Greenhouse gas fluxes across three contrasting peatlands along a latitudinal gradient in Sweden

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Abstract

Northern peatland ecosystems cover approximately 3 % of the land area and store almost one-third of the soil carbon, thus are peatlands valuable ecosystem to understand in the context of climate change and climate mitigation. Understanding how peatlands respond to key environmental drivers and how CO_2 and CH_4 fluxes vary across climate zones is crucial for predicting future carbon dynamics. Using eddy covariance measurements, this study investigated carbon and greenhouse gas fluxes at three contrasting peatlands along a latitudinal gradient in Sweden, from hemi-boreal to subarctic conditions, with the aim of characterising climatic trends, assessing flux responses to key environmental drivers, and quantifying seasonal and annual CO_2 and CH_4 budgets. Environmental drivers, including air temperature (Ta), vapour pressure deficit (VPD), incoming shortwave radiation (SW_{IN}) and water table level (WTL), were assessed. Climatic trends reveal that temperature will increase the most in northern regions, as will precipitation. CO_2 and CH_4 fluxes were strongly regulated by environmental conditions, with ecosystem respiration (RECO) and CH_4 emissions showing the highest temperature sensitivity at the central site, while photosynthetic capacity was highest in the south and light-use efficiency was strongest in the north. Gross primary production (GPP) increased with both VPD and Ta but levelled off at higher values. Despite all three sites functioned as net CO_2 sinks in most years, CH_4 emissions resulted in a positive greenhouse gas balance (GWP100) across all sites, indicating a net warming effect over a 100-year horizon. These results highlight that both the magnitude and environmental sensitivity of greenhouse gas (GHG) fluxes differ among peatlands along a latitudinal gradient, emphasising the need for site-specific assessments when evaluating peatland climate feedback.

Keywords: gross primary production, bog, fen, climate change, environmental variables, water table level, photosynthesis, nonlinear regression, greenhouse gases

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Abbreviations

Abbreviation	Description
CH_4	Methane
CO_2	Carbon dioxide
GHG	Greenhouse gas
GPP	Gross primary production
ICOS	Integrated Carbon Observation System
NEE	Net ecosystem exchange
SW_{IN}	Incoming short-wave radiation
RECO	Ecosystem respiration
SMHI	Swedish Meteorological and Hydrological Institute
Ta	Air temperature
Ts	Soil temperature
VPD	Vapour pressure deficit
WTL	Water table level

1. Introduction

1.1 Peatlands and climate change

Today, we are experiencing a rapidly changing climate, with high latitude regions exhibiting the fastest rate of warming worldwide (IPCC 2023). Anthropogenic activities, including agriculture, forestry, and industrial processes, are major drivers of climate change. Two key greenhouse gases (GHG) emitted through these activities are carbon dioxide (CO_2) and methane (CH_4) (Filonchyk et al. 2024). With CH_4 having a substantially higher global warming potential despite its shorter atmospheric lifetime, approximately 27 times greater than CO_2 over a 100-year time horizon. Due to anthropogenic emissions, atmospheric GHG concentrations have increased considerably since the pre-industrial period. CO_2 concentrations have risen from approximately 280 ppm to nearly 410 ppm, while CH_4 concentrations increased from 729 ppb to 1866 ppb (IPCC 2021). Consequently, increasing GHG emissions can be recognized as a driver for more frequent and severe climate events, including rising temperatures, prolonged dry periods, and extreme precipitation events (IPCC 2023). Both CH_4 and CO_2 are the two most abundant GHGs in peatlands and largest natural reservoirs. Peatlands cover around 3% of the global land area, with the majority of peatlands are in boreal and Arctic regions accounting for approximately 15% of the boreal land area (Frolking et al. 2011; McPartland et al. 2019). In these regions peatlands are a part of the terrestrial ecosystem, interacting with surrounding forests through shared hydrology (van der Velde et al., 2021). Peatlands store approximately 600 Gt C, nearly twice as much carbon as global forest biomass (Yu et al. 2010; Pan et al. 2011) representing about 30% of the world´s soil carbon. This accumulation occurs because plant production consistently exceeds decomposition rates under waterlogged and anoxic conditions (Yu et al. 2010). Boreal and subarctic peatlands, hereafter referred to as Northern peatlands, contain most peatland carbon stocks, storing approximately 547 Gt C, compared to 50 Gt C and 15 Gt C in tropical and southern peatlands (Yu et al. 2010).

Furthermore, of the global CH_4 emissions estimated at 0.5–0.6 Gt CH_4 yr^{-1}, wetlands contribute approximately 40% (~0.14-0.2 Gt CH_4 yr^{-1}). Northern peatlands alone account for about 0.035 ± 0.003 Gt CH_4 yr^{-1}, corresponding to roughly 6–7% of global methane emissions (Kirschke et al. 2013). Despite peatlands relatively small proportion of the Earth's surface, they store a disproportionately large share of global soil carbon and serve as a source of CH_4 emissions, highlighting their importance for climate regulation (Limpens et al. 2008). Thus, natural peatlands are valuable ecosystems in the context of climate change mitigation (Turetsky et al. 2014; Barthelmes et al. 2015).

1.2 Controls on peatland GHG fluxes

Fluxes of CO_2 and CH_4 and their magnitude are controlled by multiple environmental variables. In this study, key drivers such as air temperature (Ta), precipitation (P), vapour pressure deficit (VPD), water table level (WTL), and incoming shortwave radiation (SW_{IN}) are considered in relation to GPP, NEE and CH_4 emissions (Abdalla et al., 2016).

1.2.1 Variation of GHG fluxes across peatland types

Peatlands are typically defined by a peat depth exceeding 30 cm (Joosten and Clark, 2002; Rydin & Jeglum 2013). There are different types of peatlands, of which bogs and fens are the most common. Bogs are ombrotrophic peatlands that accumulate most of their water from rainfall, resulting in oligotrophic conditions with low nutrient availability. In contrast, fens receive groundwater from surrounding ecosystem, usually supporting higher nutrient levels (Bridgham et al. 2008). Such variation in hydrology, water table conditions and plant communities can therefore lead to differences in GHG exchange within and between peatland sites (Bubier 1995; Helbig et al. 2020)

1.2.2 CO_2 fluxes and environmental control

The peatland net ecosystem exchange (NEE) of CO_2 is defined as the balance between gross primary production (GPP) and ecosystem respiration (RECO). GPP is the total CO_2 uptake through photosynthesis by an ecosystem, and RECO is the sum of autotrophic and heterotrophic respiration from the ecosystem to the atmosphere. When a peatland's GPP exceeds RECO, it acts as a net CO_2 sink and when RECO exceeds GPP, it becomes a CO_2 source. Peatlands have a vertical structure consisting of an aerobic surface layer (acrotelm), where photosynthesis and decomposition occur, and an underlying anaerobic layer (catotelm), where decomposition is slow (Rydin & Jeglum 2013). This structure has historically allowed GPP to generally exceed RECO in peatlands, making them a global CO_2 sink. Ta is a fundamental control on peatland processes, influencing both photosynthesis and respiration. Increasing Ta generally enhance photosynthetic activity, but also stimulate microbial decomposition, by an increase in soil temperature that potentially increases RECO (Lloyd & Taylor, 1994; Updegraff et al., 2001). Photosynthesis is also regulated by SW_{IN} that regulates the available energy for the ecosystem, thus influencing GPP (Peichl et al. 2018). VPD is influenced by Ta, where high VPD can limit peatland CO_2 uptake by inducing stomatal closure and thereby reduce GPP (Helbig et al. 2020). Yet, while RECO remains primarily temperature-driven, increased VPD may enhance evapotranspiration and reduce WTL, thereby weakening the overall CO_2 sink strength of peatlands, particularly during warm summer conditions (Helbig et al. 2020).

1.2.3 CH_4 fluxes and environmental control

In the deeper anaerobic layer CH_4 is produced, through microbial decomposition by methanogens, a process that is enhanced by increasing temperatures (Updegraff et al. 2001). CH_4 is transported to the atmosphere via three pathways, diffusion through the peat profile, plant-driven transport through tissues in vascular plants, and ebullition, which is sudden releases of gas bubbles that result in emission peaks (Lai 2009). CH_4 can be emitted directly to the atmosphere through vascular plants or oxidized by methanotrophs when passing through the aerobic layer and thereby converted into CO_2 before reaching the atmosphere, a process strongly regulated by WTL (Abdalla et al. 2016). A large proportion of CH_4 is oxidized in the aerobic layer before reaching the atmosphere (Rydin & Jeglum 2013). Net CH_4 emissions are therefore determined by the balance between production, oxidation, and the dominant transport pathway, all of which are strongly regulated by WTL and vegetation composition (Bubier 1995; Whalen 2005). Water availability, primarily governed by precipitation and temperature, regulates peatland hydrology (Rydin & Jeglum 2013). WTL determines oxygen availability in the soil, thereby influencing the balance between aerobic and anaerobic processes (Updegraff et al. 2001). High WTL promotes anaerobic conditions, favouring CH_4 production, while lower WTL enhances CO_2 emissions through increased decomposition (Bubier & Moore 1994; Whalen 2005). However, drought may reduce CH_4 emissions through reduced methanogenesis, enhanced oxidation, and limited plant-mediated transport (White et al. 2023). In permafrost r
egions such as in the subarctic region, thawing may promote the expansion of wetter minerotrophic conditions and alter vegetation composition, which potentially can increase CH_4 emissions (Łakomiec et al. 2021).

1.3 Latitudinal gradients in current and future environmental conditions across Sweden

Sweden spans 1570 km from its most southern to northern borders (Lantmäteriet 2026). Within this wide national latitudinal gradient, environmental variables such as Ta, P, SW_{IN}, and hydrology influence peatland carbon cycling and GHG. Based on meteorological data from Swedish Meteorological and Hydrological Institute (SMHI), differences in for instance Ta, SW_{IN}, P are observed across the latitudinal gradient (SMHI 2026). Notably, northern regions are projected to warm faster than southern regions, while changes in precipitation and hydrology are also expected to differ spatially (SMHI 2026). Higher SW_{IN} can enhance carbon uptake in peatlands, due to prolonged growing season and higher photosynthetic activity (Gallego-Sala et al. 2018). However, this also increases evaporation and extends the thawed period, which stimulates the microbial activity and leads to degradation of organic material and increased CO_2 emissions (Rydin & Jeglum 2013). Furthermore, in northern regions, permafrost is a central part of regulating the CO_2 balance. The frozen soil prevents degradation of organic material, which could result in increased carbon storage (Łakomiec et al. 2021). Within Sweden, peatland structure and GHG fluxes vary along a latitudinal gradient (Gong et al. 2013a; Gallego-Sala et al. 2018). The role of peatlands in the climate system remains uncertain, as changes in temperature, hydrology, vegetation composition may alter the balance between CO_2 uptake and GHG fluxes (Rydin & Jeglum 2013; Helbig et al. 2020). Understanding how peatland CO_2 and CH_4 fluxes respond to environmental drivers (Armstrong et al. 2015) across a latitude gradient is therefore important for predicting future climate feedbacks (Gallego-Sala et al. 2018).

1.4 Aim

Using flux tower data from three contrasting natural peatlands located in southern, central and northern regions of Sweden, this study aims to investigate how GHG fluxes differ in magnitude and their response to key environmental drivers in different Swedish peatlands along a latitudinal gradient. The specific objectives are to i) to characterise how climatic trends across a latitudinal gradient in Sweden are regulated by environmental conditions ii) assess differences in CO_2 and CH_4 flux responses to key environmental drivers, and iii) quantify and compare the seasonal and annual CO_2 and CH_4 fluxes among contrasting peatlands.

Based on these objectives, the following hypotheses were tested:

H1: Trends in climatic conditions, including temperature, precipitation, and dry periods, differ across the latitudinal gradient.

H2: The response of ecosystem respiration to temperature differs between northern, central and southern peatlands

H3: The response of GPP uptake to VPD, SW_{IN}, and temperature differs between northern, central and southern peatlands.

H4: The response of CH_4 emissions to WTL and temperature differs between northern, central and southern peatlands.

H5: Annual CO_2 and CH_4 budgets differ in magnitude between northern, central, and southern peatlands.

2. Methods

2.1 Study sites

The sites chosen in this study are classified as natural peatlands which allows for a relevant comparison of CO_2 and CH_4 fluxes across different peatland types. All three sites are part of the ICOS Sweden (Integrated Carbon Observation System) network, ensuring high-quality measurements that are collected using standardized instrumentation and protocols.

