under oxic conditions, we hypothesize that the increase in plant production will enhance $CO_2$ uptake and thereby balance the $CO_2$ emissions.**

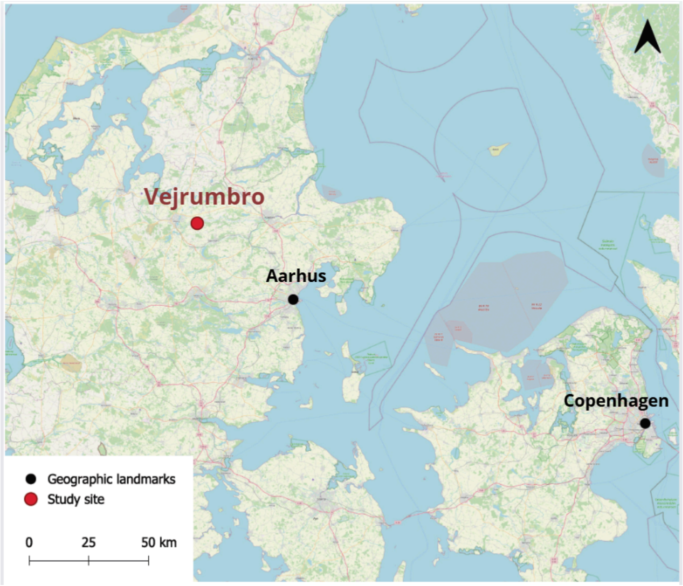
## 3. Tasks carried out during the internship

The internship required completing several tasks to ensure its achievement. The initial phase involved reviewing numerous scientific articles to understand the topic, its underlying issues, the dynamics within a rewetted peatland, and the topsoil removal process in Denmark.
The second phase focused on addressing the previously stated hypothesis concerning the reuse of topsoil for agricultural purposes.
As a starting point, environmental monitoring data were analyzed and interpreted to build a broader understanding of site conditions. In parallel, the laboratory work for phosphorus extraction was conducted in collaboration with other interns : Noémie Gay and Florian Tillon. Individual tasks related to soil analysis also included the examination of additional data concerning organic matter, carbon, and nitrogen content.
Fieldwork and greenhouse gas measurements were carried out at additional sites to gain familiarity with the monitoring equipment, although no data processing was performed for those locations. The GHG data analysis was based exclusively on raw data from the Vejrumbro site, as no direct measurements were carried out there. This work was done in collaboration with Claire Delandre, whose internship topic was complementary, particularly in the use of R for data processing.
Individual tasks included the treatment of GHG flux data from the SKY1 and SKY2 treatments, which were specific to the internship topic, covering a full monitoring year. The processed results were interpreted and presented in graphical form to support further analysis.

# II - Material and methods

## A. Presentation of the study site : Vejrumbro

### 1. Localization



The experimental site is located in Vejrumbro, in the center of Jutland (Denmark) (Figure 5). The site is part of the Nørre Å river valley, a rewetted riparian fen. This area was drained using ditches in the 1950s for grazing purposes, which continued until 2018, when grazing was stopped to install research infrastructure. Finally, in 2022, the area was gradually rewetted (Petersen et al., under review).

Figure 5 : Localization of the experimental site : Vejrumbro

**Data** : open street map, **Author** : Mathilde Sandron (2025)

### 2. Characteristics of the site

The catchment around Vejrumbro is characterized by predominantly agricultural land use and mainly sandy soils. Geologically, the valley has a complex history. The Nørreå stream valley was originally formed during the last glaciation as a tunnel valley beneath the ice sheet. Later, during the post-glacial marine transgression, the valley was transformed into a long and narrow fjord. This marine phase led to the deposition of a gyttja layer enriched with shell fragments. After the sea retreated, peat formation occurred on top of the gyttja deposits, resulting in the accumulation of 2 to 3 meters of fen peat (Petersen and al., 2025).

Briefly, the soil at the site is composed as follows (from top to bottom): 30 cm of degraded peat, 1.5 to 2 meters of partially decomposed peat, followed by a thin layer of gyttja, and finally approximately 20 meters of sand before reaching the Paleogene clay layer. The upper layer of degraded peat is highly altered. According to the Von Post scale, the degree of decomposition is approximately 9 at the surface and decreases to 4 in deeper layers (Petersen et al., 2025). This means that it is no longer possible to distinguish the structure of the plant material that originally composed the topsoil (the uppermost and most altered layer) (Amstrong and Castle, 2015).

## B. Experimental setup

### 1. Treatments along the transect

It consists of 5 plots (3,75 x 2m) aligned along a 30 m transect. Each plot, labeled SKY1 through SKY5, received a specific treatment since February 2023 :

- **SKY1 : Drained mineral soil**
- **SKY2 : Drained mineral soil mixed with 20% Topsoil**
- SKY3 : ditch filled with topsoil
- SKY4 : Rewetted fen with TSR
- SKY5 : Rewetted fen with no TSR

However, only the results from two of them (SKY1 and SKY2, figure 6) will be analyzed, because this study focuses on the impact of degraded peat mixed with mineral soil on mineral soil properties. SKY1 and SKY2 consist of two large wooden boxes that are perforated at the bottom. This perforation simulates the drainage effect. The mineral soil at SKY1 originates from the surrounding cultivated fields. To prepare the SKY2 mixture, this mineral soil was combined with 20% degraded peat from the study site using a concrete mixer.

Figure 6 : Treatment 1 and 2 in drained wooden boxes. SKY1(farthest) contained mineral soil. SKY2(closest) contained mineral soil mixed with 20% topsoil.

Author : Ecoscience Department

## 2. Moisture, temperature and electrical conductivity measurement

To measure soil moisture, temperature, and electrical conductivity, we used the Dragino SE01-LB/LS sensor (figure 7), which is factory-calibrated for mineral soils. This sensor uses the Frequency Domain Reflectometry (FDR) method with compensation for soil temperature and conductivity. Data were collected automatically every 20 minutes using the sensor's LoRa wireless technology, starting from May 30, 2024 to June 2025.

Figure 7 : Dragino SE01-LB/LS sensor

(Mathilde Sandron, 2025)

Source : Dragino.com

## 3. Soil characteristics measurement

At the Vejrumbro site, five soil samples per SKY were randomly collected in April 2024 and July 2025, allowing soil characteristic analyses to be conducted in the same respective months. In July, samples were collected with a 5 cm diameter auger.

### 3.1 Phosphorus fraction measurement

To quantify the different phosphorus fractions present in SKY1 and SKY2, we followed a protocol established by Zak et al. (2008). The aim of this protocol is to assess the forms and availability of phosphorus and to better understand the potential mobilization mechanisms in rewetted peatlands.

It consists of several successive extraction steps (Zak et al., 2008) to isolate and quantify the different phosphorus fractions in a sample of approximately 5g (figure 4) :

- The first fraction is phosphorus bound to ammonium chloride ($NH_4Cl$-P), also referred to as desorbable P. It represents phosphorus present in the pore water and weakly bound to the surfaces of compounds such as Fe, Ca, and organic matter.
- The second extraction targets phosphorus bound to redox-sensitive ferric compounds, such as Fe(III). At this step we used BD-P (Bicarbonate Dithionite–Phosphorus). The extracted phosphorus is referred to as reductant-soluble P.
- Then pH-sensitive phosphorus, also known as acid-soluble P, is extracted using an HCl–NaOH solution.
- The last extraction step targets base-soluble P, which is extracted using sodium hydroxide (NaOH). This final step alone does not allow for the separation of humic acid P and non-humic acid P. To calculate the amount of humic acid P, the quantity of non-humic acid P must first be determined. This latter fraction is extracted from the base-soluble P using a highly acidic HCl solution.

The total phosphorus content was determined using peat samples that were dried to constant mass and homogenized with a stainless steel mill (figure 8). The total phosphorus content was then measured as soluble reactive phosphorus (SRP) following acid digestion.

Finally, the residual P is calculated by subtracting the sum of the four extracted phosphorus fractions from the total phosphorus.

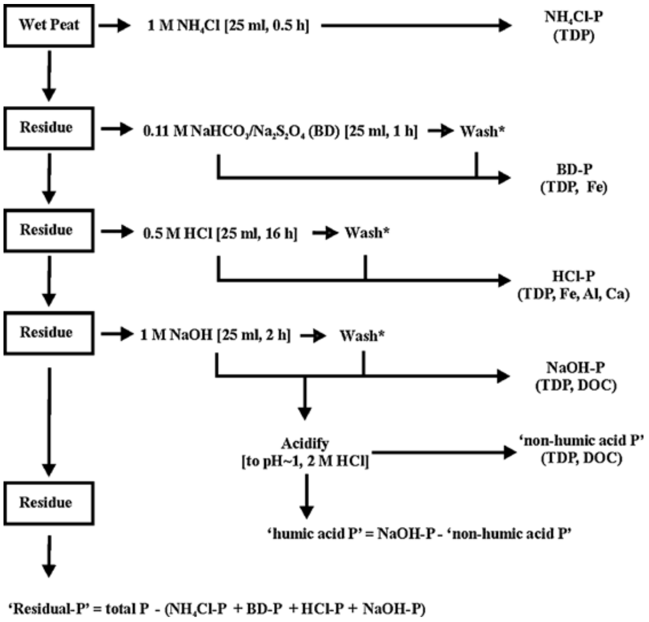


Figure 8 : The extraction steps of phosphorus fractions
from Zak et al., 2008

### 3.2 Organic matter content and dry bulk density measurement

To determine the proportion of dry matter, and thus of organic matter, the site sample should be analyzed as soon as possible. It can be stored at 4 °C for a maximum of one week. The sample of known weight (~ 10g) is first dried in an oven at 60 °C for two days, allowing the initial determination of dry mass (DM).

The percentage of dry matter in the site sample is determined from this first drying step. The water content is calculated by subtracting the weight of the sample after drying from the fresh mass. This step also allows the determination of dry bulk density (DBD) if the total sample volume and the dry mass of a subsample are known.

The remaining material was then placed in a furnace at 450 °C for 4 hours. This temperature was chosen because it allows for the combustion of organic compounds without significant loss of inorganic material. The proportion of dry matter in the site sample can be determined by subtracting the weight of the sample after oven-drying from its weight before drying. The proportion of organic matter is calculated relative to the dry mass. The weight obtained after heating at 450 °C is subtracted from the weight obtained after the first drying step.

### 3.3 Dissolved organic matter measurement

In the present work, dissolved organic matter (DOM) was analyzed from the KCl fraction obtained through the P-fractionation protocol (Zak et al., 2008). DOM consists of a mixture of water-soluble compounds that vary in molecular weight, structural composition, and complexity (Leenheer and Croué, 2003). In this study, DOM can be classified into three subcategories based on size-related characteristics :

- Biopolymers: Non-humic, high molecular weight substances (>10 kDa) with a hydrophilic nature and no unsaturated structures, such as polysaccharides and proteins.
- Aromatics: Humic or humic-like substances, including structural building blocks.
- Low molecular weight substances: Including low molecular weight acids and neutral compounds.

The quantification of these subcategories is determined using size-exclusion chromatography (SEC) coupled with organic carbon and nitrogen detection (LC-OCD-OND analyzer, DOC-Labor Huber, Karlsruhe, Germany) as described by Huber et al. (2011). The detection limit for each fraction was 0.01 mg C $L^{-1}$. All samples were kept at 5°C for a maximum of two weeks to minimize potential alterations in DOM composition. (Heinz and Zak, 2018).

### 3.4 Carbon and Nitrogen content measurement

The carbon and nitrogen contents were measured using dried peat samples that had been previously homogenized with a stainless steel mill. The C and N content were then quantified using a CN analyzer (Vario EL; Elementar, Mt. Laurel, New Jersey, USA) (Zak et al., 2010).

### 3.5 Soil fertility measurement : Harvesting

To assess soil fertility, biomass harvesting was carried out on SKY1 and SKY2 treatments in July 2025. For each treatment, five zones measuring 0.70 m × 0.70 m were clipped at ground level, which represented plot areas designated for GHG measurements (see below). The harvested plant material was stored in 10 separate bags, weighed on the same day as the cutting, and then oven-dried at 40 °C for one week to obtain the dry mass. The harvested plants were stored in plastic bags throughout the experiment to prevent losses.

## 4. Greenhouses Gas measurement

### 4.1 The skyline

The Skyline system (figure 9 & 10) was designed along a 30-meter transect to monitor greenhouse gas fluxes precisely. To set this up, two 3-meter-high aluminum scaffolds were installed at both ends of the transect (figure 5a). Each scaffold is anchored with a 1000-liter water tank acting as a counterweight to ensure stability. Between the scaffolds, two parallel ropes are stretched, forming the tracks for the Dolly robot. This robot travels along the ropes, moving above the five Sky boxes to automatically measure greenhouse gas emissions.

