



Diurnal patterns in methane fluxes vary along a boreal hydrological gradient

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Abstract. Methane (CH₄) exchange in peatland landscapes is strongly controlled by hydrological conditions and exhibits pronounced spatial and seasonal variability. However, much less is known about how CH₄ exchange varies over the course of a day and whether the drivers of diurnal variability differ across hydrological gradients. We investigated seasonal and diurnal CH₄ flux dynamics across a hydrological gradient in the Siikaneva peatland complex, Finland, comprising a well-drained upland forest, an intermediate transition site, and an ombrotrophic bog. Automated chamber measurements were used to quantify CH₄ fluxes at high temporal resolution over an annual cycle and to identify environmental controls on diurnal variability.

Methane exchange ranged from persistent daily mean uptake of up to $-6.6 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ at the upland forest to persistent emissions of up to $108.5 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ at the bog. All sites exhibited pronounced diurnal variability, but the direction and seasonal expression of these patterns varied along the hydrological gradient. The bog and intermediate sites generally showed greater CH₄ emissions or weaker uptake during nighttime than daytime, whereas the upland forest exhibited stronger CH₄ uptake at night. While the bog remained a net CH₄ source throughout the year, the intermediate site shifted seasonally between continuous uptake during autumn and winter and daytime uptake combined with nighttime emissions during spring and summer. Maximum day–night differences reached $146.0 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ at the bog but only 4.2 and $6.5 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ at the upland and intermediate sites, respectively.

The environmental controls on diurnal CH₄ variability differed systematically among sites. At the upland forest, CH₄ flux variability was most strongly associated with ecosystem



respiration (ER), ambient atmospheric CH₄ concentrations, and air temperatures, potentially reflecting links between ecosystem carbon cycling and methanotrophic activity and enhanced near-surface CH₄ concentrations under stable nocturnal boundary-layer conditions. At the intermediate site, CH₄ variability was associated with ambient CH₄, PAR, and an interaction between shallow soil temperature and soil moisture, indicating that temperature effects on CH₄ exchange became stronger under wetter conditions. This may reflect greater sensitivity of CH₄ oxidation to diurnal temperature fluctuations when high water tables restrict the aerobic layer. At the bog, CH₄ variability was most strongly associated with ER, soil temperature, and water table position, consistent with interactions between ecosystem carbon supply, temperature-sensitive CH₄ production and oxidation, and hydrological control of their balance. Together, the results suggest that processes governing short-term CH₄ variability differ from those controlling seasonal mean fluxes and that CH₄ oxidation can contribute substantially to diurnal variability even at sites where CH₄ production dominates net CH₄ exchange.

Our findings indicate that neglecting diurnal variability can substantially influence CH₄ budget estimates and apparent differences among ecosystems, highlighting the importance of high-frequency measurements for both process understanding and accurate quantification of ecosystem-scale CH₄ exchange across heterogeneous boreal landscapes.

1 Introduction

Boreal ecosystems play an important role in the global CH₄ budget due to their extensive wetlands, large soil carbon (C) stocks, and strong spatial heterogeneity in hydrological conditions. Boreal wetlands are among the largest natural CH₄ sources globally, where waterlogged soils promote anaerobic decomposition and methanogenesis (Euskirchen et al., 2014; Hugelius et al., 2020). Well-drained upland soils on the other hand can act as atmospheric CH₄ sinks through microbial oxidation (Emmerton et al., 2014; Virkkala et al., 2024; Voigt et al., 2023). The balance between CH₄ production and oxidation is strongly controlled by soil moisture and water table position, resulting in pronounced differences in CH₄ exchange across boreal landscapes (McGuire et al., 2012; Whalen, 2005). However, boreal landscapes are rarely composed solely of clearly separated wetland and upland ecosystems. Transitional areas with intermediate hydrological conditions, characterized by seasonally fluctuating water tables, are widespread and may represent particularly dynamic environments where small changes in hydrological conditions can shift the relative importance of methanogenesis and methanotrophy (Baysinger et al., 2025; Paradis et al., 2015). Understanding CH₄ dynamics across the entire range of hydrological conditions, from well-drained uplands to water-saturated wetlands, is therefore essential for improving estimates of boreal CH₄ budgets.

Methane fluxes vary strongly at seasonal timescales, with both wetland CH₄ emissions and upland CH₄ uptake generally peaking during the warm growing season. In wetlands, higher temperatures and increased substrate availability stimulate CH₄ production, whereas in upland soils warmer conditions enhance methanotrophic activity and CH₄ oxidation (Dunfield et al., 1993; Whalen, 2005). Transitional ecosystems may show particularly complex seasonal dynamics, because changes in water table position can alter the balance between CH₄ production and oxidation over relatively short timescales (Paradis et



al., 2015). In addition to seasonal variation, recent studies have highlighted substantial variability at sub-daily timescales, demonstrating that CH₄ fluxes can exhibit pronounced diurnal cycles driven by interactions among temperature, hydrological conditions, microbial activity, vegetation, and atmospheric processes (e.g., Duan et al., 2025; Long et al., 2010; Mikkilä et al., 1995; Voigt et al., 2023).

Observed diurnal CH₄ dynamics often do not strictly follow the daily temperature cycle and therefore provide important insights into the processes regulating CH₄ exchange beyond the established temperature-dependence of both methanogenesis and methanotrophy (Dunfield et al., 1993). Several peatland studies have reported maximum CH₄ emissions during nighttime and upland soils have similarly been found to exhibit enhanced nighttime CH₄ uptake despite lower nighttime temperatures (e.g., Dooling et al., 2018; Mikkilä et al., 1995; Voigt et al., 2023). These patterns suggest that additional processes contribute to regulating short-term CH₄ exchange, such as differences in the spatial distribution of CH₄ production and oxidation processes within the soil profile, hydrological constraints, substrate availability, and vegetation-mediated transport.

Despite increasing recognition of diurnal CH₄ variability, the mechanisms generating these patterns remain poorly constrained. Previous studies have reported contrasting diurnal patterns among ecosystems, vegetation communities, and measurement approaches. In wetlands, both nighttime and daytime emission maxima have been observed, with differences potentially reflecting methodological effects as well as genuine ecological variation (Koskinen et al., 2014; Kowalska et al., 2013; Lai et al., 2012; Long et al., 2010; Mikkilä et al., 1995). Similarly, upland soils can exhibit diurnal patterns in CH₄ uptake that differ from the dynamics expected based on temperature dependence alone, potentially reflecting interactions between methanotrophic activity and ecosystem respiration (Voigt et al., 2023). Moreover, most studies investigating diurnal CH₄ variability have focused on summer or the growing season, when soil temperatures and vegetation activity are highest. Consequently, the seasonal development of diurnal CH₄ patterns and their persistence during colder periods are poorly understood.

This lack of year-round observations limits our ability to determine whether diurnal CH₄ dynamics represent persistent ecosystem characteristics or transient responses to seasonal environmental changes. Furthermore, disregarding diurnal variability, as often done in manual chamber-based studies, can introduce uncertainty into CH₄ budget estimates as daytime measurements only might not be representative of daily mean fluxes (Dooling et al., 2018; Mikkilä et al., 1995; Voigt et al., 2023). High-frequency automated measurements across seasons and contrasting ecosystems are therefore needed to quantify the magnitude, timing, and environmental controls of diurnal CH₄ variability.

In this study, we investigate seasonal and diurnal CH₄ flux dynamics across a natural hydrological gradient in boreal Finland using one year of high-frequency automated chamber measurements. The study includes an upland forest, a transitional intermediate ecosystem, and a bog, representing a gradient from well-drained upland conditions with persistent net CH₄ uptake to waterlogged bog conditions characterized by net CH₄ emissions.

This design allows us to assess whether diurnal CH₄ patterns and their environmental controls change systematically along hydrological gradients and whether transitional ecosystems exhibit unique dynamics compared with the two end



members. Specifically, we aim to (1) quantify seasonal changes in the magnitude and structure of diurnal CH₄ variability over a complete annual cycle, (2) compare diurnal CH₄ patterns among ecosystems differing in hydrological conditions, and
 95 (3) identify the environmental and biological processes controlling diurnal CH₄ patterns at each site along the hydrological gradient. By extending observations beyond the growing season and across a hydrological gradient, this study provides new insights into the temporal dynamics of boreal CH₄ exchange and improves the understanding of the processes regulating short-term CH₄ variability in heterogeneous boreal landscapes.