2.1.1 Abisko

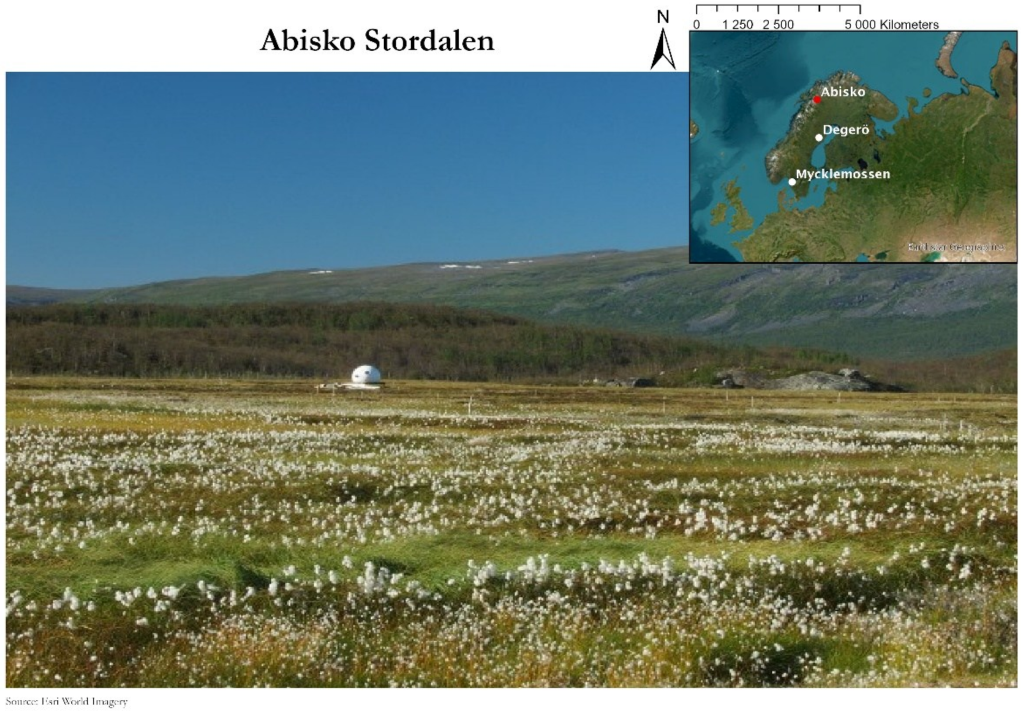

Figure 1. The photograph shows the peatland research site at Stordalen (Abisko) with flux measurement instruments. The inset map shows the location of all three study sites in Sweden. Photo: (ICOS n.d.b).

Figure 1 shows Abisko Stordalen (68°21´N, 19°03´E), a peatland in the subarctic region located at 360 m.a.s.l. in the county of Norrbotten. It is a 25 hectare palsa bog, where palsas are frozen peat mounds and typically located in regions with discontinuous permafrost (Rydin & Jeglum 2013). Abisko is mainly an oligotrophic mire and consists of palsa plateaus, hollows, and permafrost zones. The flux tower is located at the transition zone between a dry palsa and hollows area. Because of the permafrost, only a thin layer (0.5-1 m) active peat during the summer, of the 1-3 m peat depth (Faucherre et al. 2018; Łakomiec et al. 2021).

2.1.2 Degerö Stormyr

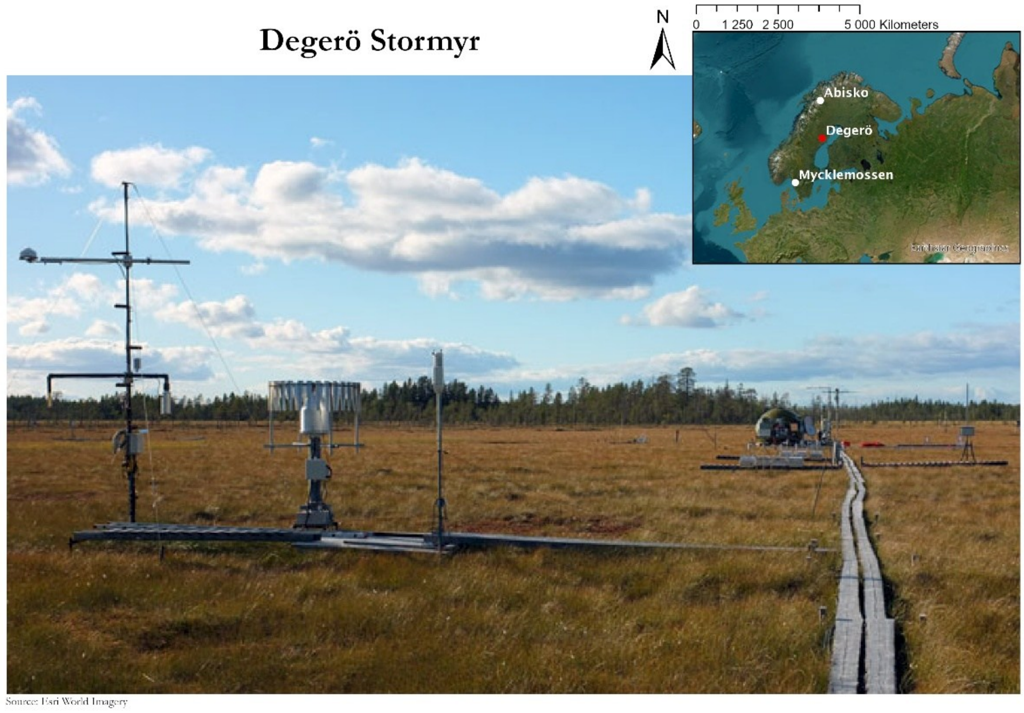

Figure 2. The photograph shows the peatland research site at Degerö equipped with flux measurement instruments. The inset map shows the location of all three study sites in Sweden. Photo: Paul Smith/(ICOS n.d.c)

Figure 2 shows Degerö Stormyr (64°11′N, 19°33´E) in the county of Västerbotten and is a part of Kulbäcksliden Experimental Forest and is 250-300 m.a.s.l. Degerö is an oligotrophic fen and a mixed mire system that consists of smaller mires, divided by islets and ridges of glacial till. The study area is located on a flat, open part of the mire, dominated by hummocks, hollows and carpet plant communities. The depth of the peat is between 3 and 4 meters (Nilsson et al. 2008; Noumonvi et al. 2023).

2.1.3 Mycklemossen

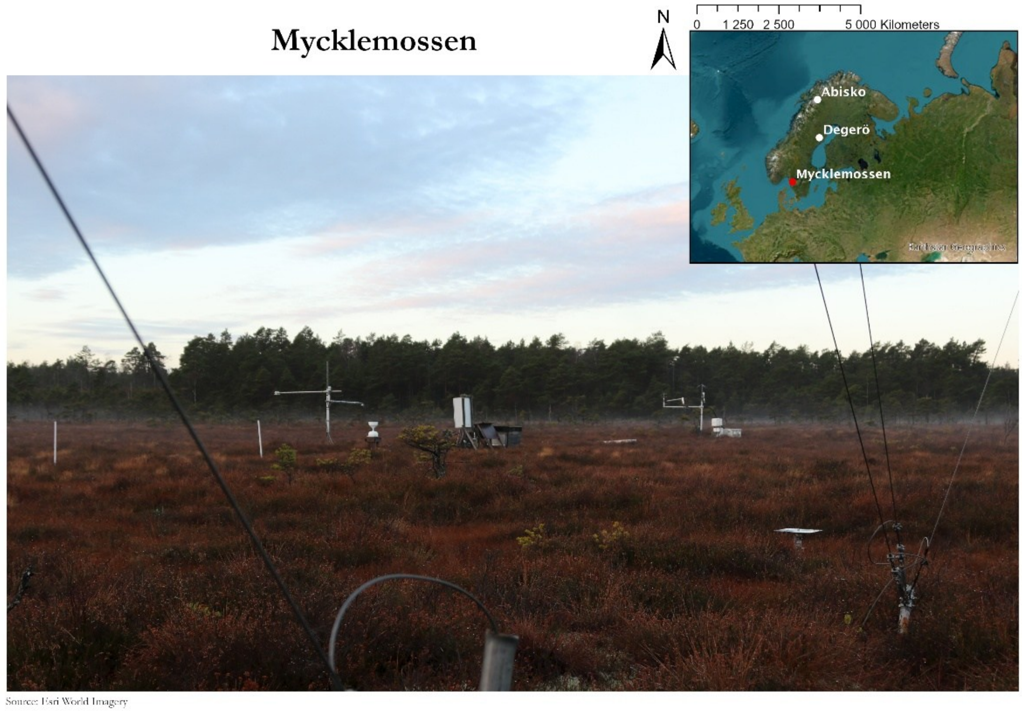

Figure 3. The photograph shows the peatland research site at Mycklemossen and the flux measurement instruments. The inset map shows the location of all three study sites in Sweden. Photo: (ICOS n.d.d).

Mycklemossen (58°21'N 12°10'E) is in the south-west part of Sweden in the county of Västra Götaland (Fig. 3), roughly 80 kilometres outside of Gothenburg, located at 80 m a.s.l. In contrast to the other two sites, Mycklemossen is in a hemi-boreal region and 59 hectares large. It is an oligotrophic bog but consists of a mosaic of hummocks and wetter hollows. The peat depth is over 6 meters (White et al. 2023).

All sites shared *Sphagnum* spp. and *Eriophorum vaginatum*, while the remaining vegetation composition differed between sites. However, the table does not represent the complete vegetation composition at each site (Table 1).

Table 1. Dominant vegetation at each study site. Species listed are those reported in the ICOS site descriptions and do not represent the complete vegetation composition of each site.

Species	Mycklemossen	Degerö	Abisko
Sphagnum spp.	x	x	x
Eriophorum vaginatum	x	x	x
Calluna vulgaris	x		
Erica tetralix	x		
Rhynchospora alba	x		
Pinus sylvestris	x		
Vaccinium uliginosum	x		
Vaccinium myrtillus	x		
Vaccinium vitis-idaea	x		x
Vaccinium oxycoccos		x	
Andromeda polifolia		x	
Trichophorum cespitosum		x	
Carex spp.		x	
Carex rotundata			x
Eriophorum angustifolium			x
Empetrum hermaphroditum			x
Rubus chamaemorus			x

2.2 Flux data

Future projections under Representative Concentration Pathway 4.5, a moderate greenhouse gas emission scenario (RCP4.5) were used to assess projected changes in temperature and precipitation across the study region through 2100. These climate projections were obtained from the Swedish Meteorological and Hydrological Institute (SMHI) for the counties Norrbotten, Västerbotten and Västra Götaland in which each site is located. The environmental data and GHG flux variables were collected from ICOS for Abisko and Degerö (Nilsson et al., 2026; Lundin et al., 2026) and Swedish Infrastructure for Ecosystem Science (SITES) for Mycklemossen (SITES 2026). Both ICOS and SITES are research infrastructures that focuses on GHG exchange and fluxes in the atmosphere, as well as the ecosystem and ocean. At each site, fluxes were measured using the eddy covariance technique, which is based on fast-response instruments installed on a flux tower providing continuous half-hourly measurements of net ecosystem CO_2 exchange (NEE) and CH_4 fluxes. These instruments measure the exchange between the ecosystem and atmosphere within an area of approximately one kilometre around the tower (ICOS n.d.a). In addition, meteorological variables were recorded, including Ta, soil temperature (Ts), P, VPD, WTL, and SW_{IN}.

Table 2: Environmental and greenhouse gas (GHG) flux variables included in the study.

Environmental variables	**GHG flux variables**
Air temperature (Ta)	Carbon dioxide (CO_2)
Precipitation (P)	Methane (CH_4)
Vapor pressure deficit (VPD)	
Water table level (WTL)	
Incoming short-wave radiation (SW_{IN})	

2.3 Data processing and analysis

Meteorological and flux data were processed by the ICOS Ecosystem Thematic Centre (ETC) and provided via the ICOS Carbon Portal. In this study, data were compiled both for years 2023-2024 Abisko, and Myckle mossen and 2022-2023 for Degerö. The dataset included variables such as Ta, SW_{IN}, NEE, RECO, GPP, WTL and VPD. To visualize the overall pattern of the environmental variables and GHG flux variables both time series both original data and gap filled was use.

2.4 Annual carbon budgets

Annual budgets of NEE and CH_4 were calculated for 2023 by integrating gap-filled half-hourly flux measurements over the full year. Negative NEE values indicate net CO_2 uptake, whereas positive values indicate net CO_2 release.

$$NEE_{annual} = \sum_{i=1}^{\infty}(NEE_i \times \Delta t) \quad \text{(eq. 1)}$$

$$CH_{4,annual} = \sum_{i=1}^{\infty}(CH_{4,i} \times \Delta t) \quad \text{(eq. 2)}$$

2.5 Flux partitioning

RECO and GPP

The RECO was estimated from nighttime NEE observations. To only get the RECO, only data with $SW_{IN} < 10$ W m^{-2} were used, representing nighttime conditions which photosynthesis is assumed to be zero (Wutzler et al. 2018). A Lloyd–Taylor model (Lloyd & Taylor, 1994) was fitted to the relationship between nighttime NEE and Ta to estimate RECO during daytime:

$$Reco = R_{10} \cdot e^{E_0\left(\frac{1}{T_{ref}-T_0} - \frac{1}{T-T_0}\right)} \quad \text{(eq. 3)}$$

where R_{10}represents ecosystem respiration at 10 °C and E_0 describes the temperature sensitivity of respiration. To allow comparison among sites, a reference temperature of 10 °C was used (Davidson and Janssens, 2006).