Along the transect, there are 25 measurement points, with 5 in each Sky box. Dolly can identify its measurement points using magnetic markers that are fixed to one of the two ropes. When Dolly stops above a measurement point, the chamber is lowered and positioned directly over it. This chamber collects the gases and sends them to the gas analyzer through tubes. These tubes connect the chamber to the analyzer, which is located near SKY5. Each measurement lasted 5 minutes, not including the time needed to lower and lift the chamber. A pause of 4 minutes and 35 seconds was observed between two measurements. This pause between measurements also allowed the chamber to be flushed. To clearly separate the data from each cycle, a longer break of 45 minutes was introduced after every cycle.

Over a 24-hour period, approximately 5.25 measurement cycles were completed, during which greenhouse gases including $CO_2$, $CH_4$, and $N_2O$ were measured.

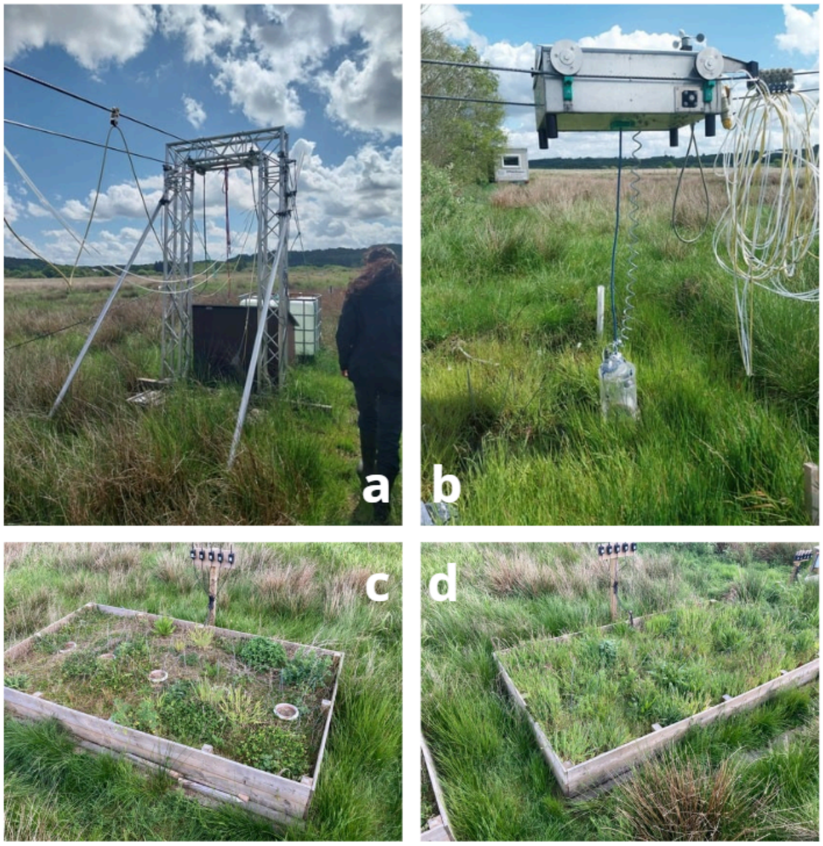


Figure 9 : a - structure and gas analyzer of the skyline system. b - gas chamber during a measure. c - Sky 1 after years of treatments. d - SKY2 after 2 years of treatments

(a&b Mathilde Sandron, 2025 and c&d Dominik Zak, 2025)

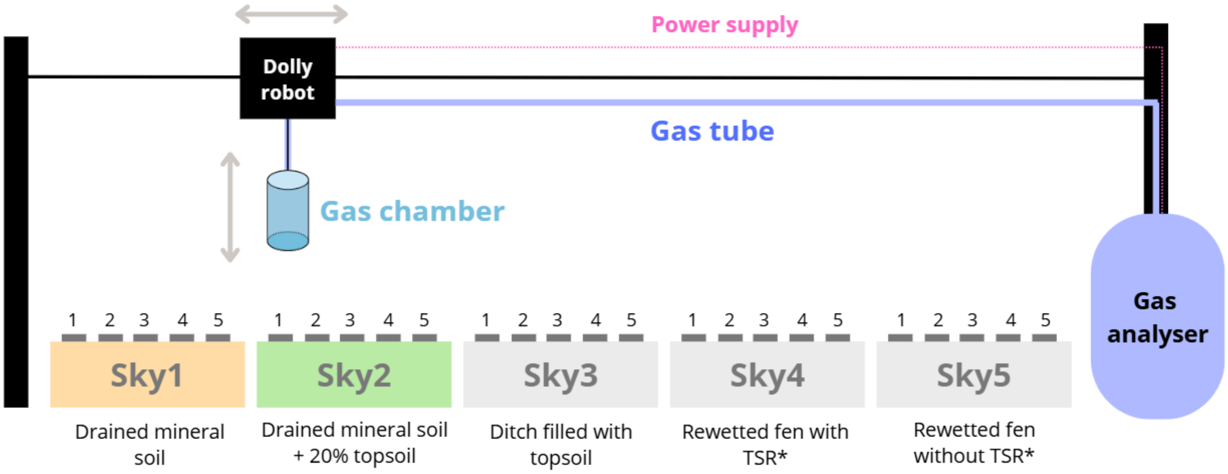


Figure 10 : Schematized structure of the Skyline system

**TSR : Top Soil Removal*

(Mathilde Sandron, 2025)

### 4.2 Gas flow measurements

Picarro Inc. model G2508 (figure 11) is the analytical gas model used to estimate the concentration of greenhouse gases ($CO_2$, $N_2O$, and $CH_4$) in ppb or ppm. Through the tubing system, an airflow was established between the measurement chamber and the gas analyzer using a pumping system (figure 11). This system included two pumps that created a pressure and vacuum effect at the inlet and outlet of both the chamber and the analyzer. Additionally, the continuous airflow helped homogenize the gas composition inside the chamber, thus minimizing the risk of stratification.

Figure 11 : Gas analyzer, Picarro model G2508 with circular airflow system driven by pumps. Pump 1 creates a constant vacuum inside the analyzer for correct pressure inside the analyzer. Pump 2, has a vacuum and pressure outlet, creating the airflow circulation in the system.

(Source : Ecoscience Department, 2025)

## C. Data analysis

### 1. Greenhouses Gas analysis

In this report, for the analysis of GHG fluxes, data from **one month per season** will be considered, except for summer, where measurements were taken manually over three months due to technical issues. During this period, GHG fluxes were measured using another manual chamber connected to the Skyline gas analyzer. Fluxes were recorded for 5 minutes, with a 1-minute break between each plot. One set of measurements was taken per week, over 8 weeks in June, July, and August.
The processing of greenhouse gas data ($CO_2$, $CH_4$, and $N_2O$) was carried out using the **R programming language in RStudio** (Annex 1).

The **code** is composed of **3 parts**, the first being designed to produce an **interactive graph**. This graph allows the determination of the actual start time of each flux measurement. Indeed, although each measurement is programmed at regular intervals, environmental and technical conditions can cause delays of several tens of seconds. The actual start times determined are manually recorded in an auxiliary file, which will be used in the second part of the code. In the case where a cycle overlaps two days, it will be counted on the day it started.

The **data analysis** is performed day by day with the GoFlux package (Rheault et al., 2024), which is used for the second part of the code. This second part of the code can be summarized in **7 sub-steps** :

1. The first step consists of loading the raw data.
2. Then, the study period is selected (it is necessary to specify the month of study as well as the start time of the first measurement of the day being processed).
3. Third, the auxiliary file is used to account for the actual start times of each measurement. Other data are also required to calculate GHG fluxes, such as the temperature in the Vejrumbro. This temperature is recorded every half hour. Since GHG measurements are taken at a smaller timescale, the temperature is estimated by interpolation between each measurement.
4. With these data, flux identification can be performed using the “autoID” function from the GoFlux package. This function links the identified measurement cycles to the correct data segments. To do so, key parameters were defined: an observation duration (obs.length) of 300 seconds, and dead times to be ignored at the beginning and end of each cycle (dead band = 60s and crop.end = 70s).
5. Then the “goFlux” function is used to create the fluxes for each gas, followed by the “best.flux” function from the package to determine the best flux model.

To use the **“goFlux” function**, the data frame must contain information specific to the chamber used, such as its volume, pressure, soil surface area inside the chamber, and chamber temperature (Rheault et al., 2024). In the experiment, the total internal volume involved in the gas measurement comprising the chamber, the connecting tubes, the vertical gap between the soil surface and the chamber, and the gas analyzer was estimated at 0.0116 $m^3$. Measurements were conducted under standard pressure conditions : 1 atm, and the chamber's base surface area was 0.0283 $m^2$.

The gas flux is determined using the following **equation** :

$$Flux = \frac{\Delta C}{\Delta t} * \frac{P * M}{R * T} * \frac{V}{A}$$

*Flux : diffusive flux (g C $m^{-2}$, $day^{-1}$)*
*$\Delta C/\Delta t$ : change in concentration per time unit (ppm/ppb)*
*P : atmospheric pressure (Pa)*
*R : gas constant (Pa $m^3$ $mol^{-1}$ $K^{-1}$)*
*T : temperature (K)*
*M : molar mass of Carbon (g $mol^{-1}$)*
*V : volume of the chamber ($m^3$)*
*A : area ($m^2$) of the chamber*

**The “Best Flux” function** allows estimating the best flux for each measurement. To estimate the best flux, either a linear or a non-linear model can be applied. The choice between the two relies on the ratio between the non-linear and linear models, also known as the g-factor. When this ratio exceeds a value of 2, the linear model is preferred. This approach helps avoid overestimating fluxes, which can sometimes be artificially increased by the presence of gas bubbles.

Additional precautions were taken, particularly for estimating methane fluxes. Specifically, two extra criteria were implemented in the code to reduce the likelihood of including ebullition events in the dataset. The first condition required that only flux measurements with a coefficient of determination ($r^2$) greater than 0.9 were kept, ensuring high confidence in the linear fit. The second condition excluded values exceeding a threshold of 1000 nmol $m^{-2}$ $s^{-1}$, in order to filter out unrealistically high fluxes. Indeed, the second condition helps remove ebullition events, even if they have a high $r^2$ value.

6. Finally, flux plots are generated for each gas and each measurement. The graph also indicates which model was selected by the “best.flux” function. In total, about 125 plots per day and per gas are produced, except for the summer period.
7. A phase of checking and correction is carried out based on the produced graphs. It is important to review each graph produced daily to readjust the start time if necessary. Moreover, a quality check is performed when the linear and non-linear models differ significantly and the selected model appears to under- or overestimate the flux. Such data must be excluded.

The third and final part of the code consists of **creating graphs** to visualize the evolution of the flux of each gas over time. Given the large amount of data produced, the best flux values selected by the model are averaged daily by SKY, with standard error accounted for across the different plots of measurements.

## 2. Moisture, temperature and electrical conductivity analysis and statistics

The data were processed using the R programming language in RStudio. First, graphs were created to compare soil moisture, conductivity, and temperature between the two treatments over time. These parameters were related to precipitation measured at Foulum, which is an automatic climate station, over the study period. Then, Wilcoxon tests with paired samples were performed on the data to determine whether there was a significant difference in moisture, temperature, and conductivity between the two treatments.

## 3. Soil characteristics analysis and statistics

The results obtained in this category were processed using Excel software and Rstudio.
As the five replicates cannot be compared directly with each other, the mean values will best reflect any potential differences in the soil characteristics between amended and non-amended soil. The test will always compare 10 independent (non-paired) samples, so two main tests will be used : the Wilcoxon test and the Student’s t-test.
Student's t-test for independent samples is applied when the samples are normally distributed according to the Shapiro-Will test. If the normality assumption is not met, the significant difference is tested using the Wilcoxon rank-sum test for independent samples.

# III. Results and discussion

## A. Result

### 1. Soil characteristics result

The quantitative results will be presented as follows: mean ± standard error, to estimate the variation around the mean and provide an initial indication of the differences between the two treatments.

**1.1 Organic matter content and dry bulk density results**

In April 2024, measurements of the organic matter content indicated that the SKY2 treatment with topsoil contained approximately twice as much organic matter as the SKY1 treatment without topsoil, with average values of **3.97% ± 0.19%** and **1.93% ± 0.06%**, respectively. Similarly, analyses conducted in July confirmed this trend. The treatment with added topsoil exhibited an average organic matter content of **5.12% ±0.29%** of DM, which was higher than the treatment without topsoil : **2.20% ±0.02%** dry matter. The Wilcoxon test shows a significant difference in OM content between the two treatments in April and July (Annex 9).
According to the Wilcoxon test for independent samples, significant differences in dry bulk density were observed between the two treatments in the July analysis (Annex 9). The average dry bulk density was found to be **1.30 ± 0.03 g/cm³** for SKY2 with topsoil, compared to **1.14 ± 0.01 g/cm³** for SKY1 without topsoil.