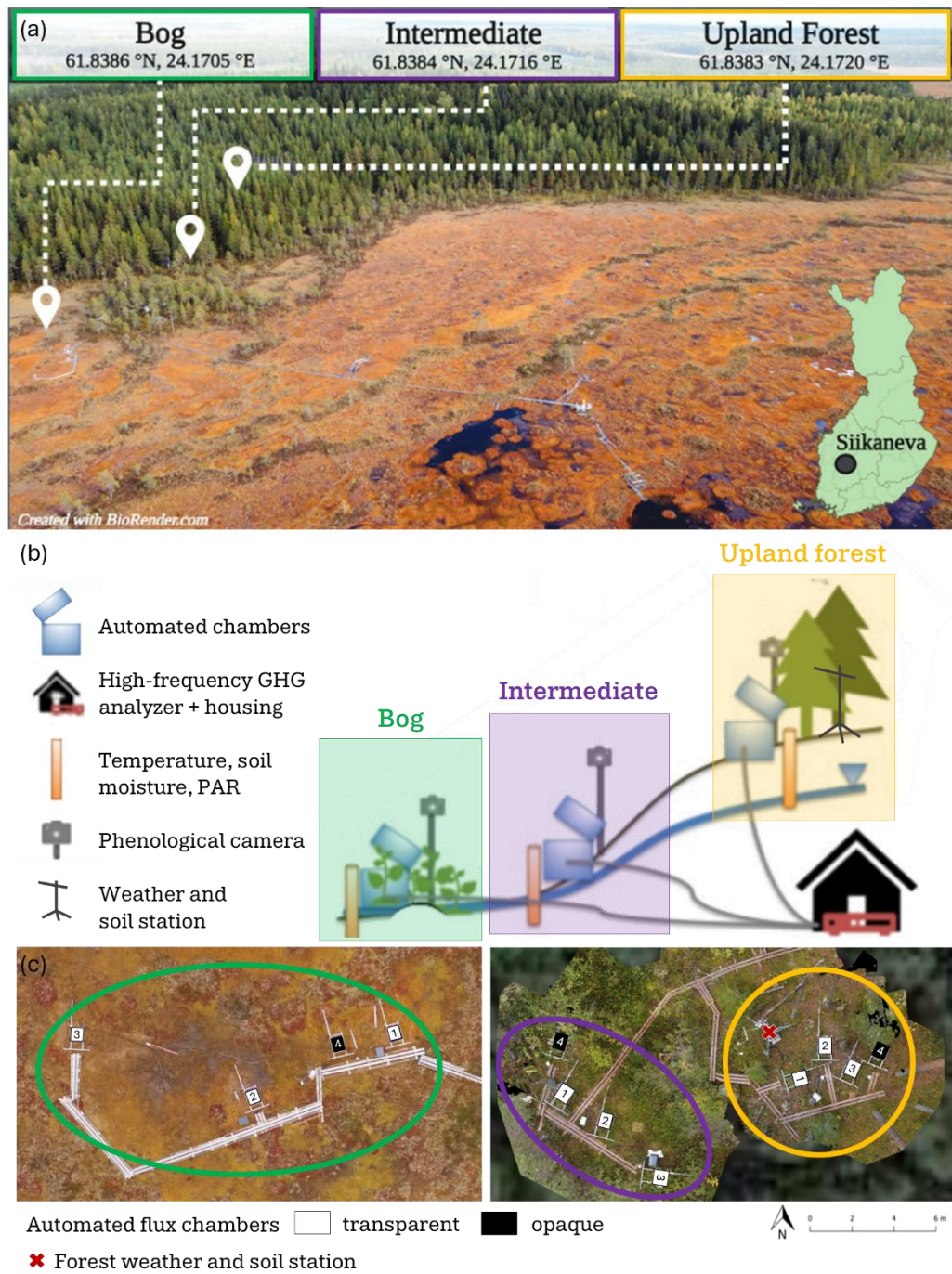
2 Methods

100 2.1 Study site and hydrological gradient

Measurements were conducted in the bog part of the oligotrophic Siikaneva peatland complex in boreal southern Finland (61°50' N and 24°12' E, 169 m a.s.l.) (Figure 1a) from 1 January to 31 December 2022. The long-term mean annual temperature and annual precipitation sum in the area are 4.1 °C and 688 mm, respectively, according to 30-year averages (1993–2022) from the Juupajoki–Hyytiälä weather station that is located 6.3 km east of the bog site (Finnish Meteorological
 105 Institute, 2023a). About one-third of the annual precipitation falls as snow (Riutta et al., 2020) and the area is typically snow-covered for six months from late October until late April.

An automated chamber system was established at three microsites along a hydrological gradient representing well-drained upland forest conditions, intermediate conditions at the forest margin, and saturated bog conditions during much of the year (Figure 1a, Figure A1). The microsites span a distance of approximately 85 m with an elevation gain of about 2 m
 110 from the bog to the intermediate site and about 1 m from the intermediate to the upland forest site. The vegetation of the forest microsite is characterized as Scots Pine (*Pinus sylvestris*) forest with the understory dominated by feather moss (*Hylocomium splenens*), ferns (*Dryopteris dilatata*) and lichen (*Cladonia spp.*). The soil profile is a ~60 cm deep Podzol according to the World Reference Base for Soil Resources (WRB, IUSS Working Group, 2014). The intermediate microsite has a sparser tree cover than the upland forest and is characterized by blueberry (*Vaccinium myrtillus*), bog rosemary, and
 115 cranberry shrubs. The soil type at the intermediate site is a Histosol with highly decomposed peat. The soil profile is affected by a strongly varying WTD over time, resulting in the formation of 2–5 cm thick air-filled gaps at approximately 20 cm below the soil surface when the WTD falls below 25 cm depth.

The bog microsite is located in a low-lying hollow area of the patterned bog and has a moss layer consisting of *Sphagnum cuspidatum* and *Sphagnum majus*, and a vascular plant cover dominated by aerenchymatous sedges, such
 120 as *Carex limosa*, *Rhynchospora alba* and *Scheuchzeria palustris* (Korrensalo et al., 2018) on a soil categorized as Histosol with only slightly decomposed peat reaching down to 2 m. Detailed soil properties at the three sites can be found in Baysinger et al. (2025).



125 **Figure 1: Location and instrumentation of three microsites covering a hydrological gradient, ranging from the wet bog over an intermediate site to a drained upland forest, at Siikaneva peatland, Finland.** (a) Location of the Siikaneva peatland within Finland and of the three microsites within Siikaneva bog (adapted from Baysinger et al., 2025). (b) Schematic of the measurement setup along the hydrological gradient. (c) Top view of the sites and locations of chamber replicates along the hydrological gradient obtained from drone images. Drone images in (a) and (c) were taken in August 2022 by ©T. Rettelbach and L. Golde.



130 2.2 Automated chamber system

The automated chamber system (SUVILUMI OY, Finland) was built and implemented based on the design of Koskinen et al. (2014), who describe the system operations and performance in detail. Briefly, the basic system structure includes a stainless-steel frame with the chamber as a moveable lid, a stainless-steel collar inserted 10 cm into the ground, a waterproof actuator (Linak Techline LA-35, Linak, 2009) to move the lid and threaded steel rod legs and bolts, on which rests the weight of the construction. U profiles under the edges of the chamber lids insulated with foam tape ensured air-tight sealing. During winter, the frame can be lifted to add snow extensions according to the developing snow height. The chamber dimensions are 60 cm x 60 cm x 40 cm (l x w x h; ~144 L) to accommodate shrubs inside the system. According to the extensions, the additional headspace of the collar is added to the chamber volume when calculating the total headspace and corrected for vegetation or snow cover inside each chamber by measuring the vegetation or snow height on four sides inside the collar and taking the average. A fan ensures constant mixing of the air inside the chamber headspace. A pressure vent ensures equalization during changing environmental conditions and sampling.

Each of the three microsites accommodates three transparent chamber replicates and one opaque chamber (Figure 1c). The opaque chamber measures the ecosystem respiration (ER) compared to the Net Ecosystem Exchange (NEE) of CO₂ of the transparent chambers. The three transparent chamber replicates were strategically chosen to represent each microsite's heterogeneity in vegetation and topography. The chambers close one after another following a set schedule, alternating the chambers from each microsite (Table A1). The measurement setup allows for 48 separate measurements per day for the total of 12 chambers, equalling four flux measurements per chamber and day. A multiplexer switches between the sampling loops of the chambers with two minutes of flush time with ambient air before each chamber closure. During flush time, ambient CH₄ concentrations are derived as the average of the CH₄ concentration measurements from the open chamber. To avoid heat stress on the plants during the day but include traceable changes of lower concentrated gases such as CH₄ and N₂O, we compromised the chamber closure to 10 min during summer but extended it to 20 min during autumn and winter (since 23 September 2022) to increase the detection limit of small fluxes, in particular of N₂O.

During chamber closure, a headspace gas sample is pumped through polyurethane tubes by a Picarro internal vacuum pump (flow rate up to 230 sccm) into an in-situ Picarro G2508 (Picarro, USA) located in a nearby shed, which continuously measures CO₂, CH₄, N₂O and H₂O concentrations once per second with cavity ring-down spectroscopy (CRDS). Afterwards the gas sample is discarded through a vent. The lag times resulting from the various sample line lengths were accounted for during the data processing and flux calculation.

2.3 Ancillary measurements

Each chamber was equipped with three platinum resistance temperature sensors (IKES-50-6.0-5M PT100, Nokeval, Finland) measuring air temperature inside the chamber and soil temperature at 2 cm and 10 cm depth at an accuracy of ±0.3



°C. At the upland forest and intermediate sites, soil volumetric water content (VWC) in the upper 10 cm of soil was measured using ML3 ThetaProbe sensors (Delta-T Devices Ltd., UK), which estimate soil moisture at an accuracy of $\pm 0.01 \text{ m}^3 \text{ m}^{-3}$ over $0-0.5 \text{ m}^3 \text{ m}^{-3}$ and $0-40 \text{ }^\circ\text{C}$ from the dielectric permittivity of the surrounding soil using a 100 MHz electromagnetic signal (Delta-T Devices Ltd, 2017). The bog microsite was regularly waterlogged and therefore VWC measurements were replaced by measurements of the WTD. Photosynthetically active radiation (PAR) was measured at each microsite with PQS1 quantum sensors (Kipp & Zonen, Netherlands) which quantify photon flux density in the 400-700 nm waveband (Kipp & Zonen, n.d.). PAR measured at the forest and intermediate microsite has limited relevance for the individual chambers due to inconsistent shading by the surrounding trees but rather represents general PAR levels of the respective microsite. Environmental variables measured at the chamber sites were recorded every 3 s and averaged over the first minute of each chamber measurement to be matched with the half-hourly flux data.

When no site-specific environmental data were available for the bog site, data was used from the SMEAR II Siikaneva 1 wetland (Pavel Alekseychik et al., 2024) station in 1 km distance. From this station, additionally, air temperature, air pressure, wind speed and snow depth data were obtained for the open bog at half-hourly resolution. For the upland forest and intermediate sites, these variables were provided by a weather station located at the forest microsite at half-hourly resolution (Boike et al., 2026; Figure 1c).