GPP was calculated as the difference between measured NEE and modelled RECO during daytime (Reichstein et al. 2005):

$$GPP = Reco - NEE \quad \text{(eq. 4)}$$

Growing season was defined separately for each site and year using a daily GPP threshold. Days with daily mean GPP exceeding 1.5 μmol CO_2 m^{-2} s^{-1} were considered a part of the growing season. Similar threshold approaches are commonly used in flux-based phenology studies to identify periods of sustained ecosystem CO_2 uptake from eddy covariance data (Melaas et al. 2013).

2.6 Flux–environment relationships

2.6.1 CO_2 fluxes

The sensitivity of RECO to Ta was derived from equation 3 above. For GPP, Michaelis Menten hyperbolic rectangular regression (Johnson & Goody 2011) was used as a non-linear regression (nls), to describe the relationship between photosynthesis and SW_{IN}:

$$GPP = \frac{\alpha \cdot SW\ IN \cdot Pmax}{\alpha \cdot SW\ IN + Pmax} \quad \text{(eq. 5)}$$

where α represents the initial light-use efficiency and P_{max} the maximum photosynthetic capacity.

2.6.2 CH_4 flux

The sensitivity of CH_4 fluxes to Ta dependence was described using an exponential model(Rinne et al. 2007):

$$CH_4 = a \cdot e^{bTa} \qquad \text{(eq. 6)}$$

where *Ta* represents air temperature, and *a* and *b* are fitted parameters describing baseline flux and temperature sensitivity.

2.6.3 Statistical analysis

Unlike SW_{IN} and Ta responses which have well-established mechanistic relationships with ecosystem fluxes, the effects of VPD and WTL are indirect, non-linear, and context-dependent, which makes them difficult to describe using a single mathematical function. Therefore, to reveal their underlying relationships with GPP and CH_4, binning was applied. Binning, in this case, means that observations were aggregated into discrete intervals (Kar et al. 2021). Bins containing at least 10 observations were retained to ensure robust estimation. Binning was performed separately for each site to avoid confounding site-specific responses. For each bin, mean values of GPP and CH_4 and their associated standard errors were calculated. Data density was uneven across the environmental gradients, resulting in greater uncertainty in bins with fewer observations. However, this limitation is mitigated here by analysing each site independently.

ANOVA and Tukey's test was performed for testing differences among the last four bins means representing the highest VPD values and highest WTL at each site. The analysis was restricted to these four highest bins for each variable, to focus on conditions where biological and physical processes are expected to be most extreme. This approach enables comparison of site differences under conditions where responses are likely to be strongest and most ecologically meaningful. Data from year 2023 from each site was compared and followed by a post hoc test between the sites, if any significant differences were found. Although ANOVA assumes normally distributed residuals, it still works well even if the data is not perfectly normally distributed, particularly when sample sizes are large (Quinn and Keough, 2002; Field, 2013). The ANOVA was done on GPP response to VPD and Ta, and CH_4 response to WTL relevant.

To analyse the response of GPP to VPD, only biologically active daytime (i.e. SW_{IN} >10 W m^{-2}) observations were retained. Parameter uncertainty was evaluated using 95% confidence intervals derived from the fitted regression models and to determine the significance of individual predictors, t-tests were used. Statistical analyses were conducted using only original data for all sites year 2023. All data processing, statistical analyses, and visualizations were performed in R version 4.4.0 (R Core Team, 2024). Data handling and visualization were conducted using packages from the `tidyverse` (Wickham et al., 2019), including *`ggplot2`*, as well as additional packages such as *`readxl`*, *`lubridate`*, and *`zoo`*.

3. Results

3.1 Climatic trends along the latitudinal gradient

Under the moderate RCP4.5 climate scenario, past and projected temperature, precipitation and dry days trends for Norrbotten, Västerbotten and Västra Götaland counties, where the study sites Abisko, Degerö and Mycklemossen are located, respectively (Figs. 1,2,3). All three regions show a clear and consistent warming trend through 2100. Figure 4 shows observed and projected annual temperatures. By 2071–2100, temperatures are projected to rise across all regions, with the largest increase expected in Norrbotten (+3.6 °C), followed by Västerbotten (+3.4 °C) and Västra Götaland (+2.7 °C). Together, warming was observed across these three regions in Sweden.

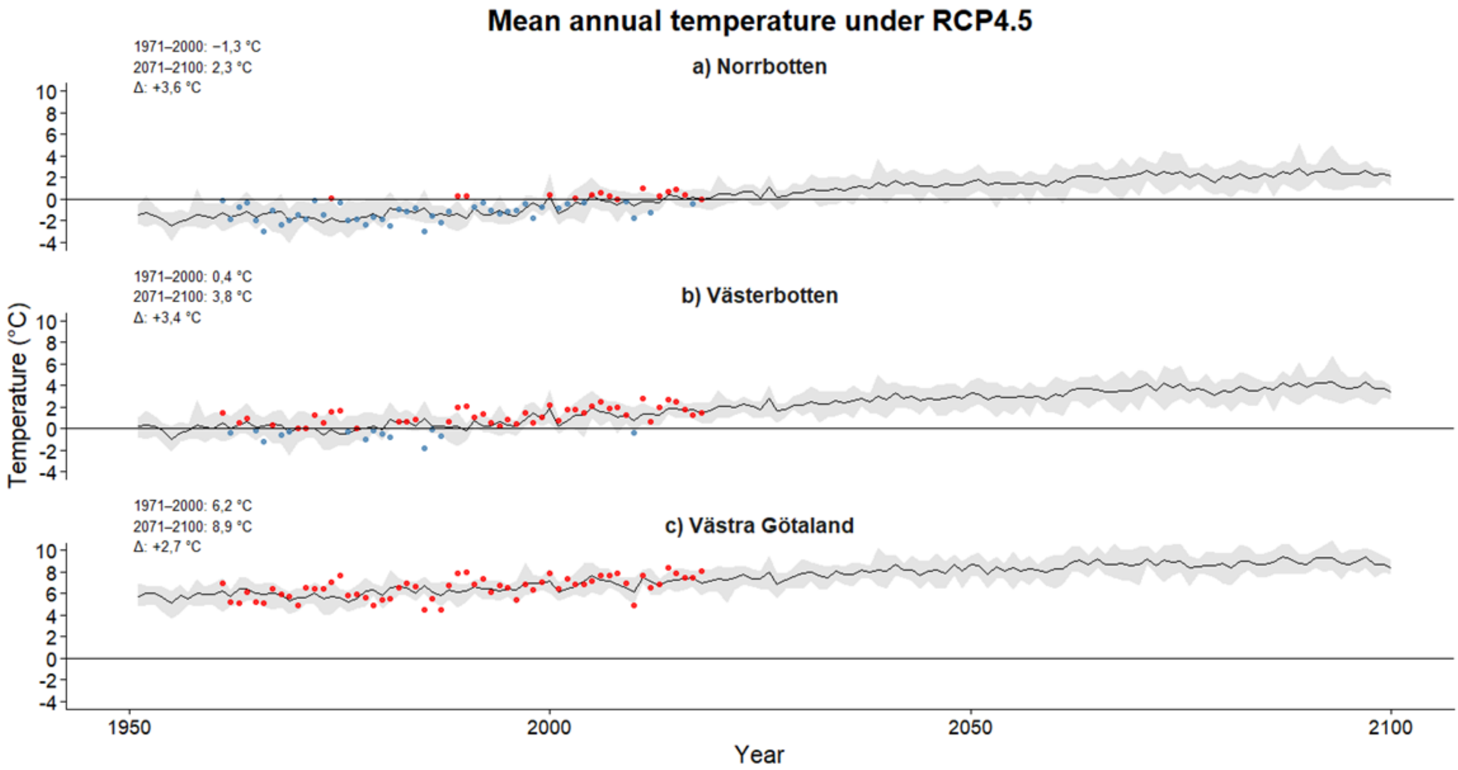

Figure 4. Mean annual temperature under RCP4.5 for a) Norrbotten, b) Västerbotten, and c) Västra Götaland. The black line shows modelled values, the grey band indicate model uncertainty. Red bars and blue bars show observed historical values above and below zero, respectively. Δ values indicate the projected change between 1971–2000 and 2071–2100.

In Figure 5, all regions show increasing precipitation trends under the RCP4.5 scenario. Projected mean monthly precipitation for Norrbotten and Västerbotten are both expected to see an increase of 9 mm/month respectively, while the increase in Västra Götaland is slightly smaller at 7 mm/month by 2071–2100 relative to 1971–2000.

In contrast to the projected increases in temperature and precipitation, the number of dry days remains relatively stable across all three regions throughout the century (Fig. 3). The number of dry days is projected to remain largely stable across all regions by 2071–2100, with Norrbotten and Västerbotten, a decrease of 6 days is projected respectively, while Västra Götaland a decrease with only 1 day.

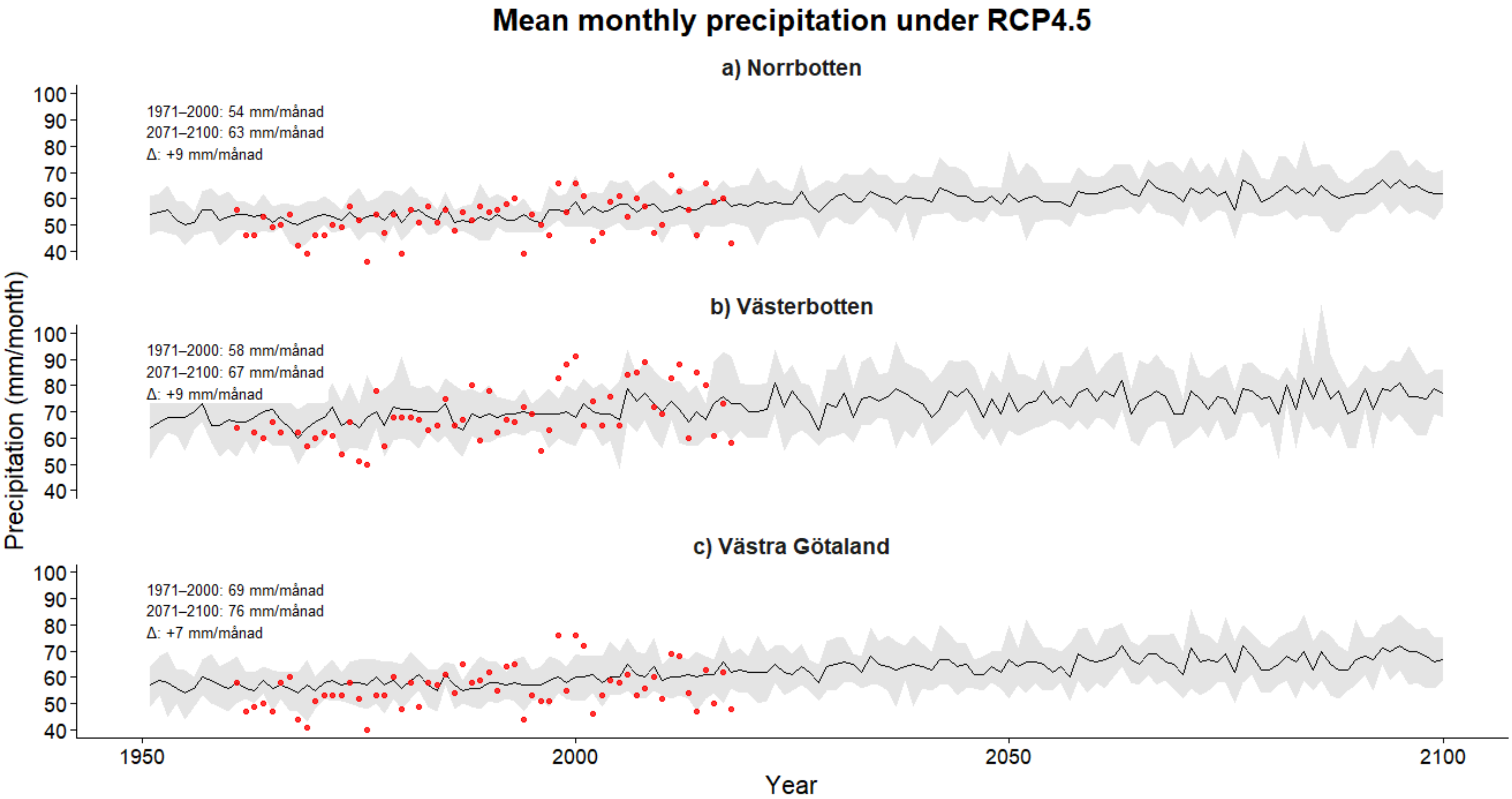

Figure 5. Mean monthly precipitation under RCP4.5 for a) Norrbotten, b) Västerbotten, and c) Västra Götaland. The black line shows modelled values, the grey band indicates model uncertainty, and red dots show observed historical values. Δ values indicate the projected change between 1971–2000 and 2071–2100.