**1.2 P-fractions and metals results**

Despite the quantitative analysis showing that the non-amended treatment contained less total phosphorus **(SKY1: 545 ± 21 mg/g of DM)** than the amended treatment **(SKY2: 598 ± 14 mg/g of DM),** the statistical tests did not show any significant difference (Annex 9).
Regarding the distribution of phosphorus among the different fractions, only BD-P differs significantly between SKY1 and SKY2. The BD-P fraction, which corresponds to redox-sensitive phosphorus bound to iron, was twice as high in the amended soil (**SKY2: 3.7 ± 0.29 %**) as in the soil without topsoil (**SKY1: 2.2 ± 0.16 %**).

Despite the residual phosphorus fraction being slightly higher in SKY1 **(73.6 ± 1.13%)** than in SKY2 **(70.7 ± 2.71 %)**, the Student's t-test revealed no statistically significant differences for this fraction, nor for the KCl-P and HCl-P fractions (Annex 2 ; Annex 9).

There was **no significant difference** in calcium, aluminum and iron concentrations between treatments, although the topsoil-amended treatment exhibited slightly higher mean values for all three metals (Annex 3 ; Annex 9).

**1.3 Dissolved organic matter**

At the topsoil-amended treatment, the average concentration of dissolved organic carbon was substantially higher (Annex 9) than at the non-amended treatment in April **(SKY1: 0.03 ± 0.0009 mg/g of DM ; SKY2: 0.06 ± 0.008 mg/g of DM)** and in July **(SKY1: 0.018 ± 0.001 mg/g of DM ; SKY2: 0.02 ± 0.002 mg/g of DM)**. However, the difference in dissolved organic carbon concentration between SKY1 and SKY2 is **less pronounced in 2025**, decreasing from an 86% difference in April to a 24% difference in July (with SKY1 as the reference), so that **the difference which was statistically significant in April is no longer significant in July.**

In April 2024, of the six DOC fractions (%) analyzed, two differed significantly between SKY2 and SKY1, while four showed no significant change (Annex 4 ; Annex 9). Notably, the biopolymer fraction more than tripled from 4% to 13% in SKY2, and the humic substance fraction fell from 61% in SKY2 to 47% in SKY1. In contrast, the proportions of hydrophobic organic carbon, building blocks, neutrals, and acids did not differ significantly between the two soil treatments (Annex 4 ; Annex 9).

In July 2025, the amended soil exhibited slightly higher concentrations of hydrophobic organic carbon and biopolymers, while the unamended soil showed higher levels of humic substances and neutral compounds (Annex 5). However, the distribution of the fractions (%) showed no statistically significant differences between the two soil types (Annex 9). No acidic fractions were detected in either treatment.

### 1.4 Carbon and Nitrogen content measurement

Statistical results show that both carbon and nitrogen contents are significantly higher at SKY2 compared to SKY1, with approximately twice as much C in SKY2 (Annex 6 ; Annex 9).
Additionally, the C/N mass ratio was also significantly higher at **SKY2 (~12)** than at **SKY1 (~9)**.

### 1.5 Harvesting results

It appears that the average dry biomass of the amended treatment is higher than that of the non-amended treatment, but the difference is not statistically significant according to the test performed between the replicates (Annex 9). The average dry mass of the treatment with topsoil is approximately twice that of the treatment without topsoil (**SKY2 : 859 ± 85 g/m² VS. SKY1 : 415 ± 123 g/m²; Figure 12**).

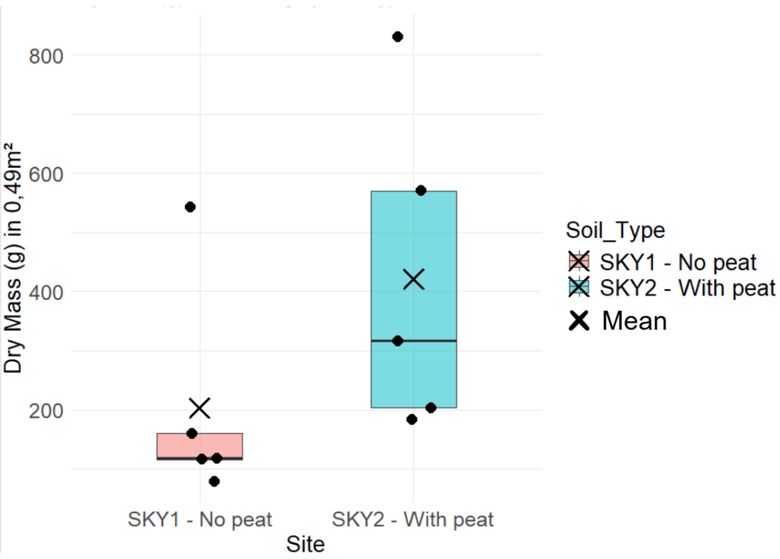


Figure 12 : Fertility results in SKY1 and SKY2 in July 2025

## 2. Moisture, temperature and electrical conductivity result

To present the results of the collected data, they were compiled into three graphics, one for each parameter. To compare the moisture, temperature, and electrical conductivity profiles over time between SKY1 and SKY2, we used daily averages. Indeed, there are five measurement points per Sky that record data for these parameters every 20 minutes. The data recorded by the five measurement points were therefore averaged to obtain a single value per Sky, per parameter, and per day (figure 12).

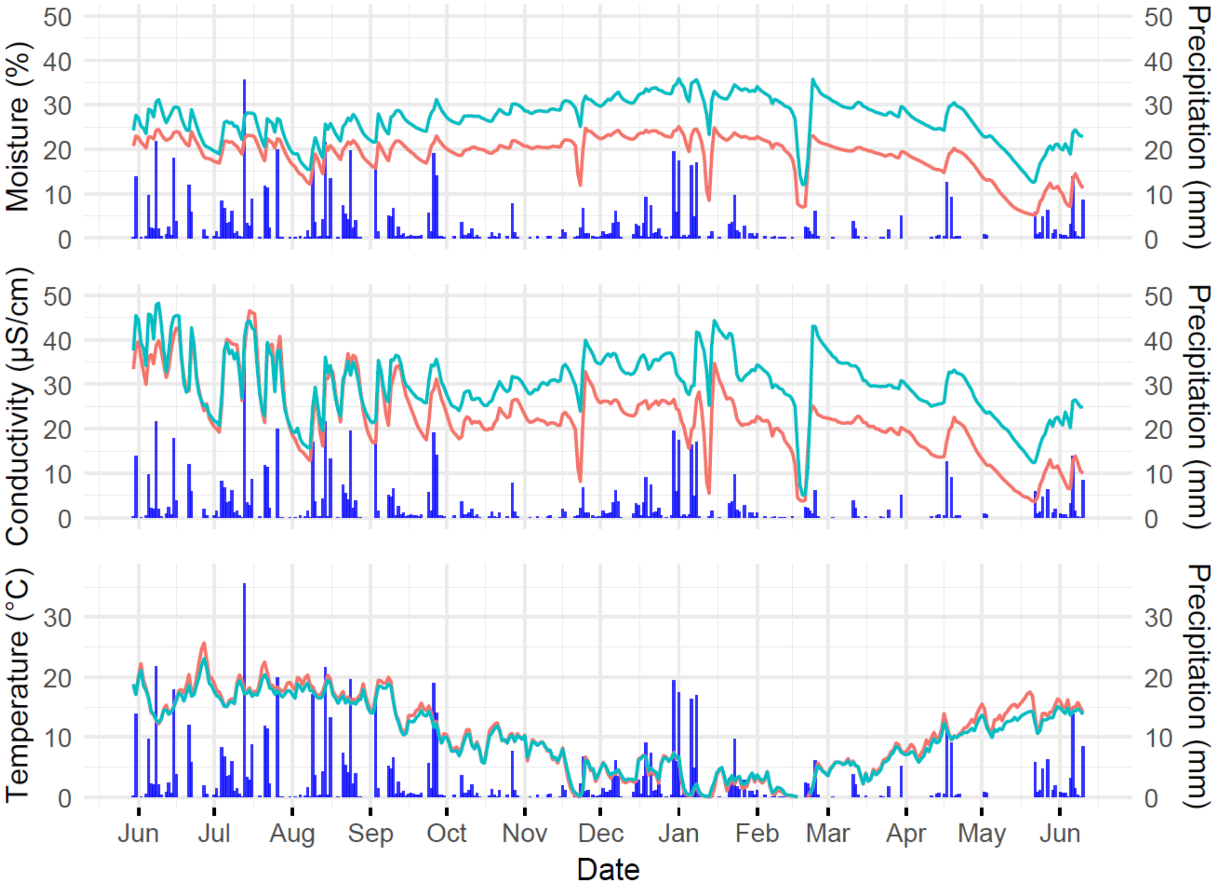


Figure 13 : Daily mean moisture, conductivity and temperature per SKY and daily precipitation over time

**Moisture :** The treatment with topsoil (SKY2) is on average **7.8 %** more humid than the treatment without (SKY1), with a **maximum** difference of up to **17%** and a **minimum of 2%** more humidity over the study period.

SKY1 is never more humid than SKY2 during the period analyzed (figure 12). The difference in moisture between the two treatments appears to increase over time (Annex 2). The statistical Wilcoxon test for paired samples shows a significant difference in moisture content between soils without peat and with peat (Annex 9). The variation in moisture within SKY1 seems to be greater than in SKY2 (Annex 1).

**Electrical conductivity** : As conductivity is related to moisture, there is also a difference between SKY1 and SKY2 (Figure 12). As the amended soil is wetter, its conductivity is higher than that of non-amended soil, a difference that has become more pronounced since mid-September 2024. A Wilcoxon test confirms that there is a significant difference in conductivity between SKY1 and SKY2 (Annex 9).

**Temperature :** At first view, it seems that the temperature difference between the two treatments is not very important, especially during winter, and appears slightly larger in summer (Figure 12). The Wilcoxon test shows a significant difference between temperature evolution in the two treatments for the study period (Annex 9). The treatment without topsoil is generally warmer than the one with topsoil , by approximately 0.42°C.

## 3. GHG fluxes results

For the SKY under study, which are predominantly mineral in nature compared to other SKY treatments, greenhouse gas fluxes between June 2024 and May 2025 were relatively low (figures 14, 15, 16, 17).

- **Carbon dioxide** fluxes ranged from **–2.45 to 7.20 $\mu mol \cdot m^{-2} \cdot s^{-1}$**. The largest $CO_2$ flux amplitude was observed in **summer**, while the smallest was recorded in **winter**.
- **Methane** fluxes varied from **–5.88 to 19.8 $nmol \cdot m^{-2} \cdot s^{-1}$**. The greatest amplitude of $CH_4$ fluxes was also observed in **summer** and the smallest in **spring**.
- **Nitrous oxide** fluxes ranged from **−3.93 to 3.51 $nmol \cdot m^{-2} \cdot s^{-1}$** during the study period. The largest amplitude of $N_2O$ fluxes occurred in **autumn** and the smallest in **spring**.