2.4 Flux calculation

The flux calculation was done in the R environment (R version 4.1.2). CO_2 and CH_4 fluxes were calculated from the temporal change in gas concentration over 8 min during each chamber closure. Measured CO_2 and CH_4 concentrations C (ppm) were first converted to pressure- and temperature-corrected gas amounts per unit chamber area X ($\mu\text{mol m}^{-2}$) using the ideal gas law:

$$X = C \frac{PV}{RTA} \quad (1)$$

where P is air pressure (Pa) measured at the SMEAR II Siikaneva 1 wetland station, V is the chamber-specific headspace volume (m^3), T is chamber air temperature (K), A is the chamber surface area (m^2), and R is the universal gas constant ($8.314 \text{ Pa m}^3 \text{ mol}^{-1} \text{ K}^{-1}$). Chamber temperature measurements (every 3 seconds) were interpolated by linear regression to correct the concentration measurements (per second, Hz).

The pressure- and temperature-corrected gas amounts were then regressed linearly against time t (s) during each chamber closure. Gas fluxes F ($\mu\text{g m}^{-2} \text{ s}^{-1}$) were calculated from the regression slope $\frac{dX}{dt}$ ($\mu\text{mol m}^{-2} \text{ s}^{-1}$) as

$$F = \frac{dX}{dt} M \quad (2)$$

where M is the molar mass of the respective gas (16.04 g mol^{-1} for CH_4 and 44.01 g mol^{-1} for CO_2). Positive fluxes indicate net emissions from the soil to the atmosphere, whereas negative fluxes indicate net uptake.



Non-linear flux calculation approaches were tested for the data set, such as the HMR package in R (Pedersen, 2020), but as those produced anomalously high or low flux estimates for some chamber measurements, we decided that the linear fit was overall the better alternative, as also indicated by Pirk et al. (2016).

2.5 Data analysis

2.5.1 Data coverage and quality control

Prior to quality filtering, CH₄ flux data availability for the measurement year 2022 was 75 % at the upland forest site and 74 % at both the intermediate and bog sites. The reduced data availability primarily resulted from a chamber system failure for almost two months between 13 July and 3 September 2022. A detailed overview of data coverage by site and season can be found in Table A2.

To ensure data quality, CH₄ flux measurements were screened for outliers separately for each chamber. A rolling mean and rolling standard deviation were calculated using a moving window of 80 measurements while allowing missing values within the window. Flux observations exceeding ± 3 standard deviations from the rolling mean were classified as outliers and removed. In addition, measurements during the periods immediately before and after the extended summer data gap were visually inspected and excluded from further analyses when the chamber system was judged to be operating unreliably. Following quality control, data coverage was reduced to 72 %, 71 %, and 67 % for the upland forest, intermediate, and bog sites, respectively. These filtered datasets were used for all subsequent analyses. The filtering and subsequent data analyses were done in R (Version 4.5.0). All timestamps are expressed in Finnish standard time (UTC+2) throughout the year, without adjustment for daylight saving time.

2.5.2 Seasonal and site differences in diurnal patterns in CH₄ fluxes

To characterize seasonal and site-specific differences in the strength and shape of diurnal CH₄ flux patterns along the hydrological gradient, the measurement period was divided into seasons and CH₄ fluxes were aggregated across the four chambers within each site.

Seasons were defined according to the classification of the Finnish Meteorological Institute (FMI, 2024) based on daily mean air temperature thresholds that persisted for at least three consecutive days using temperature measurements from the upland forest site weather station. Winter was defined as periods with mean daily air temperatures below 0 °C (until 8 April 2022 and from 15 November 2022 onward). Spring (9 April - 22 May 2022) and autumn (1 September - 14 November 2022) were characterized by mean daily temperatures between 0 and 10 °C and summer (23 May - 31 August 2022) was defined by temperatures above 10 °C.

Because individual chambers were measured sequentially rather than simultaneously, observations from all chamber replicates within a site were combined to reconstruct complete diurnal cycles. To focus on site-level diurnal dynamics rather than persistent spatial differences among chambers, the chamber-specific daily mean CH₄ flux was subtracted from each



220 observation, thereby centering the data separately for each chamber and day around a mean of zero. This procedure removed differences in average flux magnitude among chambers while preserving temporal variability around the daily mean. To retain differences in mean CH₄ exchange among sites and days, the corresponding original site-level daily mean flux was subsequently added to the centered observations. Seasonal mean site-level diurnal patterns were then calculated by averaging fluxes by hour of day for each site and season.

225 2.5.3 Environmental drivers of diurnal CH₄ flux patterns

To identify environmental drivers of diurnal CH₄ flux dynamics, we compared the strength and timing of diurnal cycles among CH₄ fluxes and environmental variables. Harmonic regression was used to characterize these diurnal patterns by their amplitude and phase.

For each site and day, measurements of CH₄ flux and ambient CH₄ concentrations from the replicate chambers were
 230 combined to reconstruct a more complete diurnal time series by subtracting the chamber-specific daily mean from each measurement (see Section 2.5.2). Chamber air and soil temperatures were measured continuously at each chamber location and showed only minor spatial variation among replicates. Therefore, these variables were averaged across chamber locations at the site level before harmonic regression. PAR was measured continuously at one location at each microsite and was therefore used directly as the site-level time series. The environmental variables were retained at their original 30-min
 235 temporal resolution for the harmonic analysis.

For each site and day, a first-order harmonic model with a fixed period of 24 h was fitted to the respective observations:

$$y_t = \beta_0 + \beta_1 \cos\left(\frac{2\pi t}{24}\right) + \beta_2 \sin\left(\frac{2\pi t}{24}\right) + \varepsilon_t \quad (3)$$

where y_t is the observation at hour of day t (0-24 h), β_0 is the intercept, β_1 and β_2 are the coefficients of the cosine and sine terms, and ε_t is the residual error.

Harmonic fits were calculated only for days with complete flux measurements from all chambers at a given site (16
 240 measurements per day for CH₄ fluxes and 4 measurements per day for ER (opaque chamber only)). To distinguish ecologically meaningful diurnal cycles from random short-term variability, subsequent analyses were limited to days with a harmonic fit to CH₄ fluxes with $R^2 > 0.3$. This quality control procedure retained a total of 72, 97, and 82 measurement days for upland forest, intermediate, and bog site, respectively.

The strength of the diurnal cycle was quantified as the harmonic amplitude:

$$A = \sqrt{\beta_1^2 + \beta_2^2} \quad (4)$$

245 where A represents half the peak-to-trough difference of the fitted diurnal cycle. Amplitudes were calculated for CH₄ fluxes and all environmental variables. Pairwise correlation analyses were first used to explore relationships among variables and to guide the selection of predictors for the multiple linear regression models, including assessment of potential



multicollinearity among predictor variables. The selected predictors were then included in multiple linear regression models to identify environmental controls on the seasonal variability of diurnal CH₄ dynamics.

250 To investigate the temporal relationships between CH₄ fluxes and environmental variables, the phase of each harmonic fit was calculated as

$$\phi = \arctan 2(\beta_2, \beta_1) \quad (5)$$

and converted to the timing of the daily peak (h_{peak}) as:

$$h_{\text{peak}} = \frac{24}{2\pi} \phi \quad (6)$$

with negative values shifted into the 0–24 h range by adding 24 h. Lag times between CH₄ fluxes and environmental variables were then calculated as the difference between their respective peak timings and used to evaluate potential
 255 temporal offsets between environmental forcing and CH₄ flux responses.

3 Results

3.1 Seasonal development of environmental conditions along the hydrological gradient

Overall, climatic conditions and their seasonal progression were similar among sites, with persistent snow cover and sub-zero temperatures during winter, rapid warming and snowmelt in spring, warm conditions during summer, and declining
 260 temperatures and radiation during autumn (Figure 2). Daylight duration increased from approximately 5 h in winter to a maximum of 20 h in summer before declining again towards winter (calculated following Reda and Andreas, 2004). Snow cover dynamics were also similar among sites, although snow depth was consistently lower at the forested upland than in the open peatland (Figure 2e).

Microclimatic conditions differed among sites as a result of vegetation structure. PAR reaching was substantially lower at
 265 the forested upland and intermediate sites than at the open bog due to tree cover, averaging 15 % and 24 % lower, respectively, over the study period (Figure 2c). This reduction in radiation was accompanied by lower near-surface soil temperatures at the forested sites throughout much of the growing season (Figure 2b).

The three sites represented a gradient from seasonally waterlogged conditions at the bog, through fluctuating conditions at the intermediate site, to comparatively dry conditions at the upland forest (Figure 2d). At the bog, the water table remained
 270 close to the peat surface, ranging from 19 cm above surface during snow melt to 17 cm below in late summer. The intermediate site showed pronounced seasonal variation in soil moisture, with VWC increasing to almost 1.0 m³ m⁻³ during 22 days of saturated conditions in spring before gradually declining to 0.1 m³ m⁻³ in summer. In contrast, VWC at the upland forest remained relatively stable at around 0.3 m³ m⁻³ for most of the year, apart from a brief period of saturation lasting eight days during spring. Across all sites, water levels increased during snowmelt, reaching their highest levels in early
 275 spring, declined through summer, and increased again during autumn.