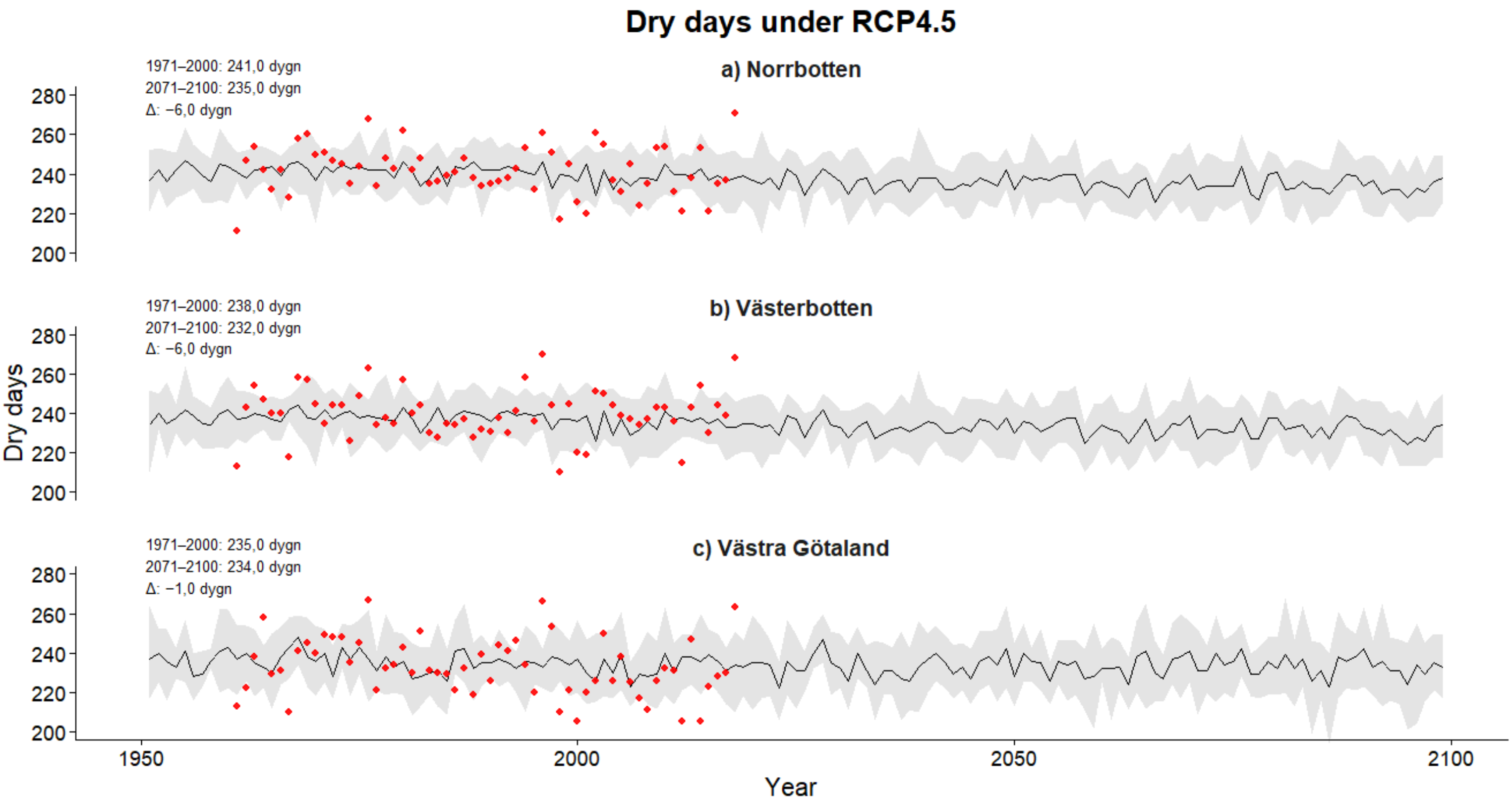

Figure 6. Dry days projection under RCP4.5 for a) Norrbotten, b) Västerbotten, and c) Västra Götaland. Black lines indicate median model projections, grey shaded areas represent model uncertainty, and red dots show observed historical values. Δ values indicate the projected change between 1971–2000 and 2071–2100.

3.1.1 Environmental conditions at the study sites during the study years

Figure 7 illustrates that Abisko generally exhibits lower Ta compared to Degerö and Mycklemossen. WTL remained consistently low at Abisko, while Degerö and Mycklemossen showed values closer to the surface and greater temporal variability. VPD showed pronounced seasonal variation across all sites, but the amplitude of summer peaks differed. Mycklemossen and Degerö exhibited higher summer VPD values than Abisko. SW_{IN} displayed similar seasonal dynamics across sites, although peak summer radiation varied somewhat among the peatlands, with higher SW_{IN} at Mycklemossen and Degerö, compared to Abisko, reflecting expected latitudinal light conditions. Overall, the three sites exhibited similar seasonal dynamics but differed in magnitude and variability of the environmental variables.

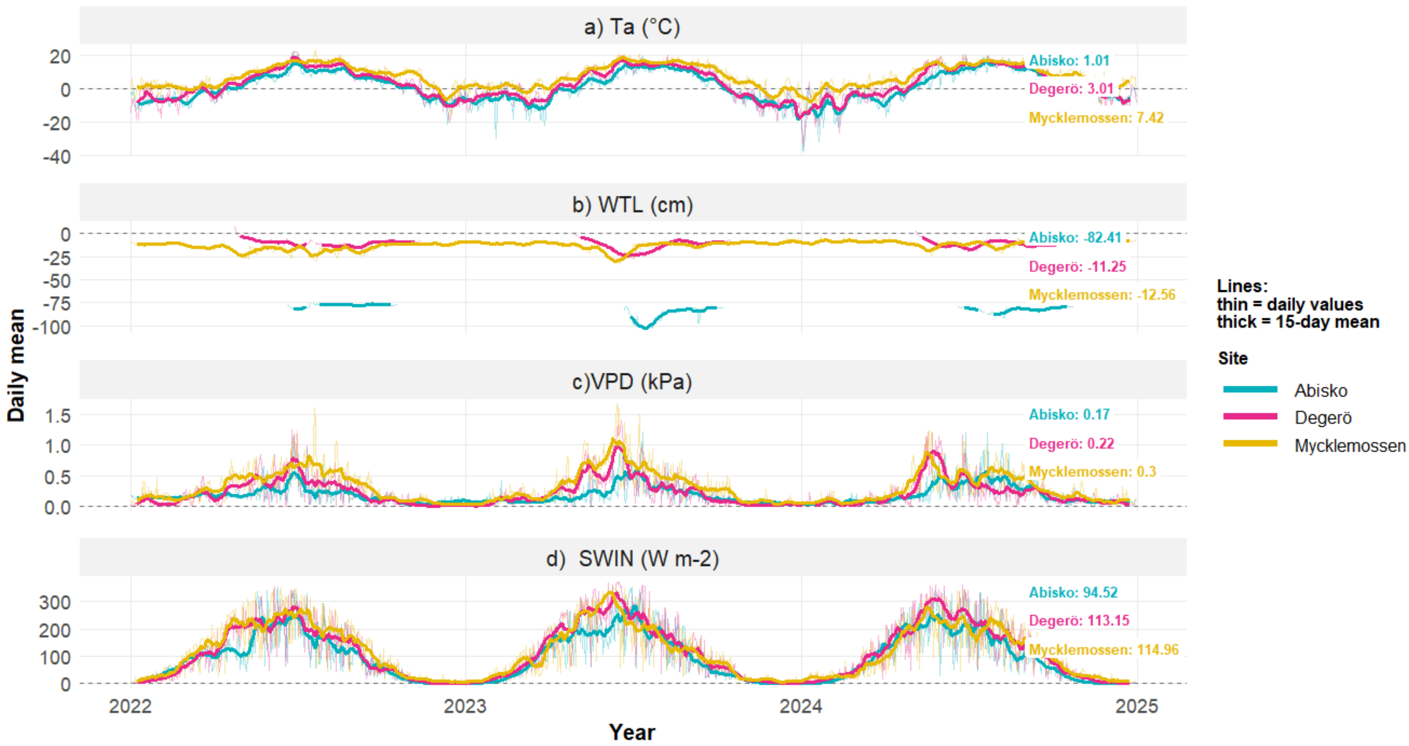

Figure 7. Daily mean of a) air temperature (Ta), b) Water table level (WTL), c) vapour pressure deficit (VPD) and d) Incoming shortwave radiation (SWIN) measured at Abisko, Degerö, and Mycklemossen between 2022 and 2025.

3.1.2 Seasonal variations in GHG fluxes

Figures 8 and 9 show the daily mean CH_4 flux and NEE for Abisko, Degerö, and Mycklemossen during the period 2022–2025. Among the three sites, Abisko shows the most negative summer NEE values, while Mycklemossen displays greater short-term variability throughout the study period. CH_4 emission fluxes are generally higher during the growing season and lower during winter periods, with Mycklemossen showing the greatest variability and several short-term periods of CH_4 uptake compared to the other sites (Fig. 9). Degerö exhibits elevated CH_4 fluxes during parts of 2022 and 2023, while Abisko shows a smoother temporal variation.

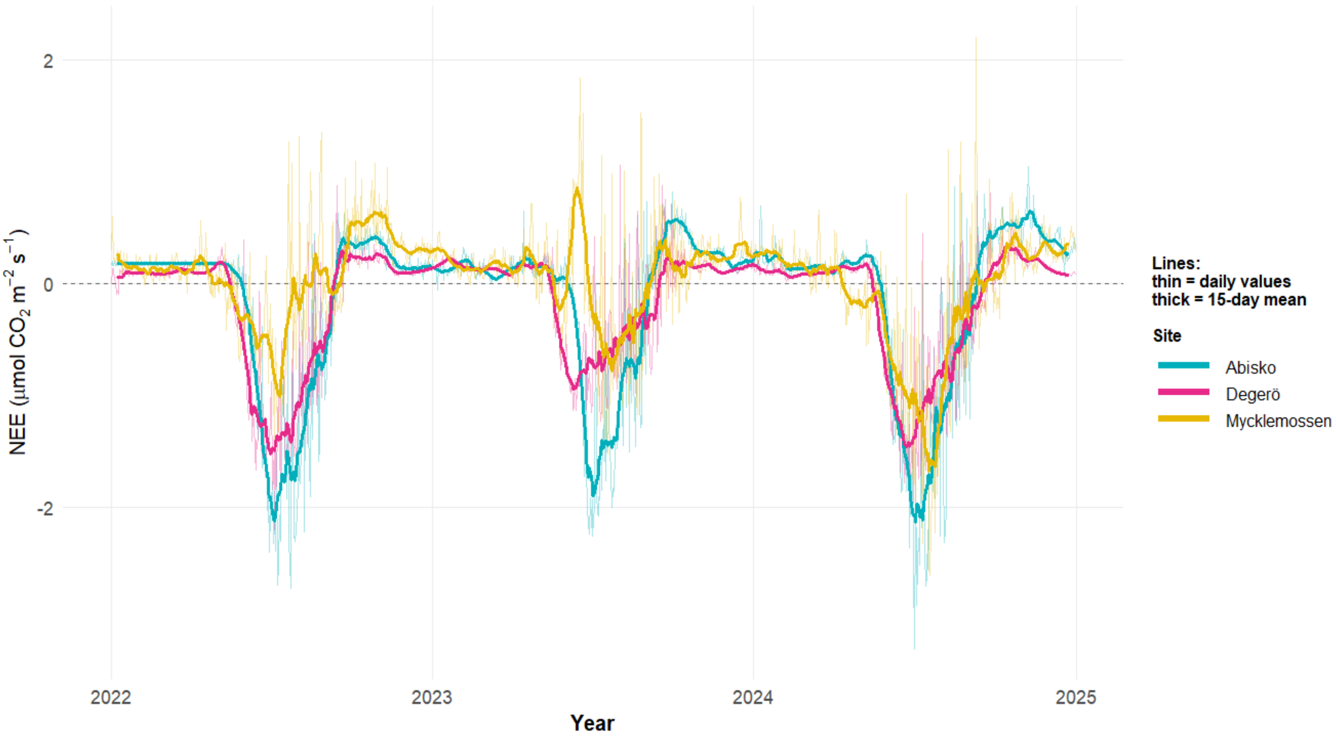

Figure 8. Daily mean net ecosystem exchange (NEE) at all three sites between 2022 and 2025. Negative values indicate net CO_2 uptake, while positive values indicate net CO_2 release.