### 3.1 Summer fluxes

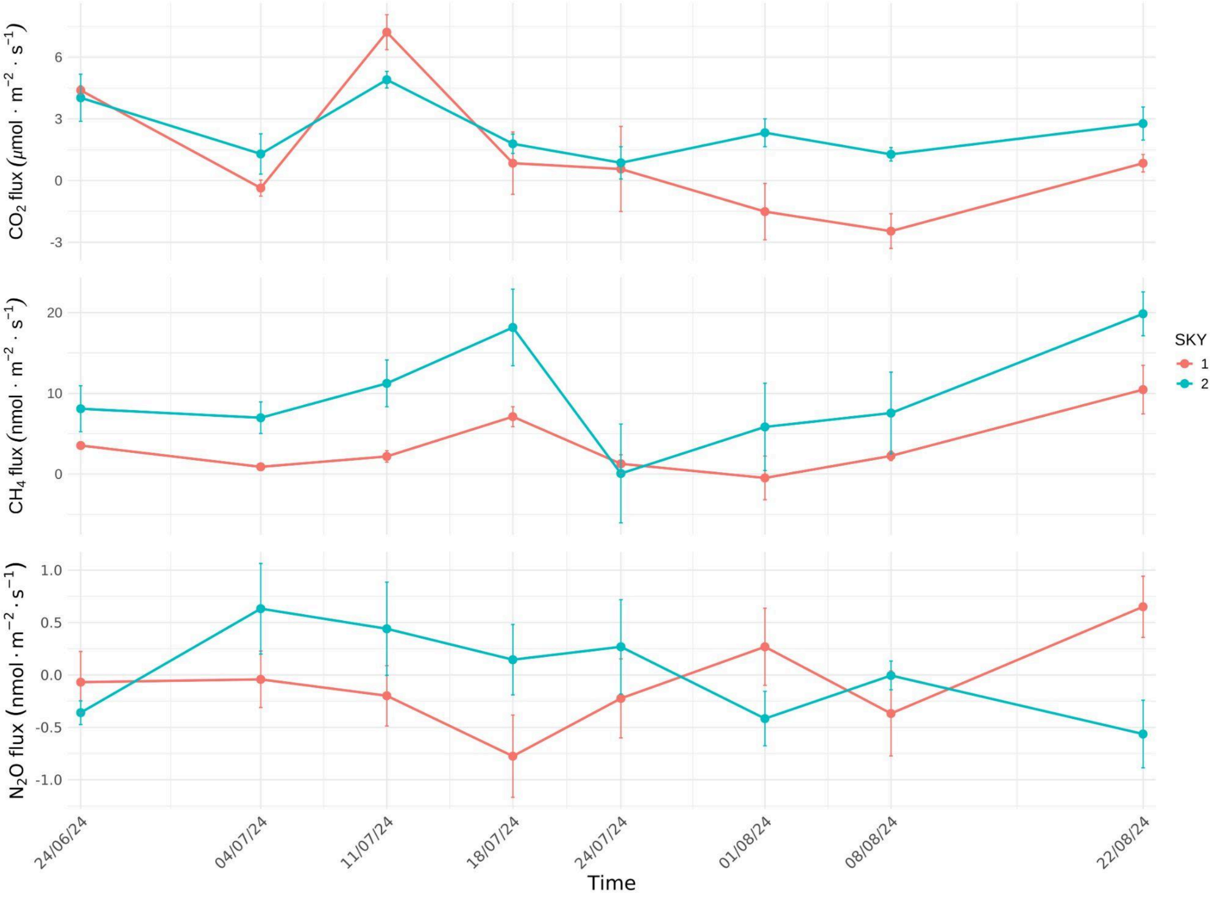


Figure 14 : Daily means CO2, N2O and CH4 fluxes for SKY1 and SKY2 representing the summer period

During the summer period (June to August 2024), daily average fluxes of $CO_2$, $CH_4$, and $N_2O$ were measured under the non-amended treatment (SKY1) in red and the amended treatment (SKY2) in blue (figure 14).

- $CO_2$ fluxes varied from –2.45 to 7.20 $\mu mol.m^{-2}. s^{-1}$, with average higher values recorded under SKY2. For SKY2, $CO_2$ fluxes remained relatively stable throughout the summer, whereas a decreasing trend was observed for SKY1.
- $CH_4$ fluxes ranged between –0.40 and 19.8 $nmol.m^{-2}.s^{-1}$, again showing elevated fluxes under SKY2. For both SKY1 and SKY2, $CH_4$ fluxes increased between the beginning and the end of the summer.

- $N_2O$ fluxes were more variable, spanning –0.77 to 0.65 $nmol.m^{-2}.s^{-1}$, with no treatment exhibiting consistently higher fluxes than the other.

According to the statistical test, only the methane fluxes show a significant difference between SKY1 and SKY2 in summer (Annex 9).

### 3.2 Autumn fluxes

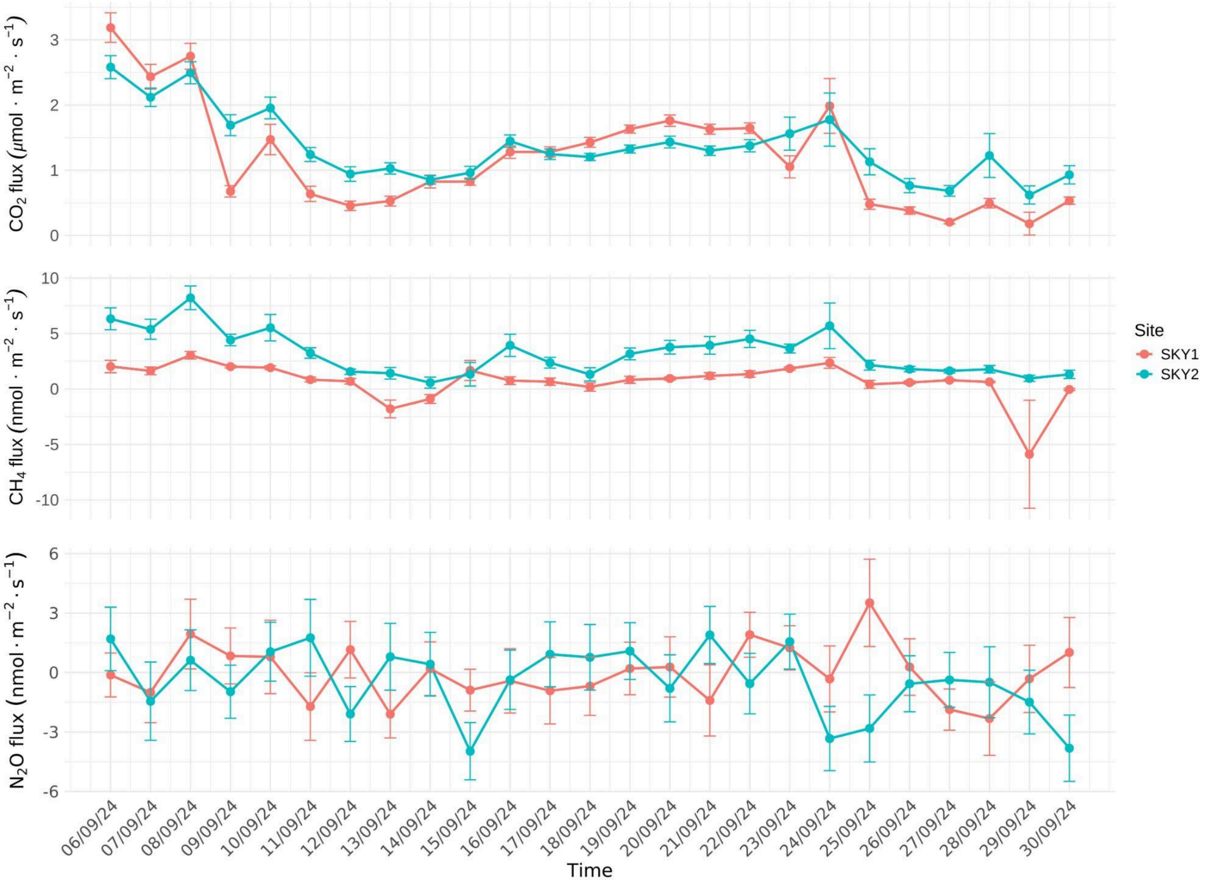


Figure 15 : Daily means CO2, N2O and CH4 fluxes for SKY1 and SKY2 representing the autumn period

During the autumn period (September 2025), the daily average fluxes of $CO_2$, $CH_4$ and $N_2O$ were measured at the non-amended treatment (SKY 1) in red and the amended treatment (SKY 2) in blue. There are missing values at the beginning of the month due to technical issues, from February 1st to February 6th (figure 15).

- $CO_2$ fluxes ranged from 0.18 to 3.18 $\mu mol \cdot m^{-2} \cdot s^{-1}$. SKY1 and SKY2 appeared to follow a similar temporal pattern throughout September. For both SKY1 and SKY2, $CO_2$ fluxes appeared to decrease over the month of September.
- $CH_4$ fluxes varied between –5.88 and 8.21 $nmol \cdot m^{-2} \cdot s^{-1}$. The amended treatment consistently exhibited higher $CH_4$ fluxes than the non-amended treatment. A notable negative peak was observed on SKY1 at the end of the month. For both treatments, $CH_4$ fluxes appeared relatively stable, showing a slight decrease at the end of the month.
- $N_2O$ fluxes ranged from –3.96 to 3.51 $nmol \cdot m^{-2} \cdot s^{-1}$, with neither treatment consistently showing higher emissions than the other.

According to the statistical test, only the methane fluxes show a significant difference between SKY1 and SKY2 in autumn (Annex 9).

### 3.3 Winter fluxes

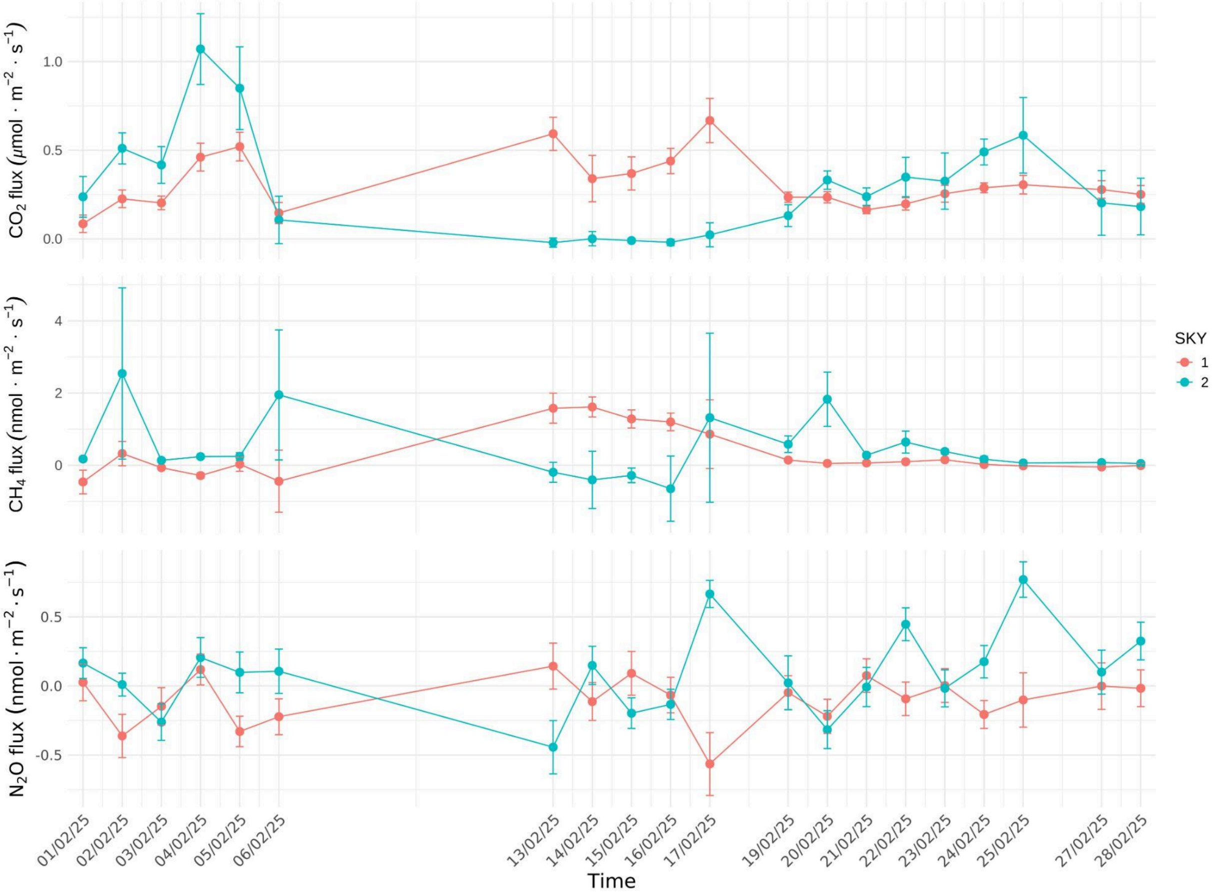


Figure 16 : Daily means CO2, N2O and CH4 fluxes for SKY1 and SKY2 representing the winter period

During the winter period (February 2025), the daily average fluxes of $CO_2$, $CH_4$ and $N_2O$ were measured at the non-amended treatment (SKY 1, red) and the amended treatment (SKY 2, blue). There are missing values due to technical issues between February 6th and February 13th, as well as on February 26th (figure 16).

- $CO_2$ fluxes varied from –0.02 to 1.07 µmol m$^{-2}$ s$^{-1}$, with higher values recorded at SKY2, particularly at the start of the month. $CO_2$ fluxes remained relatively stable throughout the month for both treatment.
- $CH_4$ fluxes ranged from –0.64 to 2.54 nmol.m$^{-2}$.s$^{-1}$. $CH_4$ fluxes remained relatively stable throughout the February month for both treatment.
- $N_2O$ fluxes varied from –0.56 to 0.76 nmol.m$^{-2}$.s$^{-1}$. At the end of the month, SKY2 showed higher $N_2O$ peaks than SKY1, suggesting a slight increase in fluxes. In contrast, $N_2O$ fluxes at SKY1 appeared to remain stable between the beginning and the end of February.