Seasonal and site-level differences in environmental conditions were also reflected in the seasonal development of diurnal patterns (Figure A2). Day-night differences (quantified as two times the harmonic amplitude; Eq. 4) in PAR, air temperature, soil temperature and ER were generally strongest during summer and weakest during winter. Summer mean PAR day-night differences were highest at the open bog ($1145 \mu\text{mol m}^{-2} \text{s}^{-1}$) and lower at the intermediate ($312 \mu\text{mol m}^{-2} \text{s}^{-1}$) and upland forest ($190 \mu\text{mol m}^{-2} \text{s}^{-1}$) sites. Mean air-temperature day-night differences increased from 4.5°C in winter to 10.6°C in summer, while corresponding amplitudes of soil temperature increased from 0.1 to 4.5°C at 2 cm depth and from 0.1 to 1.7°C at 10 cm depth. PAR and air temperature already exhibited pronounced diurnal cycles during spring, with day-night differences of approximately $540 \mu\text{mol m}^{-2} \text{s}^{-1}$ and 10.6°C across all sites, respectively. Peak PAR consistently occurred around midday, whereas peak temperatures were progressively delayed from air temperature to soil temperatures at 2 and 10 cm depth, reflecting the propagation of heat through the soil profile. ER likewise showed its strongest diurnal variability during summer with average day-night differences of $3.8 \text{ g CO}_2 \text{ m}^{-2} \text{d}^{-1}$ but exhibited an opposite pattern to PAR and temperature, with higher respiration rates during nighttime and lower rates during daytime.

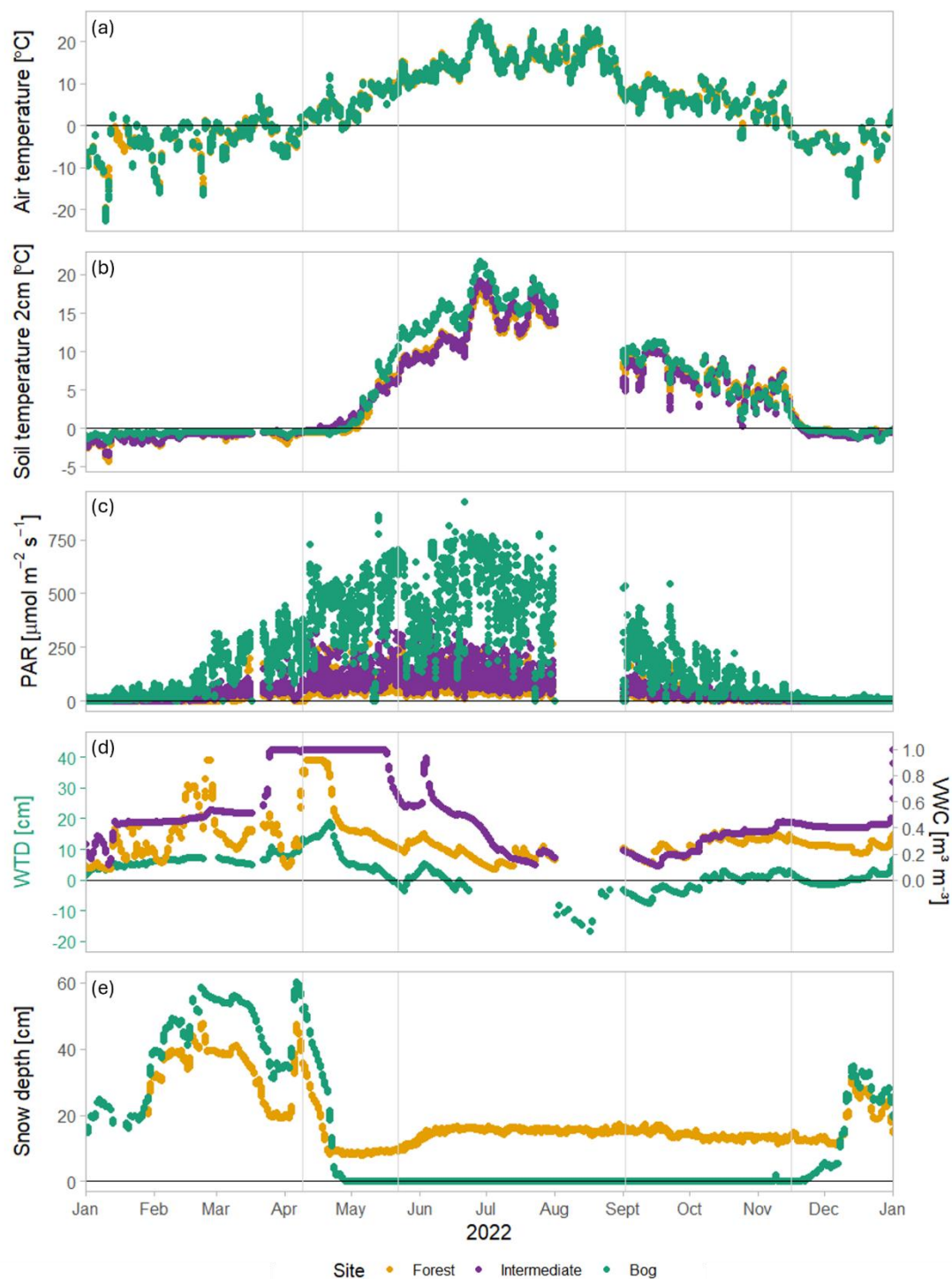




Figure 2: Seasonal development of environmental conditions along the hydrological gradient. Daily means of air temperature (a), soil temperature at 2 cm depth (b), PAR (c), hydrological conditions (WTD in the bog (left y-axis); VWC in the top 10 cm of soil at upland forest and intermediate site (right y-axis)) (d), snow depth (e) at upland forest, intermediate and bog site. At the upland forest site, the presence of snow outside of the snow cover period (May-December) reflect the vegetation height.

3.2 Seasonal development of methane fluxes along the hydrological gradient

CH₄ fluxes showed distinct seasonal dynamics along the hydrological gradient (Figure 3). Throughout the study period, the upland forest acted predominantly as a CH₄ sink (Figure 3a), whereas the bog remained a net CH₄ source (Figure 3c). The intermediate site showed dynamics more similar to the upland forest, with daily mean fluxes predominantly indicating net CH₄ uptake, but uptake was weaker and developed later in the year (Figure 3b).

In the first winter season, daily mean fluxes were close to zero at all three sites. The upland forest and intermediate sites showed weak daily CH₄ uptake (-0.2 ± 0.4 mg CH₄ m⁻² d⁻¹ and -0.1 ± 0.4 mg CH₄ m⁻² d⁻¹ (mean $\pm$ SD)), while low mean emissions occurred at the bog site (0.7 ± 0.8 mg CH₄ m⁻² d⁻¹). With the onset of snowmelt and thawing of the upper soil layers in spring (April to May; Figure 2e), flux magnitudes started to increase at both upland forest and bog site. As soil temperatures rose and vegetation started to grow in the summer period, the upland forest reached a maximum daily mean CH₄ uptake of -6.6 ± 3.3 mg CH₄ m⁻² d⁻¹ on 11 July, whereas the bog site exhibited peak emissions of 108.5 ± 89.5 mg CH₄ m⁻² d⁻¹ on 27 June.

At the intermediate site, CH₄ fluxes remained close to zero during the first half of the year but shifted towards net uptake after 1 July, with a maximum daily uptake of -5.9 ± 2.0 mg CH₄ m⁻² d⁻¹ recorded on 11 July. During this period, CH₄ emissions at the bog site declined, approaching near-zero values shortly before the onset of the data gap caused by chamber system failure.

In early autumn, CH₄ uptake decreased abruptly between 4 – 7 October at both the upland and intermediate sites but continued at lower levels into winter. At the bog site, CH₄ emissions slowly tailed off throughout the autumn, returning to close-to-zero values by the end of the year.

Seasonal dynamics were generally similar among replicate chambers within each site, with the exception of chamber 1 at the upland forest (Figure A3). From mid-autumn onwards, fluxes in this chamber first declined to near-zero values and subsequently shifted back towards CH₄ uptake towards the end of the year, whereas the other three chambers showed the opposite development. Despite the overall similar seasonal dynamics, differences in flux magnitude were apparent among chambers, with the largest differences in seasonal chamber means occurring during summer at all three sites (3.3 mg CH₄ m⁻² d⁻¹ at the upland forest site, 0.7 mg CH₄ m⁻² d⁻¹ at the intermediate site and 48.4 mg CH₄ m⁻² d⁻¹ at the bog site). At the upland forest, chambers 1 and 2 generally showed greater CH₄ uptake than chambers 3 and 4. Fluxes were more similar among chambers at the intermediate site, whereas chamber 1 at the bog consistently showed higher CH₄ emissions than the other chambers throughout the year.