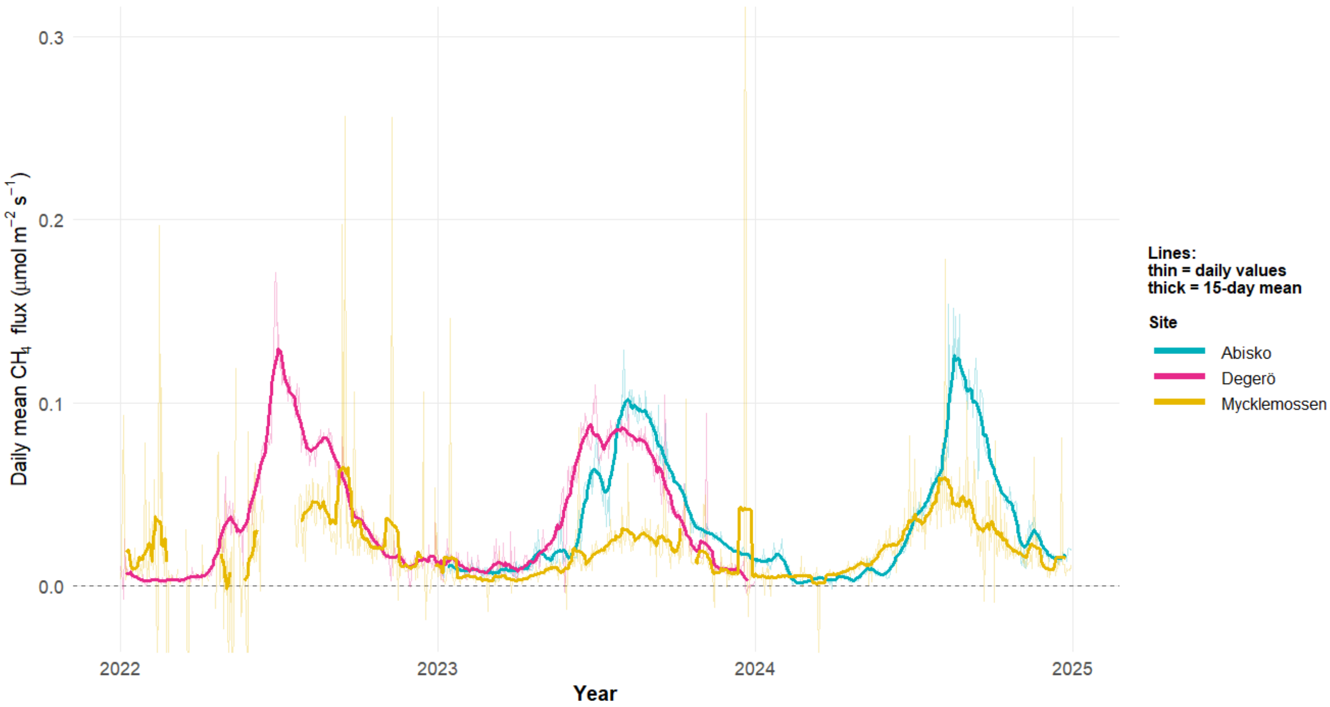

Figure 9. Daily mean methane (CH_4) flux at all three sites between 2022 and 2025. Negative fluxes represent net CH_4 uptake, while positive values represent CH_4 emissions.

3.2 CO_2 and CH_4 flux responses to environmental drivers

Figure 10 shows that RECO increased with Ta across all three sites. The temperature sensitivity was highest at Degerö, followed by Mycklemosssen, and Abisko, indicating stronger temperature control at intermediate latitude (Table 3). Despite the highest temperature sensitivity occurring at Degerö, absolute respiration rates were generally highest at Mycklemossen, particularly at higher temperatures (Fig. 10). Estimated respiration rates (R10) were similar at Mycklemossen and Abisko, and the lowest at Degerö (Table 4). Model fit was lowest at Degerö and highest at Mycklemossen, suggesting that temperature alone explains a greater proportion of the variability in RECO at Degerö compared to Mycklemossen. Standard errors were small for all parameter estimates across all sites (Table 3). Pairwise t-tests revealed significant differences among sites in RECO responses to Ta (Table 4).

Table 3. Parameters describing the response of ecosystem respiration (RECO) to air temperature (Ta) at the three peatland sites. R10 represents ecosystem respiration at 10 °C, E0 describes the temperature sensitivity of respiration, and residual standard error.

Site	R10 ± SE	E0 ± SE	Residual SE	R_2
Abisko	1.521 ± 0.012	273.94 ± 1.81	0.423	0.66
Degerö	1.137 ± 0.004	338.90 ± 2.10	0.281	0.80
Mycklemossen	1.511 ± 0.006	291.16 ± 2.36	0.596	0.54

Table 4. Pairwise comparisons of the Lloyd-Taylor temperature sensitivity parameter (E0) among sites. All comparisons were statistically significant ($p < 0.001$).

Comparison	t-value	Significance
Abisko – Degerö	23.78	p < 0.001
Abisko – Mycklemossen	6.12	p < 0.001
Degerö – Mycklemossen	−15.34	p < 0.001

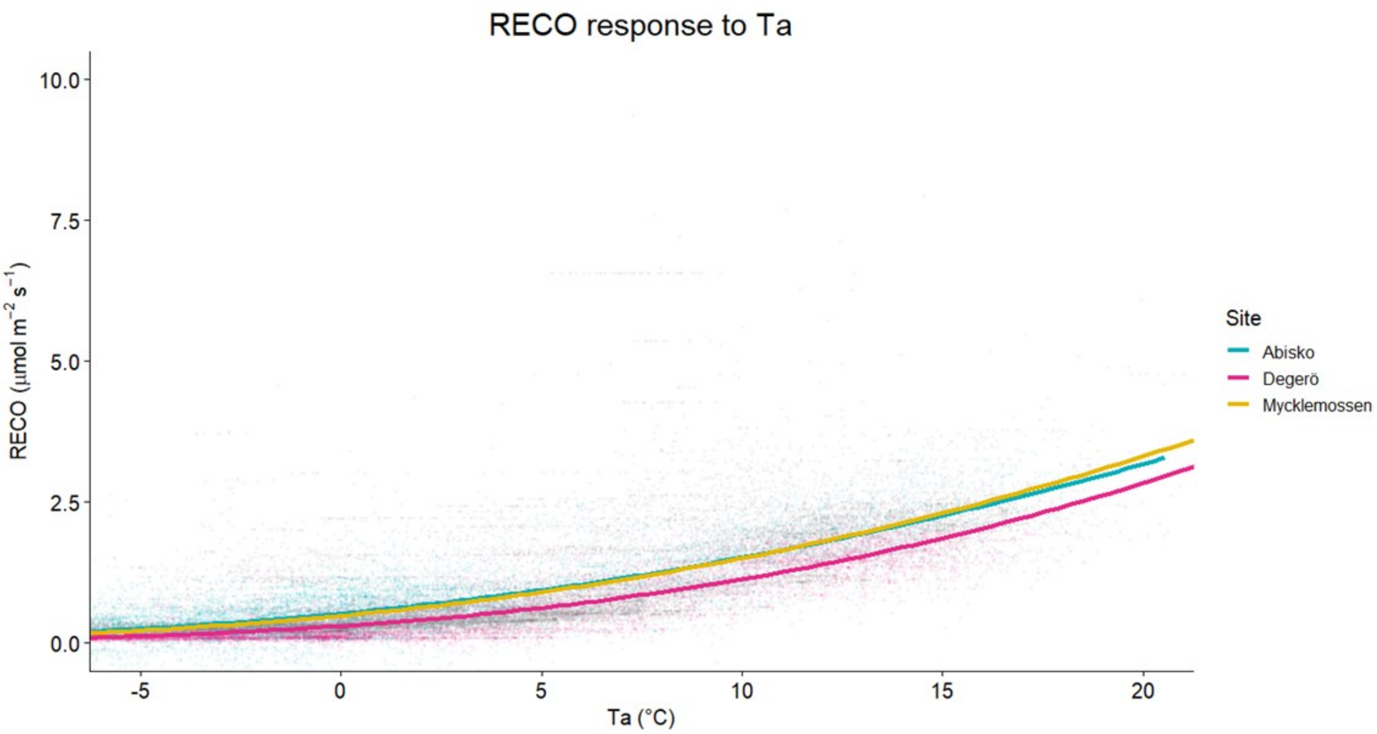

Figure 10. RECO response to Ta (2023-2024). Ecosystem respiration (RECO) as a function of air temperature (Ta) for the three sites. Points show observations and lines indicate fitted response curve.

GPP exhibited a strong saturating response to SW_{IN} for all sites (Fig. 11). The light-use efficiency (α) was highest in Abisko followed by Mycklemossen and the lowest at Degerö (Table 5). The maximum photosynthetic capacity (Pmax) was highest at Mycklemossen, followed by nearly identical values in Degerö and Abisko (Table

5). Pairwise comparisons showed significant differences in α between all sites, while Pmax differed significantly between Abisko and Mycklemossen, but not between Abisko and Degerö (ns) (Table 6).

Table 5. Parameter estimates (± SE) for each site, with the initial light-use efficiency parameter (α) and the maximum photosynthetic capacity parameter (Pmax).

Site	α ± SE	Pmax ± SE
Abisko	0.0532 ± 0.0012	7.00 ± 0.08
Degerö	0.0361 ± 0.0006	7.00 ± 0.06
Mycklemossen	0.0468 ± 0.0008	7.90 ± 0.07

Table 6. The table shows t-values and significance levels for comparisons of the initial light-use efficiency parameter (α) and the maximum photosynthetic capacity parameter (Pmax).

Parameter	Comparison	t-value	Significance
Alpha **α**	Abisko – Degerö	−13.01	$p < 0.05$
	Abisko – Mycklemossen	−4.43	$p < 0.05$
	Degerö – Mycklemossen	10.66	$p < 0.05$
Pmax	Abisko – Degerö	−0.04	ns
	Abisko – Mycklemossen	8.73	$p < 0.05$

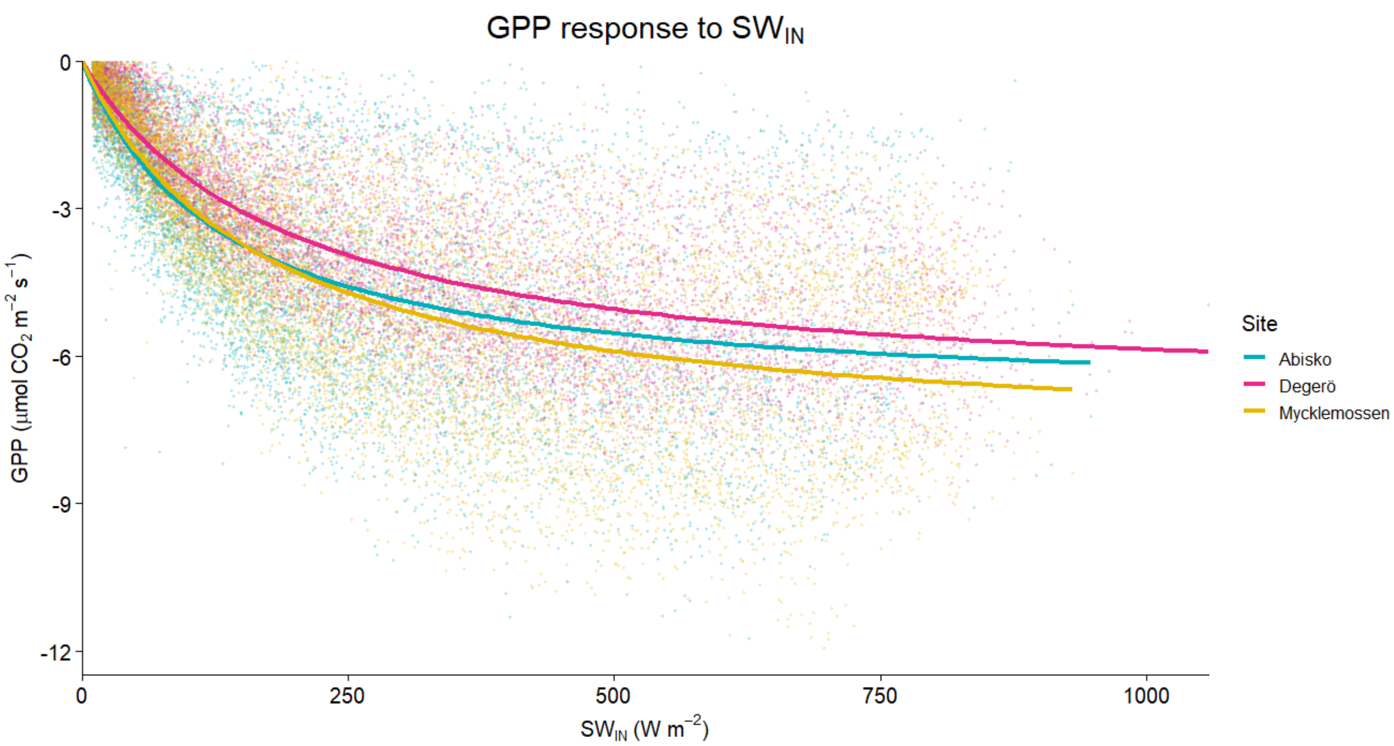

Figure 11. GPP response to SWIN (2023–2024). Gross primary production (GPP) as a function of incoming short-wave radiation (SWIN) for the three sites. Points show observations and lines represent fitted light-response curves. Negative GPP values indicate net CO2 uptake.