According to the statistical test, only the nitrous oxide fluxes show a significant difference between SKY1 and SKY2 in winter (Annex 9).

### 3.4 Spring fluxes

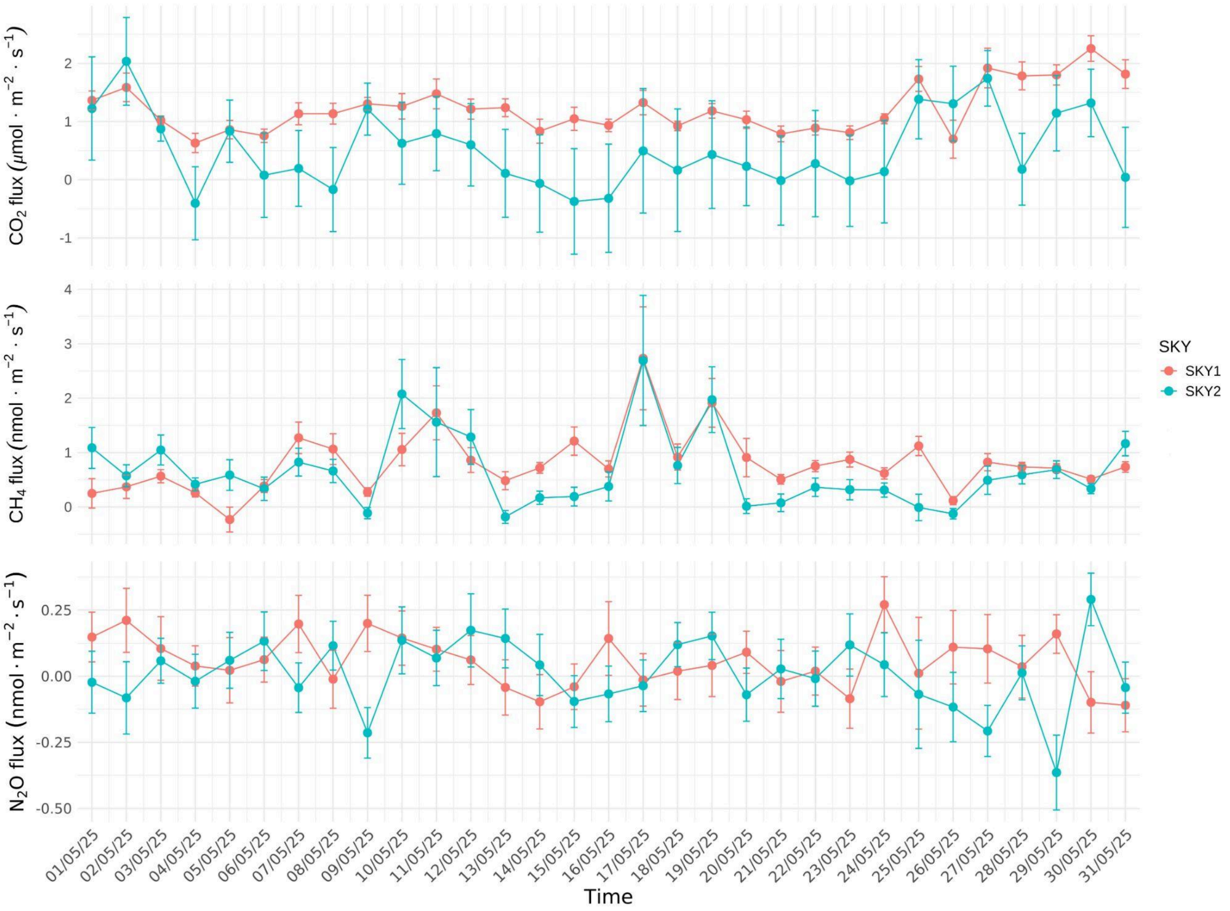


Figure 17 : Daily means CO2, N2O and CH4 fluxes for SKY1 and SKY2 representing the spring period

During the spring period (May 2025), the daily average fluxes of $CO_2$, $CH_4$ and $N_2O$ were measured at the non-amended treatment (SKY1) in red and the amended treatment (SKY2) in blue (figure 17).

- $CO_2$ fluxes appears generally higher at the SKY1 treatment, with values ranging from -0.4 to 2.25 $\mu mol.m^{-2}.s^{-1}$. For SKY1, $CO_2$ fluxes appeared to increase between the beginning and the end of the month.
- $CH_4$ fluxes ranges from -0.23 to 2.73 $nmol.m^{-2}.s^{-1}$. For both SKY treatments, methane fluxes showed a slight increase over the month.
- $N_2O$ fluxes varies between -0.36 and 0.29 $nmol.m^{-2}.s^{-1}$. $N_2O$ fluxes are quite variable, with no treatment exhibiting consistently higher fluxes than the other.

According to the statistical test, only the $CO_2$ fluxes show a significant difference between SKY1 and SKY2 in spring (Annex 9).

### 3.5 Inter-seasonal results

During summer 2024, $CO_2$ fluxes are observed to be higher at the amended treatment than at the non-amended treatment. During the spring 2025, however, this trend appears to reverse, with the non-amended treatment showing higher $CO_2$ emissions than the amended treatment. No distinct dynamics differentiating SKY1 and SKY2 were observed in autumn or winter.

For $CH_4$, fluxes are mostly higher at the peat-amended treatment during summer, autumn and winter, although the differences are slight in February.
Throughout the study period, no notable dynamic differences were observed between the two treatments for $N_2O$, except that the difference between the two treatments was significant for the winter period.

## B. Discussion

### 1. Soil characteristics discussion

Amending the mineral soil at the SKY2 treatment by adding 20% degraded peat resulted in notable changes to its composition and physical properties. As expected, the amended soil showed a significant increase in total organic carbon content, reflecting the organic nature of the added peat. In addition to higher carbon levels, the amended treatment exhibited greater total nitrogen concentrations.
However, the lower C/N ratio observed at the non-amended treatment suggests that the unamended soil has higher nitrogen bioavailability. This is because a higher C/N ratio means that soil microorganisms need more carbon to access a given amount of nitrogen, potentially limiting nitrogen accessibility in the amended soil. Nevertheless, both treatments maintained a C/N ratio of between 1 and 15, typically associated with rapid mineralization and enhanced organic matter availability (Brust, 2019).

Phosphorus content and potential mobilization were also affected by the addition of topsoil. The increased concentration of phosphorus sensitive to redox conditions observed in the amended soil is consistent with the addition of degraded peat, which typically contains higher levels of this fraction (Zak et al., 2008). Although this form of phosphorus is generally stable under oxic conditions, it may be mobilized under anaerobic conditions, such as those induced by water saturation. While this process was not directly measured in the present study, the results suggest that the amended soil could release phosphorus more easily under wet conditions, which may influence nutrient dynamics and availability.

The peat amendment also influenced the quantity and chemical nature of dissolved organic carbon present in the soil solution 1 year after the beginning of the experiment. The amended soil was enriched in high molecular weight organic carbon fractions, particularly those composed of humic compounds and large biopolymer molecules. The increase in biopolymers expands the pool of substrates readily utilized by soil microorganisms. Although differences in fraction percentages were less pronounced in the most recent results, this study may suggest that peat amendment not only alters the quantity of DOC but also its quality, potentially influencing microbial activity and carbon cycling dynamics in the soil.

On the physical side, the higher dry bulk density in the amended treatment suggests that incorporating topsoil modified the soil’s structure and texture. While higher density resulting from soil compaction typically reduces water retention, nutrient availability, and root penetration (USDA & NRCS, 2019), our results suggest the opposite. In this case, the increased dry bulk density reflects a greater proportion of organic matter, which enhanced the soil’s water-holding capacity and nutrient content.

Finally, the dry aboveground plant biomass collected in July 2025, more than one year after the beginning of the experiment, serves as an effective indicator of soil fertility, since both treatments experienced the same climatic conditions. The greater average biomass production observed at the amended treatment indicates that, despite possible limitations in nitrogen availability due to a higher C/N ratio, the overall fertility of the peat-amended soil was higher than that of the unamended control.

Taken together, these results can demonstrate that the addition of degraded peat to a mineral agricultural soil alters its composition and functioning on multiple levels. The amendment affects nutrient content, the molecular composition of organic matter, microbial substrate availability, soil physical structure, and overall fertility.

## 2. Monitoring data discussion

The addition of topsoil appears to affect the structural properties of agricultural mineral soil. As the amended treatment is wetter, it can be assumed that the addition of peat has improved the soil's ability to retain water. Consequently, the **increased moisture** may lead to reduced temperature fluctuations. Indeed, although the difference is small, the soil temperature variation at the amended treatment is slightly lower than at the non-amended treatment. This small difference in temperature could also be explained by a **shading effect** : since there is more plant cover at the amended treatment, increased shading helps keep the soil cooler.

Regarding the variation in moisture and conductivity (Annex 1), the variation in values at SKY2 is greater than at SKY1. This may be due to several factors. One possibility is that the sandbox is slightly tilted, resulting in wetter conditions in the southern plots than in the northern ones. Another possibility is that the water table has a dome-shaped profile, leading to higher moisture levels in the central plots than at the edges. However, even though the mineral soil and added topsoil were thoroughly mixed sufficiently, at least, to avoid biasing the soil moisture sensors, aggregates of degraded peat may still be present.

## 3. GHG fluxes discussion

Seasonal effects were clearly observed in greenhouse gas fluxes, likely linked to plant development as well as changes in soil composition and structure. At the start of the experiment in summer 2024, when there was little vegetation present, it is not surprising to see lower soil respiration in both treatments. However, by spring 2025, soil $CO_2$ fluxes in the peat‑amended treatment were lower than those in the unamended control. The cumulative $CO_2$ fluxes graph for the two treatments (Annex 10) shows that the non-amended soil is a greater source of $CO_2$ than the amended soil. This difference may also reflect greater carbon dioxide uptake by the denser plant cover in the amended treatment, a hypothesis supported by the higher harvest biomass recorded in.

Methane ($CH_4$) and nitrous oxide ($N_2O$) fluxes remained very low throughout the year, which is consistent with the drained, oxygenated soil conditions in the experimental setup, creating an environment that disfavors production of both gases.
The slightly higher $CH_4$ fluxes measured in the amended soil may be explained by incomplete mixing of the degraded peat, resulting in localized peat-rich zones that retain more moisture and foster anaerobic microsites favorable to methane production, particularly during summer, autumn, and to a lesser extent, winter.
Moreover, the highest $CH_4$ fluxes coincided with the warmest period of the year. This observation aligns with broader evidence indicating that methane emissions increase strongly with temperature. Some meta‑analyses have shown that seasonal methane flux variations follow a temperature dependence (Yvon-Durocher et al., 2014). Given this relationship, it is plausible that global warming may increase methane emissions from amended soils containing degraded peat, particularly when the organic matter is unevenly incorporated into the mineral soil, as this configuration may promote the formation of localized anaerobic microsites. In addition, the methylotrophic pathway, which produces methane under oxic conditions, could also be relevant in this context.

Regarding nitrous oxide, there was no marked temporal dynamic observed, likely due to the well-drained, aerobic soil conditions that limits denitrification and $N_2O$ production.

### 4. Discussion of the study’s limitations

This study has some limitations that may affect the results and conclusions. Firstly, the greenhouse gas (GHG) measurement and calculation code was not fully reproducible, since the start time of each measurement had to be manually and subjectively adjusted by the observer. Furthermore, the code occasionally produced curves that did not fit the expected model well, necessitating further review and manual correction.

It is also important to acknowledge that both greenhouse gas fluxes and soil property results obtained are a part of an evolving, dynamic system. It is unlikely that the amended and unamended soils have reached a new equilibrium within just one or two years of monitoring. Likewise, it takes time for ecosystems to respond to changes such as peat amendment, particularly with regard to biogeochemical processes, microbial activity, and gas exchange. Consequently, the results presented here may reflect a transitional phase rather than a steady state. The observed patterns, particularly with regard to greenhouse gas fluxes, may be affected by short-term disturbances and the initial adjustments of the soil following the amendment, rather than the long-term functioning of the system.

Results of this study should be interpreted with caution. To fully understand the long-term effects of peat amendment on soil processes and greenhouse gas emissions, the monitoring period must be extended to several years. Only through long term observation can the system's trajectory towards a new equilibrium be accurately assessed and its full impact understood.

# IV. Conclusion

In conclusion, the results largely support the hypothesis that incorporating degraded peat as topsoil into mineral soils enhances water retention and stimulates plant productivity.