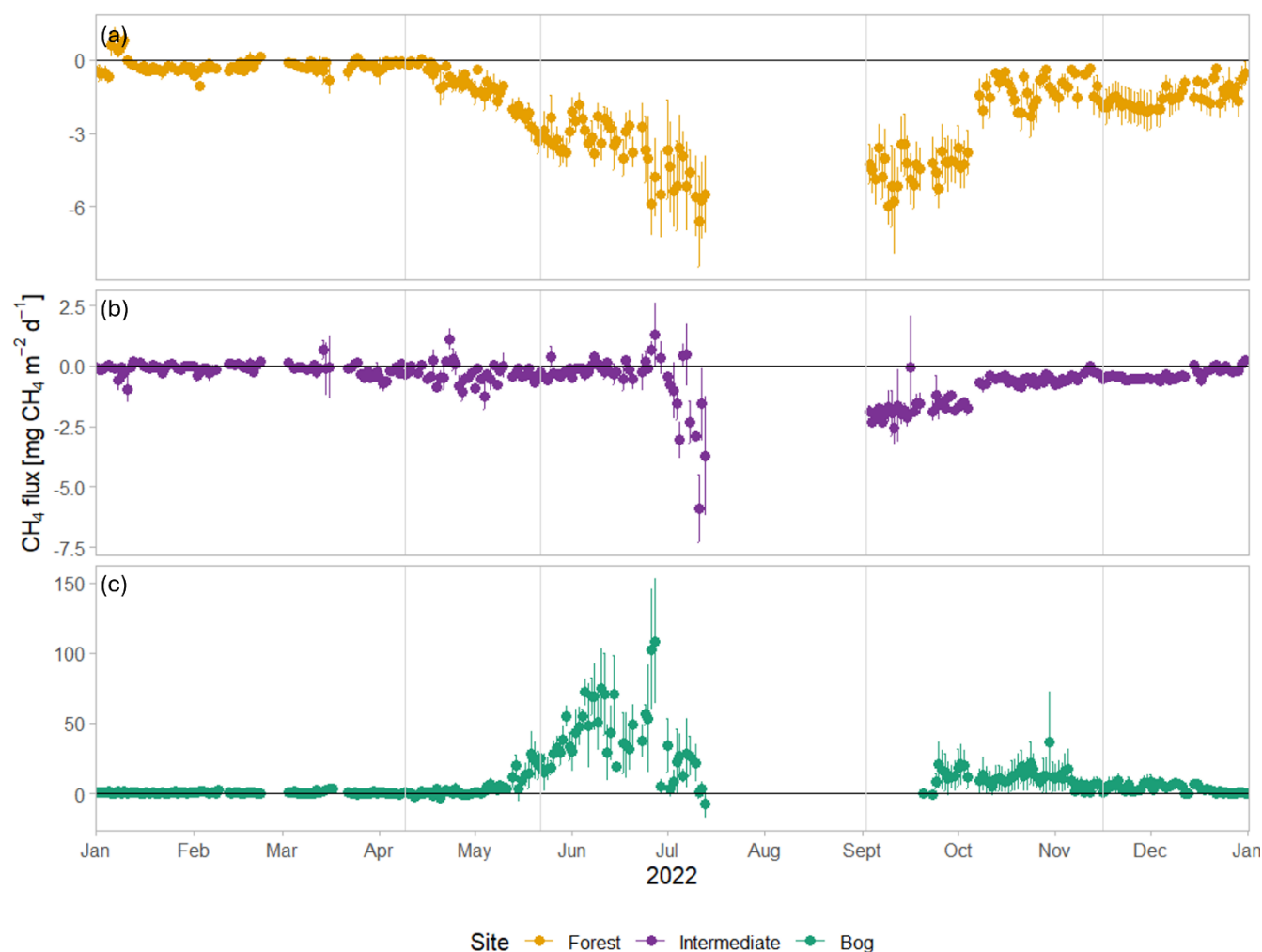


Figure 3: Daily mean CH₄ fluxes in 2022 with standard error across the four replicate chambers for upland forest (a), intermediate (b), and bog (c) sites. The grey vertical lines indicate the seasons. Negative values indicate CH₄ uptake. Values are only shown for days when fluxes from at least two replicate chambers were available.

3.3 Diurnal patterns in CH₄ fluxes

3.3.1 Observed diurnal patterns in CH₄ fluxes

Pronounced diurnal variation in CH₄ fluxes was observed at all three sites, but magnitude, direction, and seasonal dynamics of these patterns differed between sites (Figure 4). At both the bog and upland forest sites, flux direction remained consistent throughout the day over the year, with emissions at the bog and uptake at the upland forest. At both sites, flux magnitudes were greater at night than during the day. In contrast, the intermediate site showed a seasonal reversal in the



daytime–nighttime pattern of CH₄ fluxes. During spring and summer, CH₄ fluxes generally shifted from net uptake during the day to net emissions at night across all chamber replicates (Figure A4), resulting in daily mean fluxes close to zero (Figure 3). During autumn and winter, the intermediate site remained a net CH₄ sink throughout the day, but flux magnitude was greater during daytime than nighttime, opposite to the pattern observed at the upland forest and bog sites.

The magnitude of significant diurnal variation (harmonic fit $R^2 > 0.3$ and $p < 0.05$) was greatest at the bog site, where differences between daytime and nighttime fluxes across chamber replicates reached up to 146.0 mg CH₄ m⁻² d⁻¹ on 7 July, quantified as two times the harmonic amplitude (Eq. 4, Figure A5). At the intermediate and forest sites, diurnal variation was significantly smaller, with day-night differences of up to 4.2 mg CH₄ m⁻² d⁻¹ on 6 May and 6.5 mg CH₄ m⁻² d⁻¹ on 9 September, respectively. The timing of peak diurnal variation reflects overall patterns in seasonal variation in diurnal variability at each site. Seasonally, diurnal variation was most pronounced during summer at both the bog and forest sites. At the bog site, a clear diurnal pattern was already evident in spring, while at the forest site diurnal variation persisted into autumn. In contrast, the intermediate site showed the strongest diurnal variation in spring, with detectable patterns showing in all seasons.

Diurnal CH₄ flux patterns were generally consistent among chamber replicates within sites (Figure A4). This consistency was particularly evident at the intermediate and bog sites, where the overall shape of the diurnal cycle remained similar among chamber replicates throughout the year despite some chamber-differences in the magnitudes of diurnal variation at the intermediate site. At the upland forest, however, chamber-level differences in the shape of diurnal patterns were apparent during spring and summer. Chambers 2 and 3 consistently showed stronger CH₄ uptake at night than during the day, whereas chambers 1 and 4 exhibited greater daytime uptake during spring and early summer. Over the summer, the diurnal pattern in chambers 1 and 4 shifted towards that observed in chambers 2 and 3, with stronger nighttime than daytime uptake (Figure A5). These chamber-level differences partly obscure the diurnal patterns at the upland forest when considering site-mean fluxes alone, particularly during spring (Figure 4).

The seasonal change in the shape of diurnal patterns at two of the four upland chambers also shows as a pronounced shift in the timing of peak CH₄ uptake at the upland forest site derived from daily harmonic fits (Figure A5). The site-level harmonic-fit metrics form the basis for the subsequent analyses of environmental controls on diurnal CH₄ dynamics.

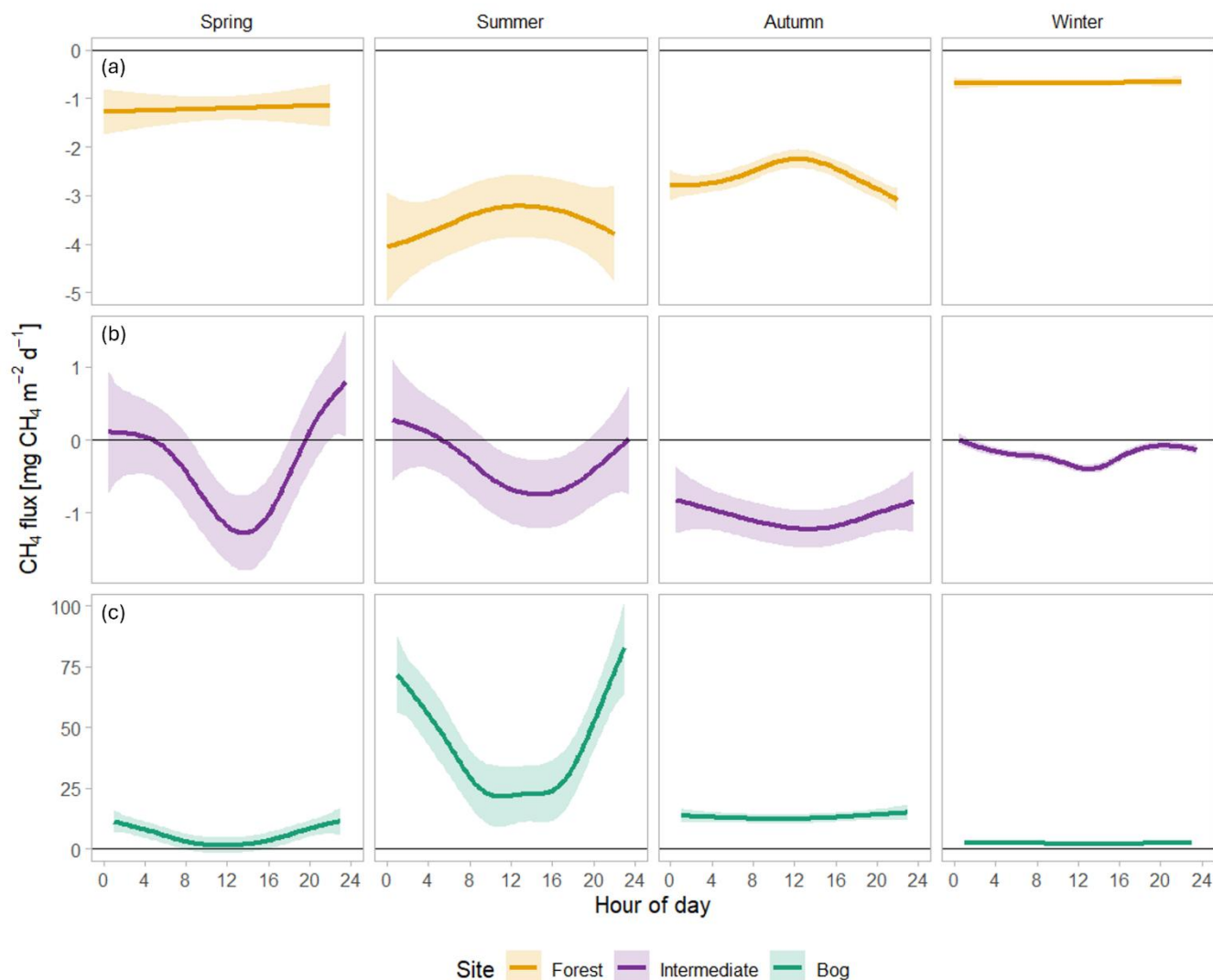


Figure 4: Diurnal variation in CH₄ fluxes along the moisture gradient by site and season. Fluxes are shown as site-level means for upland forest (a), intermediate (b), and bog (c) sites with 99 % confidence intervals derived from generalized additive model smoothing. To reconstruct complete diel cycles and minimize the influence of persistent differences in mean flux magnitude among chamber replicates, fluxes were centered separately for each chamber and day by subtracting the chamber-specific daily mean and subsequently adding the corresponding site-level daily mean prior to computing the seasonal mean for each measurement time. This procedure preserved seasonal and site-level differences in average CH₄ exchange while emphasizing diurnal dynamics common to replicate chambers. Diurnal patterns are based on 16 measurements per day from transparent and opaque chambers combined (four measurements per day by each of the four site chambers).