Table 7. Tukey HSD post hoc test comparing gross primary production (GPP) among the three study sites across varying vapour pressure deficit (VPD) conditions. The table shows mean differences in GPP, 95% confidence intervals (CI), and p-values.

Comparison	**Mean difference ($\mu mol\ CO_2\ m^{-2}\ s^{-1}$)**	**95% CI**	**p-value**
Degerö – Abisko	−1.54	−1.80 to −1.27	< 0.001
Mycklemossen–Abisko	−1.00	−1.30 to −0.69	< 0.001
Mycklemossen–Degerö	0.54	0.25 to 0.83	< 0.001

GPP increases with increased VPD at all three sites (Fig. 12). Abisko showed the strongest response, reaching the highest uptake rates at lower VPD, while Degerö showed the most moderate response (Fig. 12). In Abisko, GPP appeared to level off around 1.5 kPa, whereas Degerö showed the smallest overall uptake pattern but appeared to continue the uptake after 2 kPa. Mycklemossen showed a similar pattern but stabilised at higher VPD values. Figure 12 shows that variability is higher for all three sites, especially for Abisko. Across VPD conditions, GPP differed significantly among sites (one-way ANOVA, $F_{2,\ 771} = 93.92$, $p < 0.001$). Tukey HSD post hoc comparisons showed that GPP was significantly lower at both Degerö and Mycklemossen compared to Abisko, with Degerö showing the largest difference (Table 7).

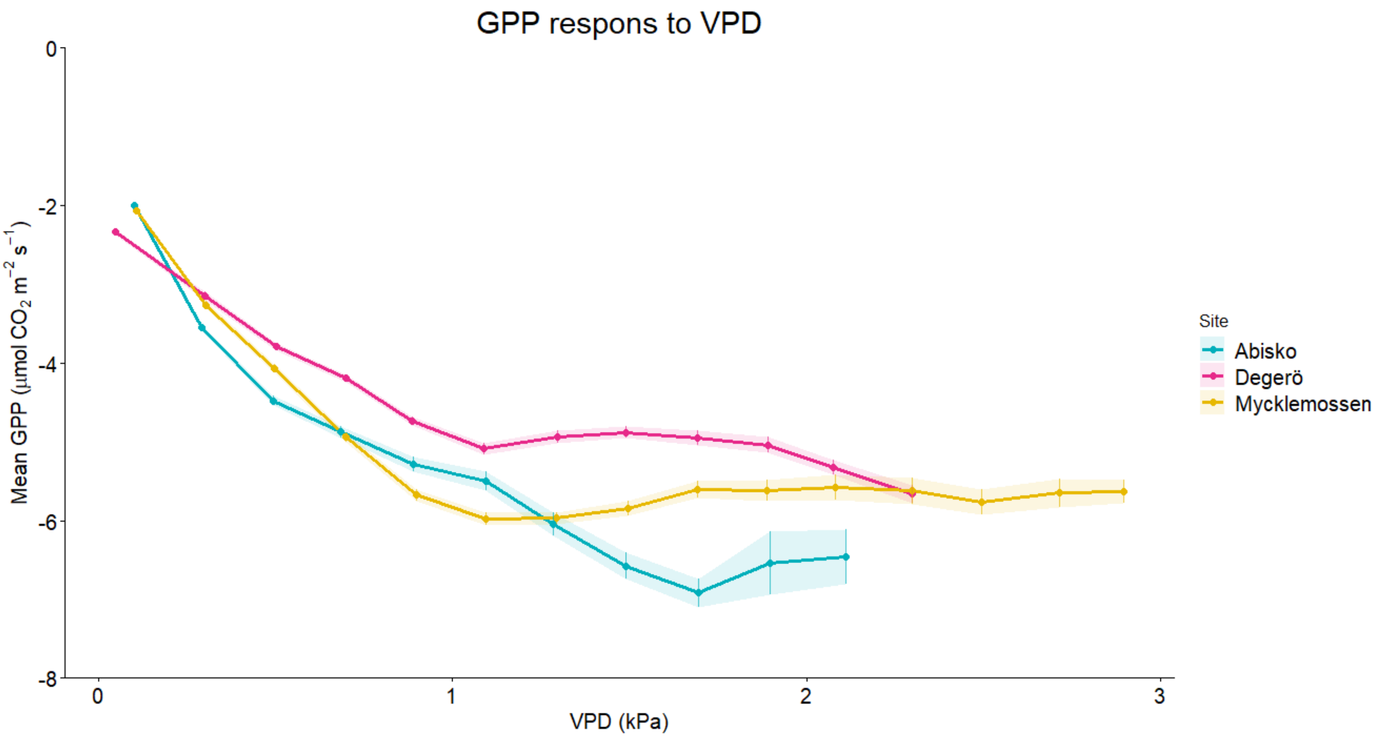

Figure 12. GPP response to VPD (2023–2024). Binned mean GPP as a function of vapor pressure deficit (VPD) for three sites. Points show bin averages with uncertainty. Negative GPP values indicate net CO_2 uptake.

Table 8. Tukey HSD post hoc test comparing gross primary production (GPP) among the three study sites across varying air temperature (Ta) conditions. The table shows mean differences in GPP, 95% confidence intervals (CI), and p-values.

Comparison	**Mean difference (μmol CO_2 m^{-2} s^{-1})**	**95% CI**	**p-value**
Degerö – Abisko	−1.43	−1.62 to −1.24	< 0.001
Mycklemossen–Abisko	−0.21	−0.42 to −0.01	0.037
Mycklemossen–Degerö	1.21	1.05 to 1.38	< 0.001

GPP increases with Ta at all three sites (Fig. 13). At lower temperatures, Abisko showed the greatest uptake, while Degerö and Mycklemossen showed similar and lower uptake. However, Mycklemossen continued to show uptake up to 30 °C, whereas Degerö showed a consistently weaker response across the whole temperature range (Fig. 13). Variability increased at higher temperatures, as indicated by greater spread around the mean values, for both Abisko and Mycklemossen. Differences among sites were statistically significantly at high temperatures (ANOVA, $F_{2,2124}$= 231.9 $p < 0.001$). Tukey HSD post hoc comparisons showed that GPP was significantly lower at Degerö compared to both Abisko and Mycklemossen, with Abisko showing the highest GPP across the Ta range. (Table 8)

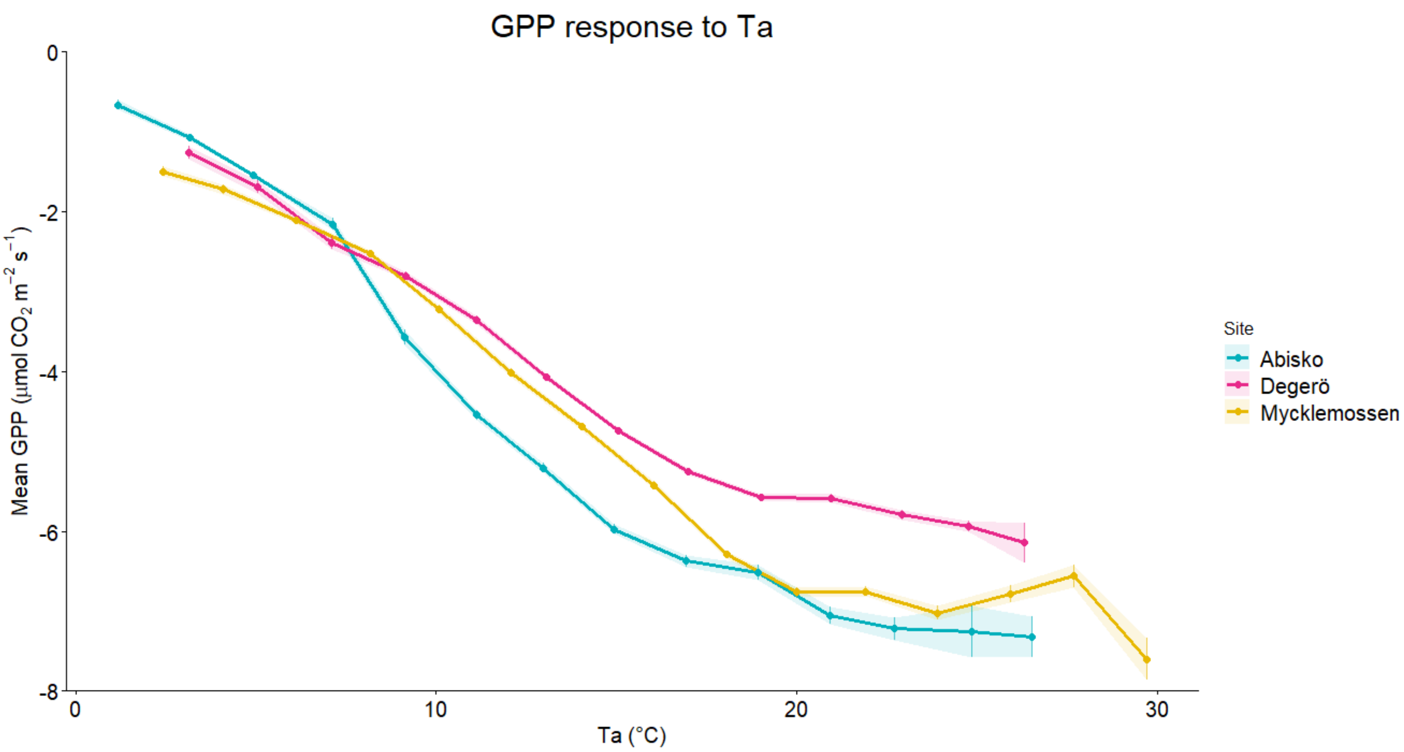

Figure 13. GPP response to Ta (2023–2024). Binned mean GPP as a function of air temperature (Ta) for three sites. Points show bin averages with uncertainty. Negative GPP values indicate net CO_2 uptake.

Figure 14 shows that emissions of CH_4 increased exponentially with Ta at all three sites. In Table 6 the strongest relationship was observed at Degerö, where temperature explained a large proportion of the variation in CH_4 flux. Abisko also showed a positive exponential response, however, the model fit was weaker. In contrast, the relationship was very weak at Mycklemossen. The exponential CH_4 temperature response was strongest at Abisko, intermediate at Degerö, and weakest at Mycklemossen (Table 9). Pairwise comparisons indicated significant differences in temperature sensitivity among all sites. Temperature sensitivity was lower at Degerö compared to Abisko, lower at Mycklemossen compared to Abisko, and lower at Mycklemossen compared to Degerö (Table 9).

Table 9. Estimated regression parameters for the relationship between CH_4 and temperature at the three study sites in 2023. Where a represents the baseline CH_4 flux and b the temperature sensitivity of CH_4 emissions.