The amended plots showed a marked increase in soil organic matter, carbon, and nitrogen contents compared to the unamended control. Total phosphorus also rose, and its distribution across extractable fractions shifted significantly. Dissolved organic carbon concentrations and molecular composition differed between treatments, indicating changes in DOM quality and potential substrate availability for soil microbes.
However, the only result that does not align with this pattern is the elevated C/N ratio in the amended plots, which suggests reduced nitrogen bioavailability for plants, which is a critical nutrient for growth.
Structurally, the peat amended soil exhibited higher dry bulk density alongside an improved water-holding capacity, addressing the inherent drainage and low moisture retention of sandy Danish soils.

Most notably, aboveground average biomass harvested in July 2025 was approximately twice as high in the amended plots, demonstrating a clear increase in soil fertility. This finding confirms that the compositional and structural changes induced by degraded peat amendment translate directly into greater plant growth. Concerning the carbon footprint, the $CO_2$ fluxes measured during the first three months did not show major differences between the two treatments. However, in the last month of analysis (spring), which represents the most recent and thus more stable ecosystem, a clear difference was observed between the two treatments : the amended soil exhibited lower $CO_2$ fluxes than the non-amended soil. This suggests that the carbon footprint of this topsoil reuse technique can be considered acceptable, or even lower than that of a soil without added degraded peat.

This study suggest that reusing removed peat topsoil as a soil amendment is an effective way to improve water retention and crop productivity in sandy, mineral soils. Future work should involve extended monitoring over multiple years and evaluation of different amendment rates in order to determine the long-term stability of these benefits and assess any associated impacts on greenhouse gas emissions and nutrient leaching.

# V. Reflective feedback on the experience

During my research internship in Denmark, I participated in various stages of the research process, including field measurements, laboratory analyses, and data processing. This experience allowed me to deepen my understanding of wetlands and the challenges related to their restoration. It also helped me improve my skills in RStudio. This internship provided me invaluable experience collaborating with an international team and enhanced my English communication skills. Furthermore, it strengthened my technical expertise in data analysis, field protocols, and laboratory techniques. I also realized that maintaining strict scientific rigor in the field was challenging due to equipment limitations, unpredictable environmental conditions, and time constraints.

During this internship, I also had the opportunity, thanks to Gitte Blicher-Mathiesen, Head of Section and Ph.D. at the Department of Ecoscience, to contribute to the organization of the scientific conference *Land Use and Water Quality (LUWQ)*. This experience was both highly interesting and enriching.

In conclusion, this internship introduced me to the world of scientific research and made me realize that it is an area I am very interesting about.

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# Annexes

## Annex 1 : R code used for Greenhouse gas measurement and analysis

### *Example from the month of July 2024*

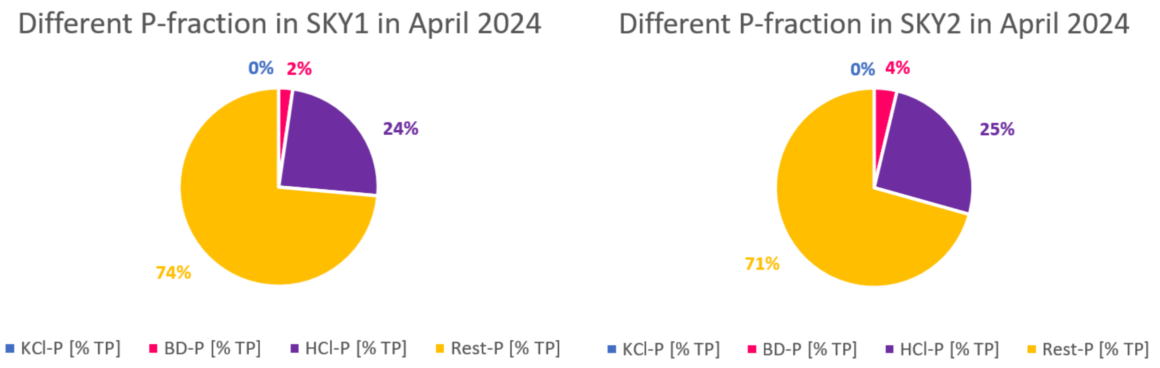
```
“ setwd("C:/Users/DELL/OneDrive - Université de Tours/Polytech TOURS/STAGE/STAGE DANEMARK/Rapport Aarhus/Rcode GHG/2024/07/P_jul_24")

if (!require("devtools", quietly = TRUE)) install.packages("devtools")
try(detach("package:goFlux", unload = TRUE), silent = TRUE)
devtools::install_github("Qepanna/goFlux")

# Install packages
install.packages("dplyr")
install.packages("purrr")
install.packages("readxl")
install.packages("openxlsx")
install.packages("plotly")
install.packages('tidyverse')
install.packages('writexl')
install.packages('goFlux')

# Load packages
library(tidyverse)
library(goFlux)
library(dplyr)
library(purrr)
library(readxl)
library(openxlsx)
library(stringr)
library(pbapply)
library(lubridate) # to set xlim for time
library(ggplot2)
library(plotly)
library(writexl)
library(readr)


################################ STEP1 : Creation of the interactive graphs  ##############################
file.path <- "raw_data/" #
import2RData(path = file.path, instrument = "G2508",
          date.format = "ymd", prec = c(0.24, 0.3, 5, 0.16, 500))

dat_files <- list.files(path = "RData", pattern = "imp.RData", full.names = TRUE) %>%
  map_df(~ get(load(.x)))

p <- ggplot(dat_files, aes(x = POSIX.time, y = CO2dry_ppm)) +
  geom_line() +
  labs(title = "Concentration de CO2_dry",
      x = "Heure",
      y = "CO2_dry (ppm)") +
  theme_minimal() +
  theme(legend.position = "none")
ggplotly(p)
```

```
##############################  STEP 2 : GHG measurement & analysis  ##############################

#____________________________  Step 2.1 :  Load all adjusted raw files ________________________________________
all.files <- list.files(path = "RData", pattern = "imp.RData", full.names = TRUE) %>%
  map_df(~ get(load(.x)))

#__________________________  Step 2.2  : Selection of the study period (month per month) ___________________________
monthly_sequence <- all.files %>% filter(POSIX.time > "2024-07-04 11:41:28" & POSIX.time < "2024-07-25 16:10:38")
# Identify start of first measurement
fig <- plot_ly(monthly_sequence, x = ~POSIX.time, y = ~CO2dry_ppm, type = 'scatter', mode = 'lines')

start_measure <- monthly_sequence %>% filter(POSIX.time > "2024-07-04 11:41:28")

#______  Step 2.3 : Using the auxiliary file for the good start time & import and interpolation of temperature data________

# Remember to set the date format in excel to dd.mm.yy.hh.mm.ss
auxfile <- read_csv2('auxfile/auxfile_CO2_04.csv')
auxfile <- subset(auxfile) # Removes the time interval data

# Create column with unique ID's
# auxfile <- auxfile %>% select(-13:-16)
auxfile_ID <- auxfile %>%
  group_by(Treatment) %>%
  dplyr::mutate(UniqueID = paste0(Treatment, "_", row_number()))

# Correct the date format from excel
auxfile <- auxfile_ID %>%

 # Use the function dmy_hms from lubridate package to convert into correct R dateformat
  mutate(start.time = dmy_hms(start.time))

auxfile <- auxfile %>%
  # Use the function as.POSIXct to convert start.time to a POSIXct format
  mutate(start.time = as.POSIXct(start.time, tz = "UTC"))

# Filter out rows with NA values
auxfile <- auxfile %>% filter(UniqueID != "_1")
auxfile <- na.omit(auxfile)

# Add temperature by interpolating from temperature file.
air_temp <- read.csv2("Air_temperature_Vejrumbro.csv")
air_temp <- air_temp %>%

# Use the function dmy_hms from lubridate package to convert into correct R dateformat
  mutate(time = dmy_hms(time))
air_temp <- air_temp %>%

# Use the function as.POSIXct to convert start.time to a POSIXct format
  mutate(time = as.POSIXct(time, tz = "UTC"))
air_temp <- subset(air_temp, select = c(time, temp_c))

# 1. Create an interpolation function from air_temp df
#    `rule = 2` means extrapolate if times in df_A are outside the range of df_B.
#    `rule = 1` means use the nearest value at the ends.
#    `rule = c(1, 2)` means nearest value for left extrapolation, linear for right.
#    `rule = c(2, 1)` means linear for left extrapolation, nearest value for right.
#    Consider if you want extrapolation or NA for points outside B's time range.
temp_interp <- approxfun(x = air_temp$time, y = air_temp$temp_c, rule = 2)
```

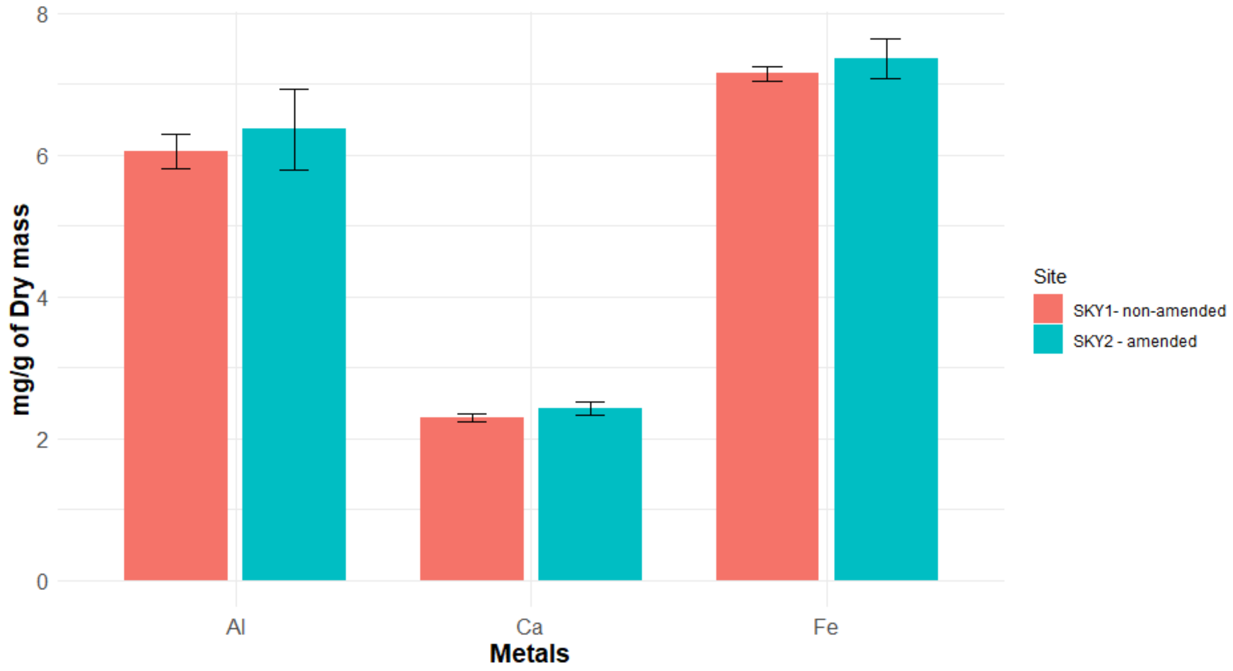
```
# 2. Apply the interpolation function to the timestamps in DataFrame A
auxfile$Inter_temp <- temp_interp(auxfile$start.time)

auxfile$Tcham <- auxfile$Inter_temp
auxfile <- subset(auxfile, select = -c(Inter_temp))

#________________________________________ Step 2.4 : Flux identification ________________________________________

# Use the autoID to identify the flux based on start.time for each measuring period in the AUXfile
autoID <- autoID(inputfile = start_measure, auxfile = auxfile, obs.length = 300, deadband = 60, crop.end = 70)
head(autoID)

#____________________________ Step 2.5 & Step 2.6 : Go flux and best flux function ____________________________

######################################## CO2 flux ####################################

# Run GoFlux and find the best flux
CO2_flux <- goFlux(autoID, "CO2dry_ppm")
CO2_best <- best.flux(CO2_flux, criteria = c("MAE", "AICc", "g.factor", "MDF",'r2'))

# Export flux data frame to folder
write.csv(CO2_best, 'results_CO2/jul_04_CO2.csv') # Change the date and only do 1 day at a time.

#### Quality check CO2 Flux plots ###
CO2_plots <- flux.plot(CO2_best, autoID, "CO2dry_ppm", shoulder=100,
              plot.legend = c("MAE", "RMSE", "AICc", "k.ratio", "g.factor"),
              plot.display = c("MDF", "prec", "nb.obs", "flux.term", 'SKYID'),
              quality.check = TRUE)

pdf(file='fluxplots_CO2/fluxplots_CO2_jul04.pdf') # Max print is limited to 1000, create sequences of more than 1000!!!
CO2_plots
dev.off()

######################################## CH4 flux ####################################

# Run GoFlux and find the best flux
CH4_flux <- goFlux(autoID, "CH4dry_ppb")
CH4_best <- best.flux(CH4_flux, criteria = c("MAE", "AICc", "g.factor", "MDF", 'r2'))

# Export fluxdataframe to folder
write.csv(CH4_best, 'results_CH4/jul_04_CH4.csv')

### Quality check CH4 Flux plots ###
CH4_plots <- flux.plot(CH4_best, autoID, "CH4dry_ppb", shoulder=20,
              plot.legend = c("MAE", "RMSE", "AICc", "k.ratio", "g.factor"),
              plot.display = c("MDF", "prec", "nb.obs", "flux.term"),
              quality.check = TRUE)

pdf(file='fluxplots_Ch4/fluxplots_Ch4_jul04.pdf')
CH4_plots
dev.off()

######################################## N20 flux ####################################

# Run GoFlux and find the best flux
N2O_flux <- goFlux(autoID, "N2Odry_ppb")
N2O_best <- best.flux(CH4_flux, criteria = c("MAE", "AICc", "g.factor", "MDF", 'r2'))
```

```
# Export flux data frame to folder
write.csv(N2O_best, 'results_N2O/jul_04_N2O.csv')

###Quality check N2O Flux plots ####
N2O_plots <- flux.plot(N2O_best, autoID, "N2Odry_ppb", shoulder=20,
                  plot.legend = c("MAE", "RMSE", "AICc", "k.ratio", "g.factor"),
                  plot.display = c("MDF", "prec", "nb.obs", "flux.term"),
                  quality.check = TRUE)

pdf(file='fluxplots_N2O/fluxplots_N2O_jul04.pdf')
N2O_plots
dev.off() ”
```