3.3.2 Environmental controls on diurnal patterns in CH₄ fluxes

Environmental drivers of the strength of diurnal CH₄ flux variability

Relationships between the diurnal amplitude of CH₄ fluxes and environmental variables differed markedly along the hydrological gradient (Figure 5, Table 1). Correlation analyses and multiple linear regression models consistently indicated shifts in the dominant predictors of CH₄ flux variability from the upland forest to the bog.

At the upland forest site, the diurnal amplitude of CH₄ fluxes was most strongly correlated with the amplitudes of ambient atmospheric CH₄ concentrations and ecosystem respiration (ER). There were moderate positive correlations between CH₄ flux amplitude and the energy-related variables. Daily mean VWC and nocturnal wind speed were weakly negatively correlated with both CH₄ flux and ER amplitude.

Based on these correlation patterns and the assessment of multicollinearity among predictor variables, the best multiple linear regression model included ambient CH₄ concentration amplitude, ER amplitude, and chamber temperature amplitude and explained 88.9 % of the variance in CH₄ flux amplitude. CH₄ flux amplitude increased with increasing ambient CH₄ concentration amplitude, ER amplitude and chamber temperature amplitude. All three predictors were highly significant and exhibited low multicollinearity (VIFs = 1.4-1.8).

At the intermediate site, CH₄ flux amplitude was most strongly correlated with the amplitude of PAR, with progressively weaker correlations for chamber temperature and soil temperatures at greater depths. Correlation with diurnal amplitude in ER was very low and daily mean VWC and nocturnal wind speed showed a moderate positive and a weak negative relationship with CH₄ flux amplitude, respectively.

Guided by these correlation patterns, the best-performing model included ambient CH₄ concentration amplitude, PAR amplitude, and an interaction between soil temperature amplitude at 2 cm depth and daily mean VWC, explaining 66.4 % of the variance in CH₄ flux amplitude. Ambient CH₄ concentration amplitude and PAR amplitude were positively related to CH₄ flux amplitude, and the positive interaction term indicated that the relationship between soil temperature amplitude and CH₄ flux amplitude became stronger at higher soil moisture. Multicollinearity was moderate but acceptable (VIFs = 1.5–6.2).

At the bog site, CH₄ flux amplitude was most strongly positively correlated with ER amplitude and ambient CH₄ concentration amplitude, followed by soil temperature amplitudes at 2 and 10 cm depth. Correlations of CH₄ flux amplitude with chamber temperature and PAR amplitudes were weaker, while there was a strong negative relationship with WTD and a moderate negative relationship with nocturnal wind speed.

Based on the correlation analysis, the best multiple linear regression model describing temporal variation in the strength of diurnal CH₄ flux variation included ER amplitude, soil temperature amplitude at 10 cm depth, and daily mean WTD, explaining 83.4 % of the variance in CH₄ flux amplitude. CH₄ flux amplitude increased with ER amplitude and soil temperature amplitude and decreased with increasing WTD. All predictors were significant and exhibited low multicollinearity (VIFs = 1.3–1.4).

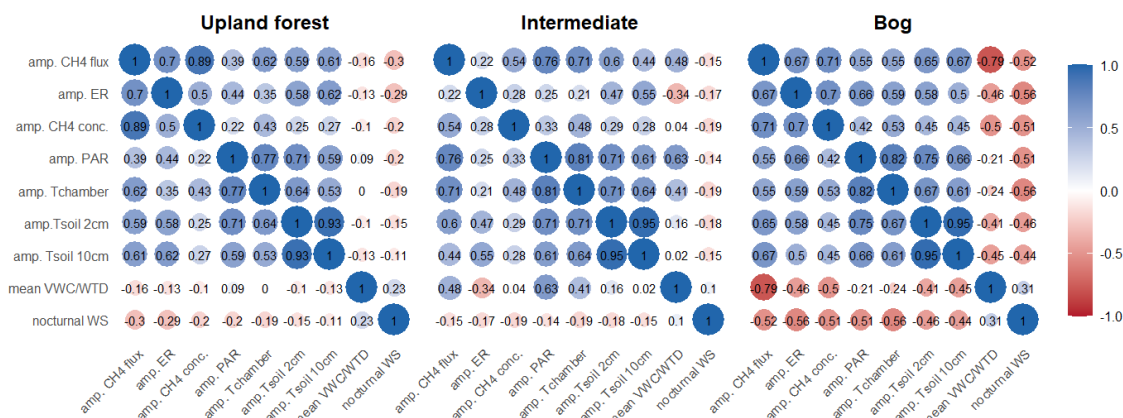


Figure 5: Correlation of strength of diurnal patterns in CH₄ fluxes and environmental variables. The strength of diurnal patterns is quantified as the amplitude of daily harmonic fits. For all variables only amplitudes of harmonic fits with $R^2 > 0.3$ were considered. To test correlation with hydrological conditions, daily means of VWC (for upland forest and intermediate sites) and WTD (for the bog site) were used and daily mean nocturnal (22:00–4:00) wind speed (WS) is included as a measure of nighttime atmospheric boundary layer stability.

Table 1: Standardized regression coefficients of environmental drivers of diurnal CH₄ flux amplitude across the hydrological gradient. All tested potential predictors are listed in the first column. All variables were standardized (mean = 0, SD = 1) across the full dataset prior to analysis. Reported coefficients therefore represent the change in CH₄ flux amplitude associated with one standard deviation change in each predictor and are directly comparable across sites. Significance codes: p=0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ns’ 1; amp: daily harmonic amplitude, temp= temperature, WS=wind speed, RSE: residual standard error, df: degrees of freedom, n: number of observations.

Predictor	Bog	Intermediate	Upland forest
<i>Ecosystem respiration amp</i>	0.22 (***)	-	0.26 (***)
<i>Ambient CH₄ concentration amp</i>	-	0.72 (***)	0.55 (***)
<i>PAR amp</i>	-	0.57 (***)	-
<i>Chamber temp amp</i>	-	-	0.25 (***)
<i>Soil temp 2 cm amp</i>	-	-0.20 (ns)	-
<i>Soil temp 10 cm amp</i>	0.17 (***)	-	-
<i>Daily mean VWC</i>	-	0.13 (ns)	-
<i>Daily mean WTD</i>	-0.47 (***)	-	-
<i>Daily mean nocturnal wind speed</i>	-	-	-
<i>Interaction soil temp 2 cm amp x daily mean VWC/WT</i>	-	0.27 (**)	-
<i>Interaction daily mean nocturnal WS x</i>	-	-	-



<i>daily mean VWC/WT</i>			
n	69	80	54
Adjusted R^2	0.826	0.642	0.883
RSE	0.371	0.615	0.382
F(df)	F(3,65)	F(5,74)	F(3,50)
Model type	Additive	Interaction	Additive

Lag time between diurnal peaks in CH_4 fluxes and environmental drivers

Lag times between diurnal peaks in CH_4 fluxes and environmental variables were most consistent during the seasons that exhibited the strongest diurnal CH_4 cycles (Figures 4, 6).

415 At the upland forest site, the most consistent lag patterns occurred during summer and autumn, when CH_4 uptake was generally higher at night than during the day. During these seasons, maximum CH_4 uptake occurred approximately 1 h after the daily maximum in ER, about 1 h before maximum ambient CH_4 concentrations and approximately 11, 9, 7, and 3 h after the daily maxima in PAR, chamber temperature, and soil temperature at 2 and 10 cm depth, respectively.

At the intermediate site, the most consistent lag patterns occurred during spring and summer. In spring, CH_4 fluxes were characterized by net emissions during the night and uptake during the day. Maximum CH_4 emissions occurred around the same time as maximum ER, approximately 1 h before the maximum in ambient CH_4 concentrations and approximately 12, 10, 7, and 3 h after the daily maxima in PAR, chamber temperature, and soil temperature at 2 and 10 cm depth, respectively. In summer, CH_4 uptake occurred throughout the day, with strongest uptake during daytime hours. Lag patterns were similar to those observed in spring, but lag times were generally larger than in spring for variables related to energy input, with minimum CH_4 uptake occurring approximately 13, 12, 9, and 5 h after the daily maxima in PAR, chamber temperature, and soil temperature at 2 and 10 cm depth, respectively. Minimum CH_4 uptake occurred about 3 h after the maximum in ER and close to the daily maximum in ambient CH_4 concentrations.

At the bog site, lag patterns were likewise most consistent during spring and summer, when CH_4 emissions were generally higher at night and lower during the day. In both seasons maximum CH_4 emissions occurred within one hour around maximum ER. In spring, maximum CH_4 emissions occurred approximately 2 h before the daily maximum in ambient CH_4 concentrations and approximately 11, 9, 6, and 2 h after the daily maxima in PAR, chamber temperature, and soil temperature at 2 and 10 cm depth, respectively. In summer, lag times relative to energy-related variables were generally larger, with maximum CH_4 emissions occurring approximately 12, 11, 8, and 4 h after the daily maxima in PAR, chamber temperature, and soil temperature at 2 and 10 cm depth, respectively. Seasonal differences in lag times increased with decreasing direct coupling to the surface energy input: Lag times relative to PAR and chamber temperature differed by only 0.8 h and 1.2 h, respectively, between spring and summer, whereas lag times relative to soil temperatures at 2 and 10 cm depth differed by 1.8 and 2 h, respectively. Maximum CH_4 emissions occurred approximately 1 h before the maximum in ambient CH_4 concentrations.