Site	**a ± SE**	**b ± SE**	**R^2**
Abisko	0.0182 ± 0.0002	0.0743 ± 0.0011	0.30
Degerö	0.0246 ± 0.0002	0.0706 ± 0.0005	0.60
Mycklemossen	0.0214 ± 0.0013	0.0522 ± 0.0049	0.01

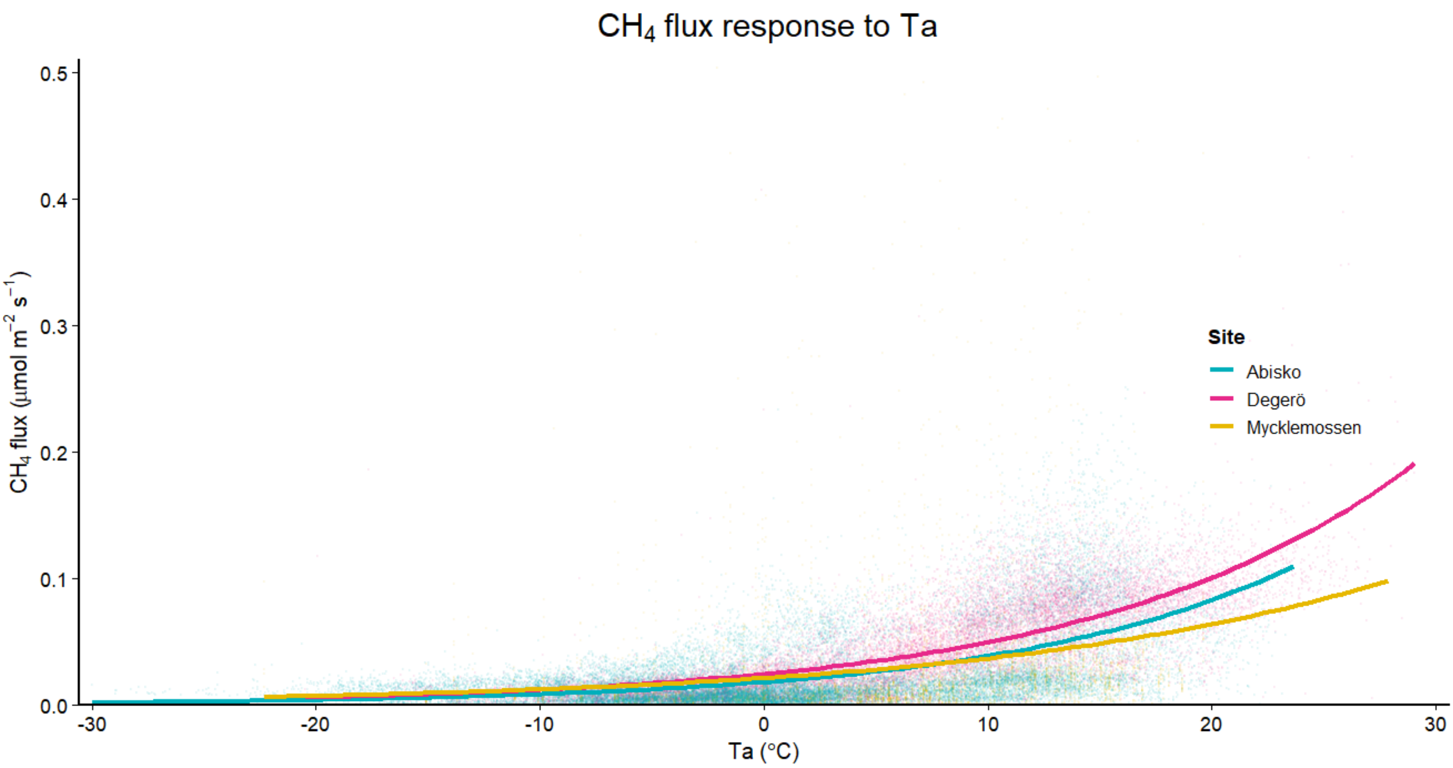

Figure 14. CH_4 response to Ta (2023–2024). Methane (CH_4) as a function of air temperature (Ta) for three sites. Points show observations and lines represent fitted temperature curves. Positive CH_4 values represent CH_4 emissions.

CH_4 flux showed a clear relationship with WTL across all sites, yet the pattern differed among all three sites (Fig. 15). Mycklemossen, exhibited low CH_4 emissions across the observed WTL range, with only minor variation in fluxes. Abisko showed relatively stable CH_4 fluxes across the observed WTL range, also with minor variation between bins. For Degerö, CH_4 flux decreased markedly as WTL approached the surface, with highest fluxes observed at lower (more negative) WTL values (Fig. 15). At the extremes of the WTL, variability increased, with the lower number of observations. CH_4 flux differed significantly among sites under high water table conditions (one-way ANOVA, $F_{2,10556} = 4062$, $p < 0.001$). Tukey HSD post hoc comparisons showed that all pairwise comparisons were statistically significant, with Abisko showing the highest CH_4 flux and Mycklemossen the lowest (Table 10).

Table 10. Tukey HSD post hoc test comparing methane (CH_4) among the three study sites across varying air temperature (Ta) conditions. The table shows mean differences in GPP, 95% confidence intervals (CI), and p-values

Comparison	**Mean difference (µmol m⁻² s⁻¹)**	**95% CI**	**p-value**
Degerö – Abisko	−0.0081	−0.0099 to −0.0062	< 0.001
Mycklemossen – Abisko	−0.0420	−0.0432 to −0.0408	< 0.001
Mycklemossen – Degerö	−0.0339	−0.0356 to −0.0322	< 0.001

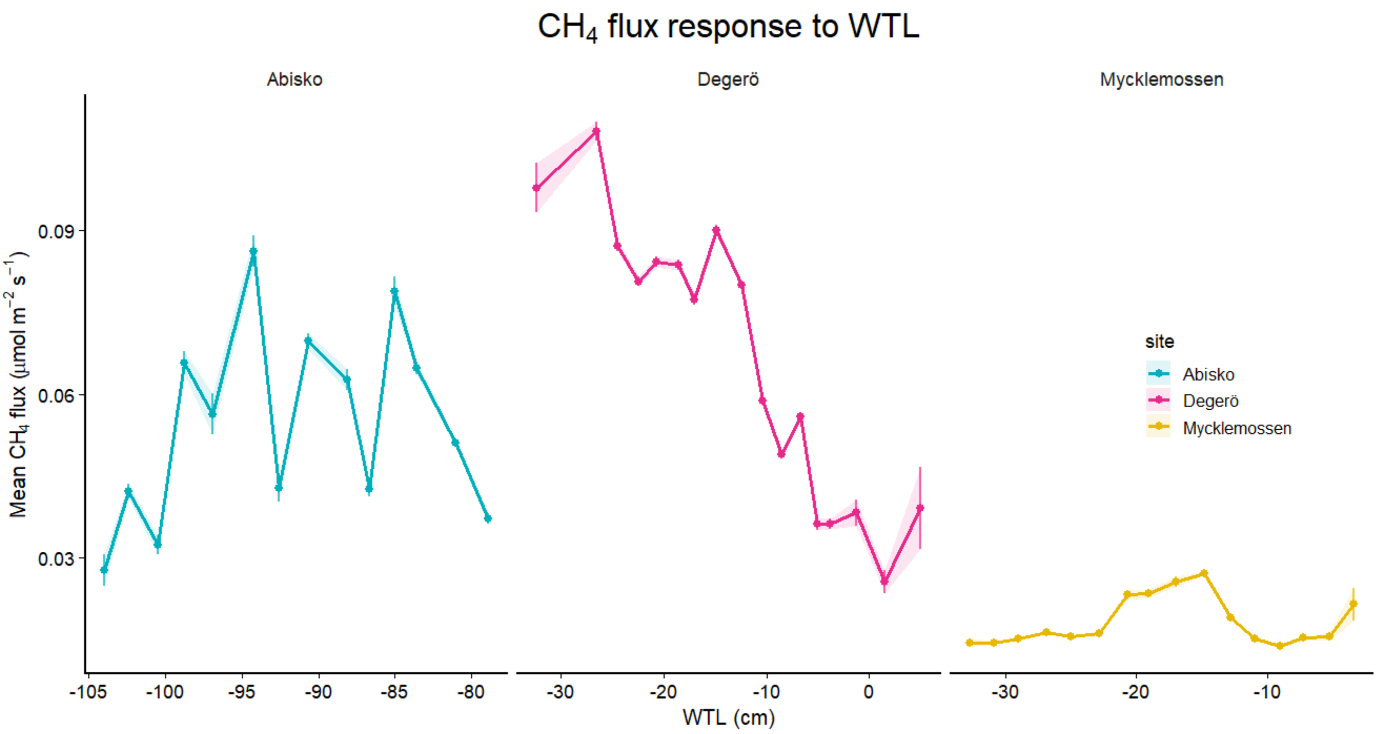

Figure 15. CH_4 response to WLT (2022–2024). Binned mean CH_4 as a function of water table level (WTL) for Abisko, Degerö and Mycklemossen. Points show bin averages with uncertainty.

3.3 Annual CO_2 and CH_4 flux budgets across peatland sites

Annual NEE budgets differed among the three peatland sites across the study years (Table 11). In 2023, both Degerö and Abisko functioned as net CO_2 sinks, whereas Mycklemossen functioned as a net CO_2 source with a positive NEE. However, in 2024, all three peatlands acted as net CO_2 sinks (Table 11), with Degerö showing the strongest uptake, followed by Abisko and Mycklemossen. All three sites were net sources of CH_4, with highest CH_4 emissions observed at Degerö and Abisko, while Mycklemossen showed lower emissions. Additionally, the GWP over a 100-year time horizon showed a positive net GHG balance despite CO_2 uptake for most of the years (Table 11).

Table 11. Annual net ecosystem exchange (NEE) and methane (CH_4) budgets for all sites year 2022, 2023 and 2024. Negative NEE values indicate net CO_2 uptake (sink), and positive values indicate net CO_2 release (source). GWP100 = global warming potential.

Site	Year	NEE[1]	CH_4[2]	CH_4[3]	CH_4[4]	CH_4[5]	NEE[6]	Net GHG balance[7]
Abisko	2023	-35.79	13.25	17.69	0.177	4.78	-1.31	3.46
Abisko	2024	-47.83	12.24	16.35	0.164	4.41	-1.75	2.66
Degerö Stormyr	2022	NA	13.89	18.55	0.185	5.01	-2.75	2.26
Degerö Stormyr	2023	-37.41	13.32	17.79	0.178	4.80	-1.37	3.43
Degerö Stormyr	2024	-74.18	NA	NA	NA	NA	-2.72	NA
Mycklemossen	2023	34.75	5.69	7.60	0.076	2.05	1.27	3.33
Mycklemossen	2024	-46.95	7.77	10.37	0.104	2.80	-1.72	1.08

[1] NEE (g C m^{-2} yr^{-1})
[2] CH_4 (g C m^{-2} yr^{-1})
[3] CH_4 (g CH_4 m^{-2} yr^{-1})
[4] CH_4 (t CH_4 ha^{-1} yr^{-1})
[5] CH_4 (t CO_2eq ha^{-1} yr^{-1})
[6] NEE (t CO_2 ha^{-1} yr^{-1})
[7] GWP100 (t CO_2eq ha^{-1} yr^{-1})

4. Discussion

The main research question was to explore differences in CO_2 and CH_4 fluxes among three peatland sites across a latitudinal gradient in Sweden and examine their relationship with different environmental variables. This study demonstrates that CO_2 fluxes across northern peatland sites are strongly regulated by environmental drivers, but the magnitude and impact vary along the latitudinal gradient. Ta was the dominant control on RECO, while GPP was primarily driven by SW_{IN} and atmospheric moisture conditions. In contrast, CH_4 fluxes showed more site-specific behaviour, reflecting the complexity of biogeochemical controls in peatland systems This study examines CO_2 and CH_4 flux dynamics by analysing both short-term responses to environmental drivers and longer-term seasonal and annual patterns, evaluated separately for each site.

4.1 Climatic trends across the latitudinal gradient

The observed climatic differences indicate a continued warming across all three sites. The strongest projected warming trend was observed in Norrbotten, followed by Västerbotten and Västra Götaland (Fig. 4), consistent with more rapid warming in the higher latitudes (IPCC 2021). This supports H1, with the largest increase in temperature projected at the northern site and the smallest in the south. Precipitation showed less directional change but increased variability across regions (Fig. 5), with implications for future peatland hydrology and CO_2 balance. The number of dry days is projected to decrease across all three sites, with the largest decrease in the northern and central regions, followed by a smaller decrease in the southern region (Fig 5). This shows that projected increases in total precipitation are consistent with fewer dry days across Sweden, and particularly in northern and central counties (Fig. 5 and Fig. 6). Year 2022 was an unusually warm, dry, and sunny year in Sweden. Temperatures were above normal across the entire country, making it one of the warmest years on record (SMHI 2022). In 2023, an initially warm and dry June was followed by heavy precipitation in August associated with Storm Hans, which caused widespread flooding particularly across central and northern Sweden (SMHI 2023). In contrast, 2024 was characterized by above-average temperatures across Sweden, warmest in the north, with above-normal autumn temperatures and elevated precipitation in western regions (SMHI 2025). These interannual differences in temperature and moisture availability likely contributed to the observed variation in annual carbon budgets between years (Table 11).

Mean annual temperature also followed a clear north–south gradient, with Mycklemossen being the warmest site, followed by Degerö and Abisko (Fig. 7).

This pattern was further reflected in VPD and SW_{IN}, with southern sites experiencing greater atmospheric drying and more incoming short-wave radiation (Fig. 7), both of which are key drivers of GPP. Although the SMHI climate projections provide are county-based, they provide a regional long-term context for the three study sites, as expected warming and altered precipitation, likely will influence local hydrology, and in turn affect both CO_2 and CH_4 emissions. Furthermore, this site-based flux analysis offer insight into how current ecosystem responses to environmental drivers may reflect future conditions under a changing climate.