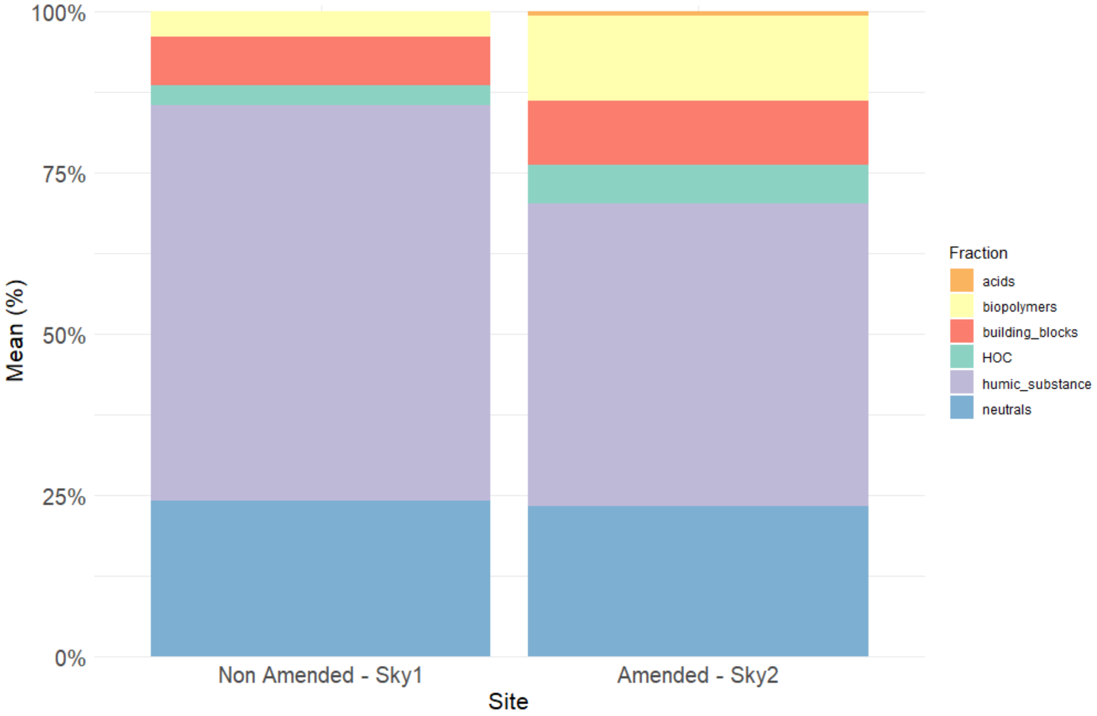
## Annex 2 : Different P-fraction in SKY1 and SKY2 in April 2024



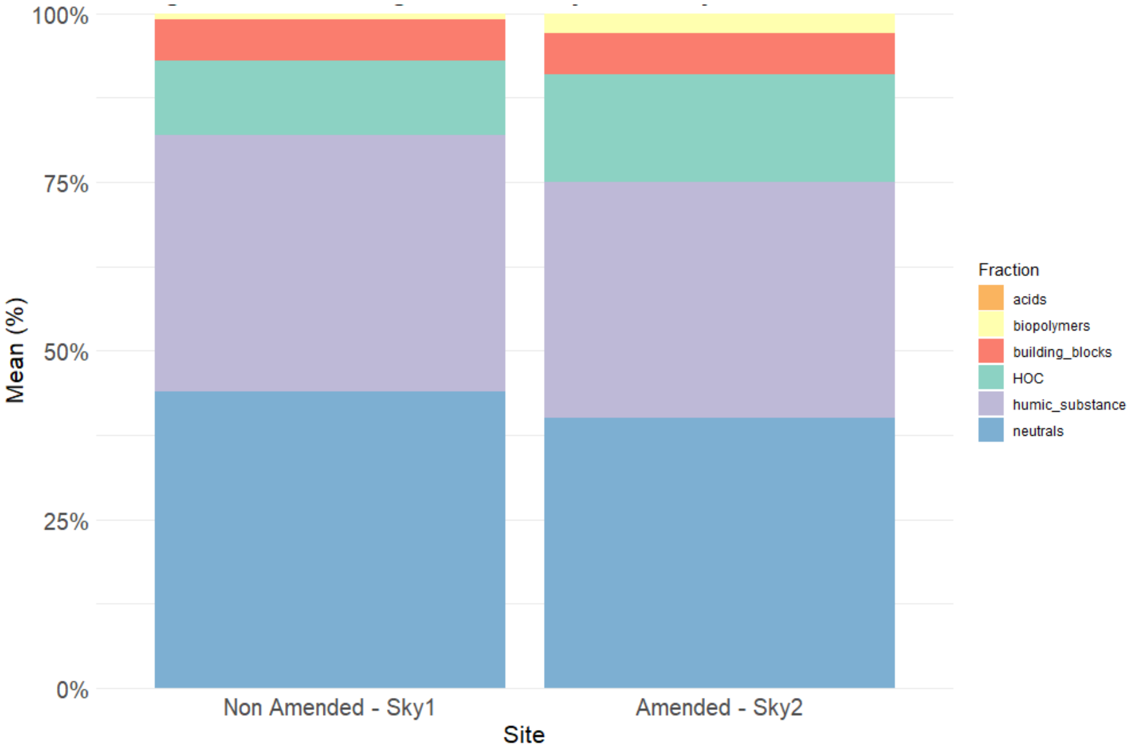
## Annex 3 : Average metal measurements in SKY1 and SKY2 in April 2024



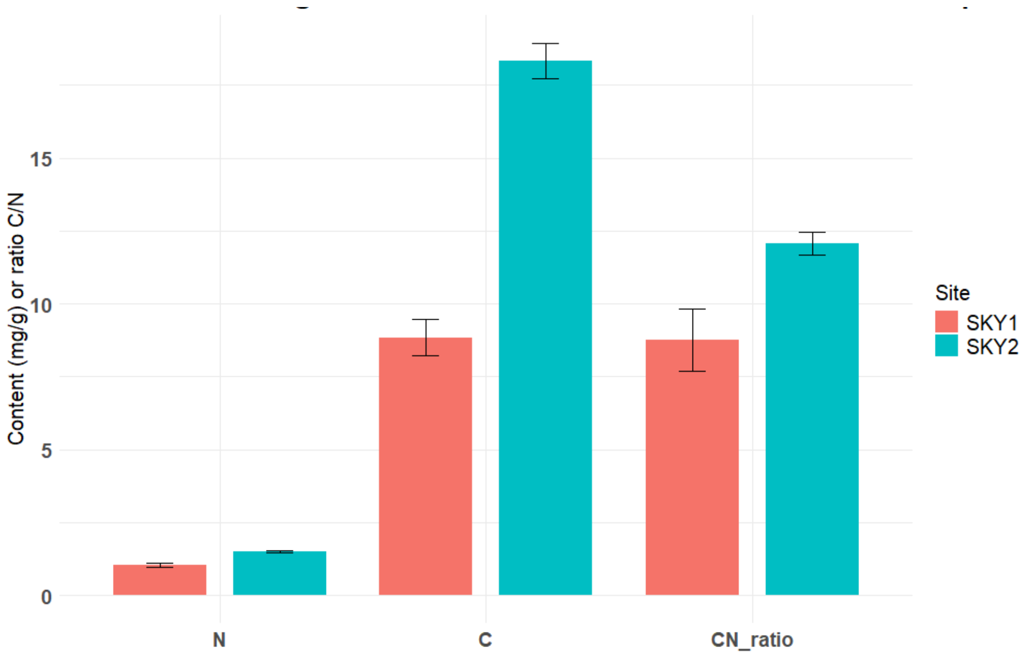
**Annex 4 : Average distribution of organic fraction by treatment in April 2024**



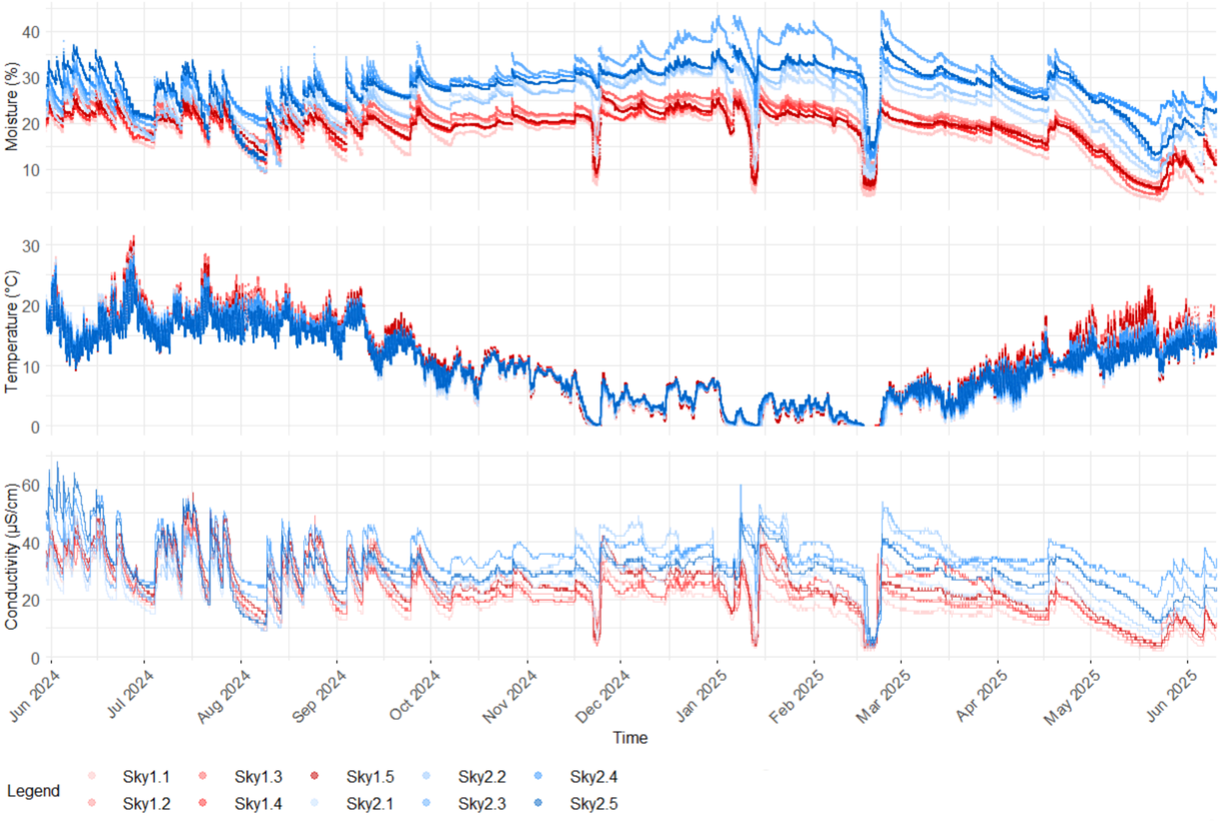
**Annex 5 : Average distribution of organic fraction by treatment in July 2025**