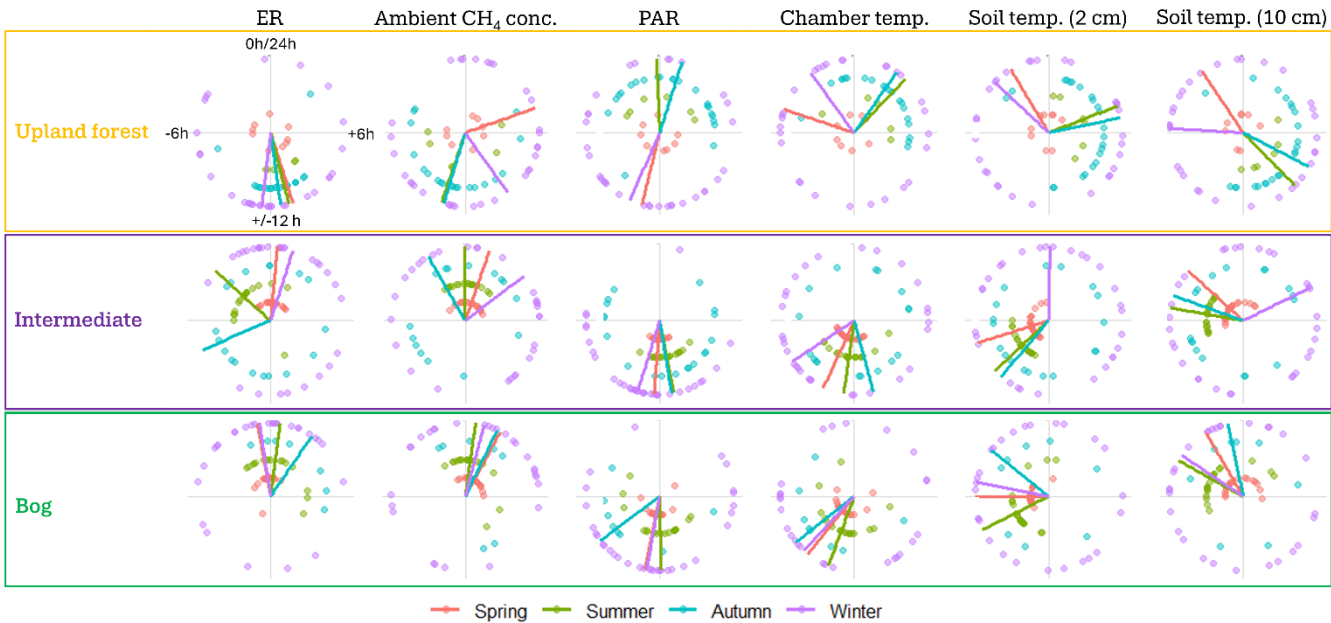


Figure 6: Lag time between daily peak CH₄ fluxes and daily peaks in ER and environmental variables. Negative lag time – environmental variable peaks before CH₄ flux; positive lag time – environmental variable peaks after CH₄ flux. Peak in CH₄ flux refers to the highest value, that is highest emission in the positive range or lowest uptake in the negative range. Coloured dots show the individual lag time and coloured lines indicate the mean lag time in each season.

4 Discussion

4.1 Methane exchange along the hydrological gradient and its seasonal variation

CH₄ fluxes differed markedly among sites and seasons, reflecting the strong influence of hydrological conditions on CH₄ cycling (Figure 3). The three sites represented a gradient from high water-table conditions at the bog, through seasonally fluctuating soil moisture at the intermediate site, to comparatively dry conditions at the upland forest. The upland forest acted as a persistent CH₄ sink, with uptake increasing during the growing season and reaching maximum rates in early summer. In contrast, the bog functioned as a substantial CH₄ source, with emissions increasing rapidly following snowmelt and peaking during summer. The intermediate site occupied a transitional position, exhibiting fluxes close to zero during much of the year before shifting towards net CH₄ uptake during summer.

The site differences are consistent with the expected influence of soil moisture and water table position on the balance between CH₄ production and oxidation (Cui et al., 2024; Lai, 2009; Le Mer and Roger, 2001; Whalen, 2005). At the bog site, saturated conditions promoted anaerobic CH₄ production throughout much of the peat profile (Figure 3), resulting in sustained emissions throughout the growing season. Conversely, the well-drained upland forest provided favorable



conditions for CH₄ oxidation, leading to net atmospheric CH₄ uptake. The intermediate site displayed characteristics of both systems, suggesting that relatively small changes in hydrological conditions may shift the balance between CH₄ production and oxidation.

4.2 Diurnal methane dynamics along the hydrological gradient

Pronounced diurnal variation in CH₄ fluxes was observed at all three sites, but both the direction and seasonal timing of these patterns differed along the hydrological gradient (Figure 4). At the bog site, CH₄ emissions occurred throughout the day and year, but were generally higher during nighttime than during daytime. Patterns at the intermediate site were more complex in their seasonal behaviour, with CH₄ fluxes shifting from net uptake during the day to net emissions at night in spring and summer, whereas the site remained a net CH₄ sink throughout the day in autumn and winter, with stronger uptake during daytime than nighttime. In contrast, at the upland forest, CH₄ uptake occurred throughout the day and year and was generally stronger during nighttime than daytime. Thus, CH₄ fluxes were generally enhanced at night at the bog and upland forest but reduced at night at the intermediate site during autumn and winter.

Higher nighttime CH₄ emissions at the intermediate and bog sites are consistent with several chamber-based studies from peatlands and wetlands (e.g., Dooling et al., 2018; Mikkilä et al., 1995; Shannon et al., 1996), whereas eddy covariance studies have more frequently reported maximum emissions during daytime (Hargreaves and Fowler, 1998; Kowalska et al., 2013; Long et al., 2010), including at the Siikanen bog (Gunnlaugsdóttir et al., 2026).

Methodological limitations may contribute to these contrasting patterns. In particular, Koskinen et al. (2014), Korkiakoski et al. (2017), and Rautakoski et al. (2024) found higher nighttime than daytime ER, CH₄ uptake, and N₂O emissions, respectively, in a drained peatland forest with an automated chamber system and attributed this pattern to chamber-induced changes in atmospheric mixing. Under calm conditions, which often occur during nighttime when atmospheric stability is high, concentration gradients can develop near the soil surface. Chamber closure and the fan-induced mixing inside the chamber can then enhance these gradients and thereby increase the apparent flux. Conversely, Lai et al. (2012) reported that chamber closure can reduce turbulence under windy conditions, potentially leading to underestimation of fluxes relative to ambient conditions. Together, these studies suggest that chamber deployment can alter natural turbulence regimes and associated gas concentration gradients, potentially leading to either over- or underestimation of fluxes depending on ambient atmospheric conditions. Importantly, such effects may not only influence the magnitude of measured fluxes but also their timing. Enhanced mixing inside the chamber may accelerate the release of gases that would otherwise accumulate near the surface under stable nocturnal conditions and be released later when atmospheric turbulence increases. Our observations provide some support for this mechanism, as both CH₄ and ER diurnal amplitudes generally increased with decreasing nocturnal wind speed across all three sites (Figure 5). This relationship is consistent with the proposed influence of atmospheric turbulence on chamber-based flux measurements and suggests that part of the observed diurnal variability may result from chamber-induced alterations of natural gas concentration gradients under stable nighttime conditions.



At the same time, eddy covariance measurements are also subject to methodological limitations, particularly during periods of weak nighttime turbulence when assumptions underlying micrometeorological flux measurements are not fully met (Aubinet et al., 2012; Jentsch et al., 2021). Under such stable conditions, gases may accumulate near the surface, potentially leading to an underestimation of nighttime fluxes at the height of eddy covariance measurements. Consistent with
 495 this, Gunnlaugsdóttir (2026) highlighted methodological limitations of the eddy covariance method as a potential contributor to the lower nighttime CH₄ emissions observed at the Siikaneva bog. As for chamber measurements, this effect may primarily influence the timing at which fluxes are detected rather than the total amount of gas exchanged. Gases stored near the surface during stable nighttime conditions may subsequently be transported to the measurement height when turbulence increases after sunrise, resulting in an apparent shift of emissions from nighttime to daytime. Consequently, differences
 500 between chamber- and eddy covariance-based studies do not necessarily imply that either method provides a fully unbiased representation of diurnal CH₄ dynamics. Rather, the two approaches may differ in how they capture the temporal dynamics of gas storage and release under changing atmospheric conditions.

The potential chamber artefact at stable boundary layer conditions complicates the interpretation of our diurnal CH₄ patterns, including their apparent relationships with ER. Higher nighttime ER, as observed at our sites, has also been
 505 reported in other automated-chamber studies, but this pattern is biologically unexpected and has been attributed to the same turbulence-related measurement effect (Koskinen et al., 2014). Consequently, the relationship between CH₄ flux and ER cannot by itself be taken as evidence for biological coupling. A similar consideration applies to the study of Voigt et al. (2023), who observed nighttime maxima in both CH₄ uptake and ER and discussed potential biological mechanisms for this pattern. Although their observations provide evidence that genuine diurnal variation may occur in well-drained northern
 510 ecosystems, the possibility that part of the observed ER and CH₄ patterns was influenced by chamber-induced mixing cannot be excluded.