4.2 Environmental controls on CO_2 and CH_4 fluxes

Temperature is an environmental variable that shows a strong impact on CO_2 uptake in peatlands (Helbig et al 2017.), as it influences respiration and photosynthesis. This study confirmed the established non-linear exponential response of RECO to Ta across all three sites (Fig. 7) (Lloyd & Taylor 1994), supporting H2, as Ta sensitivity differed across the latitudinal gradient. The observed higher RECO at equivalent Ta in Mycklemossen than Abisko and Degerö, are aligned with findings of Gong et al. (2013), who reported stronger Ta responses in southern compared to northern peatlands in Finland. Site-specific ecosystem traits, such as vegetation phenology and moisture conditions, regulate the temperature sensitivity of RECO (Järveoja et al. 2018). The low baseline RECO in Degerö, despite the high Ta sensitivity, may suggest that microbial decomposition responds rapidly to changing Ta (Table 3) (Davidson and Janssens 2006), indicating that respiration may be more temperature-limited rather than substrate-limited at this site.

For GPP, results showed a contrasting pattern across the latitude to all three abiotic factors, SW_{IN}, VPD and Ta, reflecting the different climate and ecosystem conditions at each site (Figs. 11-13) and partly supporting H4. Mycklemossen showed the highest Pmax and an intermediate light-use efficiency (Table 5). However, Abisko that exhibited the lowest Pmax but highest alpha (Fig. 8, Table 5), potentially reflecting adaptation to a short but intense growing season in high-latitude ecosystems. Moreover, the results highlight both the latitudinal and site-specific differences, likely reflecting the warmer southern climate in Mycklemossen and longer growing seasons compared to Abisko in the north. During the growing season, SW_{IN} is usually correlated with Ta. Consequently, the great variability in Pmax for Mycklemossen (Table 5), suggests that factors beyond SW_{IN} drive GPP, such as WTL, Ta, or vegetation composition (Limpens et al 2008). For Abisko the strong increase for GPP and Ta is observed already at lower temperatures (Fig. 13). This is a similar pattern to the GPP and SW_{IN} response, and may reflect adaptation to a short but intense growing season and rapid increase in

GPP (Gallego-Sala et al. 2018). Moreover, this suggests that vegetation at this high-latitude site may be highly responsive to even moderate warming. Degerö showed an intermediate response, increasing more gradually but continuing to rise at higher Ta similarly to Mycklemossen (Fig. 13). Hence, Mycklemossen continued to increase beyond 20 degrees, reflecting its warmer baseline (Fig. 13, Table 9). GPP increased with VPD at all sites until VPD reached high values (Fig. 2). Abisko exhibited the highest values, while the lowest values in Degerö and Mycklemossen (Fig. 12, Table 7). However, Degerö appeared to maintain uptake at high VPD, which may reflect the minerogenic fen, that possibly could help sustain soil moisture availability even under periods of high atmospheric demand (van der Velde et al. 2021), in contrast to Abisko and Mycklemossen, both of which are bogs.

The CH_4 fluxes reflect the complexity of CH_4 dynamics in boreal peatland ecosystems and limitations of only using single predictors. CH_4 responses to both Ta and WTL differed significantly among sites (Fig. 14 and 15), supporting H4. CH_4 showed an exponential response to Ta across all sites (Fig. 14, Table 9). In Degerö increases in temperature led to larger increases in CH_4 emissions, which is consistent with the Ta dependence of methanogenesis described across a broad range of wetland ecosystems (Yvon-Durocher et al. 2014). The observed weak CH_4 response to Ta at Mycklemossen (Fig. 14), could indicate that Ta alone is insufficient to explain CH_4 flux at this site, suggesting that drivers such as hydrology, vegetation may play a dominant role in regulating CH_4 production (Keane et al. 2021). This is consistent with findings by Gong et al., (2013b), who demonstrated that CH_4 flux controls in bog ecosystems are more complex than in fens, partly due to greater seasonal variability in WTL, which deepens the aerobic layer and promotes oxidation (Rinne et al. 2018). The intermediate Ta dependence of CH_4 observed at Abisko (Fig 14, Table 9) suggests that Ta only partially explains CH_4 flux dynamics at this site, and that site-specific conditions such as hydrology may play a larger role. The variable CH_4 emissions at Abisko likely reflect its bog hydrology and discontinuous permafrost (Łakomiec et al. 2021), where deep and stable anaerobic conditions may decouple CH_4 production from short-term Ta changes (Fig. 15) (Lai 2009). However, this may change as permafrost thaws under projected warming conditions. Furthermore, the relationship between CH_4 emissions and WTL is not straightforward. The observed results for Degerö show a decline in CH_4 with a high WTL in Degerö (Fig. 15). A study conducted by Rinne et al., (2007) at the Siikaneva fen revealed that CH_4 flux was weakly negatively correlated with WTL, however, a sudden rise in WTL coincided with a drop in emissions. This may reflect ebullition dynamics, where a falling WTL reduces hydrostatic pressure and triggers bubble release, which is then suppressed when WTL rises again. These findings suggest that the decline in CH_4 at high WTL observed at Degerö may be driven by similar mechanisms. WTL is often considered a key control on CH_4 emissions, with several studies showing a strong positive relationship (Updegraff et al. 2001), it is not consistent across time, as the importance of WTL and Ta can vary seasonally, and in some cases CH_4 emissions show weak or no dependence on WTL. This is particularly relevant given the variation among peatland types, including fens and bogs (Rydin & Jeglum 2013). For instance, in boreal fens, surrounding ecosystems can influence WTL through evapotranspiration and groundwater interactions (Limpens et al. 2008). At Mycklemossen, the lower CH_4 emission may suggest that hydrological variability interacts with other drivers to control emissions. Therefore, compared to fens, bog CH_4 dynamics may be less tightly coupled to short-term WTL fluctuations, since bogs are solely dependent on precipitation and therefore more prone to experience drier conditions and lower WTL. Drier conditions also increases oxygen availability in the peat profile and suppresses methanogenesis, while enhancing CH_4 oxidation (Rydin & Jeglum 2013; White et al. 2023). However, during summer and dry periods it is usually peak plant production and warm, which could support CH_4 production, partly offsetting the suppressing effect of lower WTL on methanogenesis. In this context, the relatively stable number of dry days projected across all regions (Fig. 3) suggests that future changes in CH_4 dynamics may be driven more by temperature and growing-season productivity (Updegraff et al. 2001). Moreover, White et al. (2023) reveal that vegetation such as *Eriphorium vaginatum* have an aaerenchyma tissue, that simplify transport of CH_4 without oxidizing to CO_2, which could result in more CH_4 emissions on sites with more *Eriphorium vaginatum.* As all three sites contain this species (Table 2), though differences in its abundance may influence the observed variation in CH_4 emissions between sites.

4.3 Seasonal and annual CO_2 and CH_4 budgets

The annual budgets varied both between sites and across years (Table 11), reflecting the influence of environmental variables on ecosystem fluxes and supporting H2. Abisko and Degerö acted as net CO_2 sinks in both 2023 and 2024, while Mycklemossen acted as a CO_2 source in 2023 but shifted to a sink in 2024 (Table 11). These differences may indicate variation in some environmental impact.

The positive annual NEE observed at Mycklemossen may reflect the interannual climate variability. RECO may increase under warmer and potentially drier conditions, as lower WTL during drought and increased temperature can increase oxygen availability in peat soils, thereby stimulating aerobic decomposition and increasing net CO_2 emissions (Rinne et al. 2020; Keane et al. 2021). This is consistent with the highest mean Ta in Mycklemossen (Fig. 7), which may promote microbial activity. The shift to a net CO_2 sink in 2024 (Table 11), may suggest more favorable moisture conditions that suppress aerobic decomposition and allow GPP to dominate the carbon balance. However, this shift illustrates how vulnerable peatlands are to interannual variation in climate and hydrology.

CH_4 budgets also differed between sites, with Degerö showing the highest emissions (Table 11), consistent with its fen characteristics, though as discussed, the relationship between WTL and CH_4 at this site is not straightforward. The comparatively lower emissions at Mycklemossen may reflect a deeper or more variable water table, limiting the anaerobic zone available for CH_4 production.

All three sites revealed a positive GHG balance under global warming potential 100 over a 100-year time horizon (GWP100), when CH_4 was included (Table 11). GHG balance for Abisko, Degerö and Mycklemossen are positive, meaning all three sites are acting as a source rather than a sink, despite the net CO_2 uptake for Abisko and Degerö during the study period, and year 2024 for Mycklemossen. This illustrates the difficulty of predicting peatland carbon balance under climate change, highlighting the need for site-specific assessments when evaluating the climate benefit of restoring drained peatland forests towards natural peatlands both national and international scales. However, this is from a 100-year time horizon, longer than that, CO_2 uptake may offset CH_4 emissions. The results indicate that it is highly site-specific and temporal changes influence CO_2 and CH_4 fluxes. The latitudinal gradient may influence the site-specific conditions and therefore their response to environmental variables. However, since the sites also differ in peatland type, where both Abisko and Mycklemossen are bogs and Degerö a fen, it is difficult to determine whether differences are driven by latitude or by peatland type. Although the relatively short study period of three years may not fully capture long-term ecosystem behaviour, the strong temperature sensitivity at Degerö for both RECO and CH_4, and the projected warming in these regions may lead to an increase in GHG emissions from this site in the future.

4.4 Study limitations and future research.

The largest limitation in this study is the short study period, which affects the robustness of the results and the ability to identify long-term trends. Moreover, eddy covariance measurements come with uncertainties, including those introduced by gap-filling procedures, which also may affect the reliability of the flux estimates. The study period covered only two years, and when testing whether peatlands differed significantly in relation to environmental variables, only a single year was used, because of data limitations. This limitation may affect the robustness and applicability of the results. In addition, the ANOVA analysis was restricted to the last four bins, which may reduce the completeness of the comparison and potentially lead to the omission of relevant variation across the full range of data.

This approach captures responses under the most extreme conditions, meaning that it may be more representative under extreme conditions than the entire environmental gradient. Furthermore, the use of single predictors in this analysis may not fully capture the multivariate complexity of CH_4 and CO_2 fluxes, as reflected in the variability observed in the result. The study includes two bog sites and one fen, which limits direct comparisons between peatland types. Future research should therefore include longer study periods and sites with the same peatland type across latitudinal gradients.

4.5 Conclusion

This study demonstrates that the three peatlands exhibited considerable variability in their GHG dynamics, both among sites and between years. While all sites functioned as net CO_2 sinks in most years, CH_4 emissions resulted in a positive net GHG balance, highlighting the importance of accounting for both CO_2 and CH_4 when evaluating the climate impact of peatlands. Climatic conditions across Sweden also reflect spatial differences in climate conditions along the latitudinal gradient, with generally warmer and more variable conditions in southern Sweden, whereas northern Sweden remains colder but has experienced a pronounced increase in temperature in recent decades. The differences in GHG dynamics among the three sites may also reflect differences in peatland type and vegetation composition. Fens and bogs differ fundamentally in their hydrology, nutrient availability and plant communities, which in turn influence both CO_2 and CH_4 fluxes. This suggests that peatlands may respond differently to climate change depending on their type and surrounding ecosystem, and that site-specific characteristics must be considered when projecting future GHG balances under changing conditions.

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Use Of Artificial intelligence (AI) tools

I used ChatGPT-5 (OpenAI) as a programming assistant for R coding and Claude Sonnet 4.6 (Anthropic, 2025) to copyedit the manuscript. I reviewed and edited the content as needed and take full responsibility for it

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Popular science summary

For thousands of years peatlands have accumulated decomposed plant material in waterlogged landscapes. Despite only covering approximately 3 % of the world´s land area, peatlands store one-third of the worlds soil carbon and almost twice as much as forests. This makes peatlands a valuable ecosystem when it comes to climate regulation. Sweden is an elongated country, with temperate forests in the south to subarctic tundra in the north and home to a variety of peatlands. This study investigates CO_2 and CH_4 fluxes across three contrasting peatlands along a latitudinal gradient in Sweden, located in the north, central, and south of the country. Northern and southern sites are bogs and the central is a fen. The aim was to examine their response to key environmental variables including temperature, incoming short-wave radiation, water table levels and vapour pressure deficit. The results revealed significant differences between the peatlands. Firstly, the peatland in the most southern region acted as a CO_2 source, while the other two as net CO_2 sinks. However, this changes for the next year, where all acted as net CO_2 sinks. CH_4 is a more potent greenhouse gas in the short term, and when including CH_4 in the global warming potential over a 100-year horizon, all three sites show a net warming effect. The response to environmental variables differed between the three peatlands, where northern peatlands respond quick to changing temperature and light, while central and southern peatlands a more moderate response but longer photosynthetic period. CH_4 emissions and ecosystem respiration were most sensitive at the central peatland, which suggest that this peatland responds strongly to warming. The relationship between water table levels and CH_4 emissions is not straightforward. At central fen CH_4 emissions declined with high water table levels, while at the northern site the water table level was generally low but with emission peaks. The southern site showed the most stable, where both water table level and emissions remain relatively consistent. Climate projections indicate that temperature will rise most in northern Sweden, which could alter how these ecosystems function. Warmer conditions can accelerate decomposition and releasing stored CO_2, therefore change whether peatlands act as sinks or sources. However, these findings come with uncertainty, as their behaviour is very site-specific and influenced by peatland type.

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