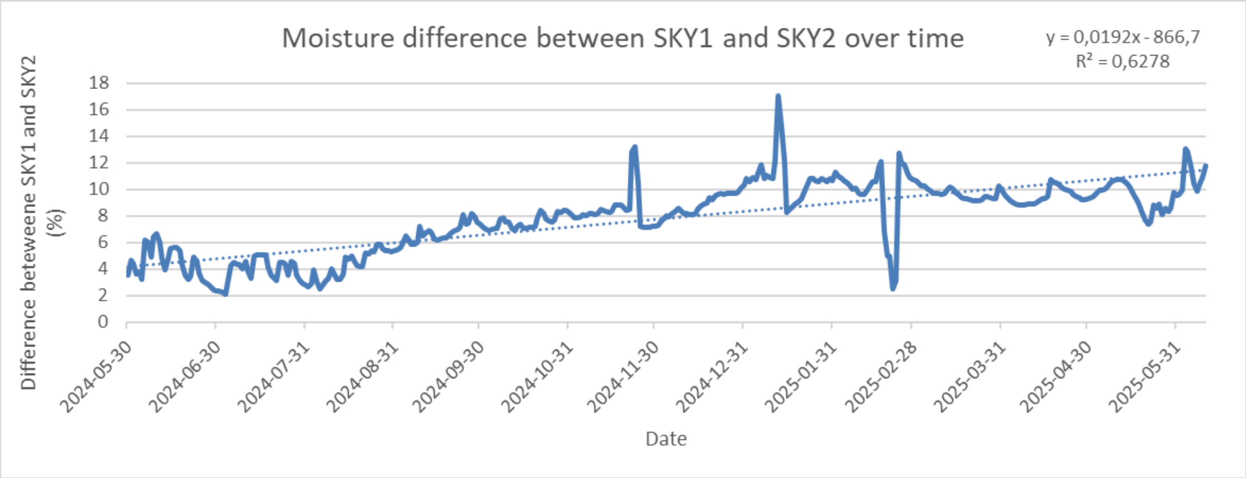
## Annex 6 : Carbon, Nitrogen and C/N ratio in SKY1 and SKY2 in April 2024



## Annex 7 : Humidity, conductivity and temperature over time per plots



## Annex 8 : Moisture difference between SKY1 and SKY2 over time



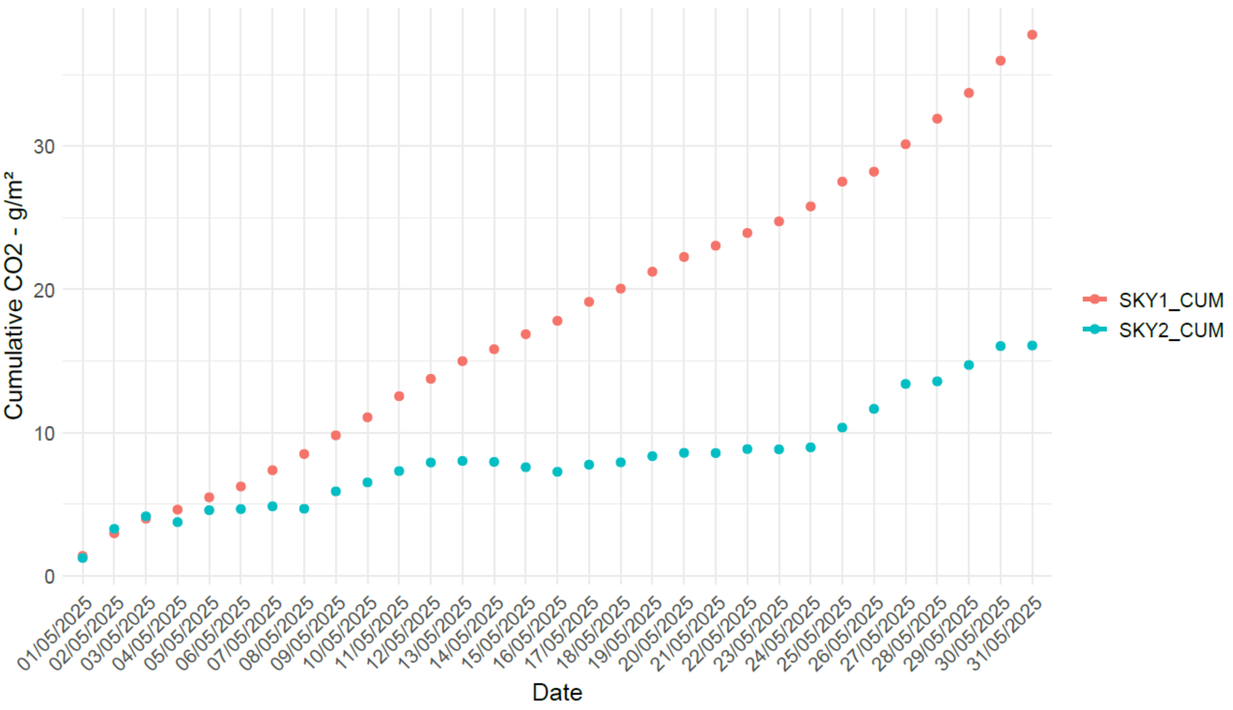
## Annex 9 : Table of statistical results showing significant differences between the two treatments

| Categorize | Applied test | p-value | Accepted hypothesis |
|---|---|---|---|
| Organic matter April | Wilcoxon rank sum test<br>Paired = FALSE | 0.007937 | Significant difference |
| Organic matter July | Wilcoxon rank sum test<br>Paired = FALSE | 0.007937 | Significant difference |
| Dry bulk density July | Wilcoxon rank sum test<br>Paired = FALSE | 0.007937 | Significant difference |
| Phosphorus content | T-test<br>Paired = FALSE | 0.0729 | No Significant difference |
| KCl-P-fraction | T-test<br>Paired = FALSE | 0.7717 | No Significant difference |
| BD-P-fraction | T-test<br>Paired = FALSE | 0.0045 | Significant difference |
| HCl-P-fraction | T-test<br>Paired = FALSE | 0.6127 | No Significant difference |
| Residual-P-fraction | T-test<br>Paired = FALSE | 0.365 | No Significant difference |
| Metals content Al | Wilcoxon rank sum test<br>Paired = FALSE | 1 | No Significant difference |

| | | | |
|---|---|---|---|
| Metals content Fe | Wilcoxon rank sum test<br>Paired = FALSE | 0.5021 | No Significant difference |
| Metals content Ca | Wilcoxon rank sum test<br>Paired = FALSE | 0.8413 | No Significant difference |
| Dissolved organic matter (DOC) - April | Wilcoxon rank sum test<br>Paired = FALSE | 0.007937 | Significant difference |
| April DOM - HOC | Wilcoxon rank sum test<br>Paired = FALSE | 0.6905 | No Significant difference |
| April DOM - biopolymers | Wilcoxon rank sum test<br>Paired = FALSE | 0.007937 | Significant difference |
| April DOM - humic substance | Wilcoxon rank sum test<br>Paired = FALSE | 0.007937 | Significant difference |
| April DOM - buildings blocks | Wilcoxon rank sum test<br>Paired = FALSE | 0.05556 | No Significant difference |
| April DOM - neutrals | Wilcoxon rank sum test<br>Paired = FALSE | 0.8413 | No Significant difference |
| April DOM - Acids | Wilcoxon rank sum test<br>Paired = FALSE | 0.4237 | No Significant difference |
| Dissolved organic matter (DOC) - July | Wilcoxon rank sum test<br>Paired = FALSE | 0.05556 | No Significant difference |
| July DOM - HOC | Wilcoxon rank sum test<br>Paired = FALSE | 0.4206 | No Significant difference |
| July DOM - biopolymers | Wilcoxon rank sum test<br>Paired = FALSE | 0.05933 | No Significant difference |
| July DOM - humic substance | Wilcoxon rank sum test<br>Paired = FALSE | 0.8413 | No Significant difference |
| July DOM - buildings blocks | Wilcoxon rank sum test<br>Paired = FALSE | 1 | No Significant difference |
| July DOM - neutrals | Wilcoxon rank sum test<br>Paired = FALSE | 0.8413 | No Significant difference |
| Carbon content | Wilcoxon rank sum test<br>Paired = FALSE | 0.01141 | Significant difference |
| Nitrogen content | Wilcoxon rank sum test<br>Paired = FALSE | 0.007937 | Significant difference |

|  |  |  |  |
|---|---|---|---|
| C/N ratio | Wilcoxon rank sum test<br>Paired = FALSE | 0.01587 | Significant difference |
| Harvesting results | Wilcoxon rank sum test<br>Paired = FALSE | 0.0556 | *No Significant difference* |
| Moisture | Wilcoxon rank sum test<br>Paired = TRUE | < 2.2e-16 | Significant difference |
| Electrical conductivity | Wilcoxon rank sum test<br>Paired = TRUE | < 2.2e-16 | Significant difference |
| Temperature | Wilcoxon rank sum test<br>Paired = TRUE | < 2.2e-16 | Significant difference |
| CO2 summer fluxes | Wilcoxon rank sum test<br>Paired = TRUE | 0.1953125 | No Significant difference |
| CO2 autumn fluxes | Wilcoxon rank sum test<br>Paired = TRUE | 0.0588 | No Significant difference |
| CO2 winter fluxes | Wilcoxon rank sum test<br>Paired = TRUE | 0.9273 | No Significant difference |
| CO2 spring fluxes | Wilcoxon rank sum test<br>Paired = TRUE | 0.000000128 | Significant difference |
| CH4 summer fluxes | Wilcoxon rank sum test<br>Paired = TRUE | 0.015625 | Significant difference |
| CH4 autumn fluxes | Wilcoxon rank sum test<br>Paired = TRUE | 0.000000119 | Significant difference |
| CH4 winter fluxes | Wilcoxon rank sum test<br>Paired = TRUE | 0.1327 | No Significant difference |
| CH4 spring fluxes | Wilcoxon rank sum test<br>Paired = TRUE | 0.0982 | No Significant difference |
| N2O summer fluxes | Wilcoxon rank sum test<br>Paired = TRUE | 0.7421875 | No Significant difference |
| N2O autumn fluxes | Wilcoxon rank sum test<br>Paired = TRUE | 0.711 | No Significant difference |
| N2O winter fluxes | Wilcoxon rank sum test<br>Paired = TRUE | 0.03999 | Significant difference |
| N2O spring fluxes | Wilcoxon rank sum test<br>Paired = TRUE | 0.256 | No Significant difference |

## Annex 10 : Cumulative CO2 fluxes in SKY1 and SKY2 during Spring 2025



*SKY1_CUM : ΔCO2 = 36.4 g/m² | SKY2_CUM : ΔCO2 = 14.8 g/m²*

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# List of acronyms

**BD-P** : Bicarbonate-extractable Phosphorus
**C/N** : Carbon-to-Nitrogen ratio
**C** : Carbon
**DBD** : Dry Bulk Density
**DIP** : Dissolved Inorganic Phosphorus
**DM** : Dry mass
**DOC** : Dissolved Organic Carbon
**DOM** : Dissolved Organic Matter
**DON** : Dissolved Organic Nitrogen
**DRP** : Dissolved Reactive Phosphorus
**FDR** : Frequency Domain Reflectometry
**GHG** : Greenhouse Gas
**GCF** : Gaseous Carbon Forms
**GEP** : Gaseous End Product
**HCl-P** : Hydrochloric acid-extractable Phosphorus
**IFN** : Inorganic Form of Nitrogen
**LC-OCD-OND** : Liquid Chromatography – Organic Carbon Detection – Organic Nitrogen Detection
**LoRa** : Long Range
**MBC** : Microbial Biomass Carbon
**MBN** : Microbial Biomass Nitrogen
**N** : Nitrogen
**OM** : Organic Matter
**P** : Phosphorus
**PBC** : Plant Biomass Carbon
**PBN** : Plant Biomass Nitrogen
**POC** : Particulate Organic Carbon
**ppm** : Parts per million
**ppb** : Parts per billion
**SRP** : Soluble Reactive Phosphorus
**TSR** : Top Soil Removal

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2024-2025

# The influence of topsoil as an amendment on agricultural mineral soil

**Résumé** : Peatland restoration involves removing the nutrient-rich topsoil to reduce both greenhouse gas emissions and the leaching of phosphorus during rewetting. This study explores the potential reuse of degraded peat topsoil as an amendment for the sandy mineral soils that dominate in Denmark. It was conducted at the rewetted riparian fen site of Vejrumbro in central Jutland. The experiment compared two treatments: mineral soil alone and mineral soil mixed with 20% degraded peat.

Soil properties such as moisture, temperature, conductivity, nutrient content, dissolved organic carbon and greenhouse gas fluxes were monitored over two years. The results supports the hypothesis that degraded peat enhances soil structure and productivity.

**Mots Clés :** Topsoil, amendment, mineral soil, soil properties

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