Nevertheless, several features of our observations are difficult to reconcile with a chamber-mixing effect alone. Most notably, the strongest diurnal variation at the intermediate site occurred during spring (Figure 4), when soil moisture was highest (Figure 2), whereas previous studies identified the strongest chamber-related effects under drier conditions with
 515 greater air-filled pore space (Korkiakoski et al., 2017; Rautakoski et al., 2024). In addition, chamber-induced mixing would be expected to affect both CH₄ and CO₂ exchange similarly, yet no significant relationship was found between diurnal CH₄ flux amplitude and ER amplitude at the intermediate site (Figure 5, Table 1). Although nocturnal wind speed was negatively correlated with diurnal CH₄ flux amplitude (Figure 5), it was not a significant predictor in the tested multiple linear regression models. Furthermore, we found no significant interaction between soil moisture and nocturnal wind speed (Table
 520 1), as might be expected if the influence of wind on chamber-related mixing depended on air-filled pore (Korkiakoski et al., 2017; Rautakoski et al., 2024). Moreover, the nighttime enhancement in CH₄ fluxes expected from the chamber-mixing effect did not occur at all sites or during all seasons. The intermediate site switched from nighttime emissions and daytime uptake during spring and summer to stronger daytime uptake during autumn and winter (Figure 4). At the upland forest, two of the four chambers similarly showed stronger daytime than nighttime uptake during spring before shifting towards stronger



525 nighttime uptake over the summer (Figure A6). Such seasonal reversals were also found for upland Tundra by Voigt et al. (2023) and for a Swedish peatland by Duan et al. (2025). These changes in the direction and magnitude of diurnal CH₄ exchange suggest that biological and local environmental controls likely contributed to the observed variability, even though changes in atmospheric turbulence and soil moisture may also have influenced the magnitude of the measured patterns.

530 Taken together, the observed diurnal CH₄ patterns likely reflect a combination of biological and physical controls affecting the gas-phase storage within the peat. Chamber-induced modification of atmospheric turbulence provides an important alternative explanation, particularly for nighttime flux enhancement under dry and calm conditions. The observed relationships between diurnal amplitudes and nocturnal wind speed support the potential importance of this mechanism. However, this mechanism may mainly affect the timing of emissions rather than the cumulative daily flux. The contrasting
 535 seasonal and chamber-level patterns suggest that biological and local environmental controls also contribute by controlling the conditions for CO₂ and CH₄ production and oxidation. The following sections therefore examine potential biological mechanisms underlying the observed diurnal variability while considering chamber-induced effects as an important source of uncertainty.

4.3 Drivers of diurnal methane dynamics along the hydrological gradient

540 4.3.1 Drivers of diurnal methane dynamics at the upland forest site: ecosystem respiration and atmospheric CH₄

At the upland forest site, diurnal CH₄ flux variability was most strongly associated with the strength of diurnal variation in ambient atmospheric CH₄ concentrations, ER, and air temperature (Table 1, Figure 5). Together, these variables explained close to 90 % of the observed variability in diurnal CH₄ flux amplitude.

The strong relationship between CH₄ uptake and ER is consistent with observations from Arctic tundra uplands reported
 545 by Voigt et al. (2023), who similarly found that nighttime periods of enhanced CH₄ uptake coincided closely with periods of high ER (Figure A2a). ER, like CH₄ oxidation, is often assumed to increase with temperature and therefore to peak during the warmest part of the day. However, both our observations and those of Voigt et al. (2023) indicate that diurnal ER dynamics do not necessarily follow this pattern. ER integrates both autotrophic and heterotrophic respiration, which may differ in their responses to temperature, resulting in temporal patterns that can deviate from a simple temperature response
 550 (Järveoja et al., 2020). Voigt et al. (2023) propose that rhizosphere processes associated with the supply of labile C may stimulate methanotrophic activity, thereby linking CH₄ uptake and ER.

Ambient atmospheric CH₄ concentrations emerged as an equally important predictor of diurnal CH₄ flux variability. One possible explanation is that atmospheric CH₄ concentrations control substrate availability for high-affinity methanotrophs, which can oxidize CH₄ at ambient atmospheric concentrations and are known to dominate CH₄ uptake in many well-drained
 555 soils (Henckel et al., 2000; Knief et al., 2003; Nazaries et al., 2013). This mechanism may be particularly relevant at the upland site, where CH₄ production within the soil is likely very low, consistent with the near absence of methanogens in the



upper 40 cm of the soil profile reported by Baysinger et al. (2025). Under such conditions, atmospheric CH₄ represents the primary substrate source for methanotrophic activity. Higher near-surface CH₄ concentrations during stable nocturnal boundary-layer conditions (Figure A2b) could therefore contribute to the observed enhancement of CH₄ uptake at night. However, the lag analysis provides only limited support for a direct substrate-driven response, as peak CH₄ uptake generally occurred one hour before instead of following peak atmospheric CH₄ concentrations. Alternatively, both variables may respond to other common environmental processes that vary systematically over the diurnal cycle.

4.3.2 Drivers of diurnal methane dynamics at the intermediate site: hydrological modulation of temperature sensitivity

The intermediate site exhibited characteristics distinct from both the upland forest and the bog. Diurnal CH₄ flux variability was most strongly associated with ambient CH₄ concentration and PAR amplitudes, as well as an interaction between soil temperature amplitude and soil moisture, indicating that the influence of temperature on CH₄ flux variability depended on hydrological conditions (Table 1).

The strongest diurnal CH₄ flux variability occurred during spring (Figure 4), when soil moisture was highest and saturated conditions persisted for several weeks following snowmelt (Figure 2). This observation is notable because diurnal soil temperature amplitudes were not largest during this period (Figure A2e,f), consistent with a higher heat capacity dampening temperature fluctuations in wetter soils. The significant positive interaction between soil temperature amplitude and soil moisture therefore suggests that CH₄ cycling became more sensitive to temperature variability under wetter conditions rather than simply responding to larger temperature fluctuations.

One possible explanation for an increased temperature response is that high water tables confined CH₄ oxidation to a relatively thin aerobic surface layer where soil temperatures respond most strongly to diurnal changes in atmospheric conditions. Although CH₄ production is generally more temperature-sensitive than CH₄ oxidation (Dunfield et al., 1993), temperature fluctuations experienced by methanotrophs in the near-surface soil are considerably larger than those experienced by methanogens in deeper, more thermally buffered layers (Granberg et al., 1997; Long et al., 2010) (Figure A2e,f). Consistent with the potential for CH₄ oxidation and production to occur in different soil layers, Baysinger et al. (2025) found that at the intermediate site, methanotroph abundance decreased with increasing soil depth, whereas methanogen abundance increased. Thus, even in places where CH₄ production and oxidation cooccur and despite the higher temperature-sensitivity of CH₄ production compared to oxidation, diurnal variation in near-surface oxidation may strongly control net CH₄ fluxes by altering the balance between production and oxidation. A similar observation was made across the microtopographic gradient at Siikaneva bog, where lower water tables in drier microforms were associated with less temporally variable CH₄ production compared to wetter microforms (Jentsch et al., 2025). Under such conditions, relatively small changes in surface soil temperature could lead to substantial variation in CH₄ oxidation rates and consequently in net CH₄ exchange. A similar mechanism was proposed by Mikkilä et al. (1995), who suggested that temperature-dependent



inhibition of CH₄ oxidation may contribute to higher nighttime CH₄ emissions in the relatively dry plant communities of a boreal mixed mire.

The intermediate site also exhibited the largest seasonal variation in hydrological conditions among the three sites, ranging from prolonged saturation during spring snowmelt to substantially lower water tables during summer, as observed during porewater sampling (Figure 3). This pattern is consistent with the topographic setting of the intermediate site at the base of the upland forest (Figure 1), where snowmelt runoff likely contributes to prolonged spring saturation, whereas greater vegetation productivity and woody plant cover may contribute to greater water loss later in the year. The strong seasonal variability in hydrological conditions was reflected in seasonal changes in net CH₄ exchange, with nighttime emissions and daytime uptake occurring during spring and summer, followed by persistent net CH₄ uptake in autumn and winter. Despite these shifts in mean flux direction, the shape of the diurnal cycle remained similar to that observed at the bog site (Figure 4). At both sites, CH₄ fluxes shifted towards greater emissions at night than during the day, and lag times relative to environmental variables were broadly comparable between the two sites.

Notably, this pattern persisted at the intermediate site even during periods when net CH₄ uptake persisted throughout the day, with daytime uptake being weaker than nighttime uptake. This suggests that the processes controlling the magnitude and timing of diurnal CH₄ variability may differ from those determining whether the ecosystem functions as a net CH₄ source or sink. While CH₄ oxidation likely exerted strong control over the mean flux at the intermediate site, particularly during summer, CH₄ production may nevertheless have remained an important contributor to the observed diurnal variability.

4.3.3 Drivers of diurnal methane dynamics at the bog site: ecosystem respiration, soil temperature and water table position

At the bog site, diurnal CH₄ variability was most strongly associated with ER, soil temperature at 10 cm depth and water table position. These variables together explained more than 80 % of the observed variability in diurnal CH₄ flux amplitude (Table 1).

As expected from the temperature sensitivity of CH₄ cycling, diurnal variability in CH₄ emissions was strongly correlated with the diurnal amplitude of soil temperatures. Peak CH₄ emissions occurred approximately 2–4 h after peak temperatures at 10 cm depth (Figure 6), in line with the lag times of 0–5 h reported by Duan et al. (2025), which were interpreted to reflect a direct temperature dependence of CH₄ production. Increasing lag times between spring and summer between diurnal peaks in energy-related variables and peak CH₄ emissions may reflect changes in the relative contributions of CH₄ production and oxidation to net CH₄ fluxes (Figure 6). As water tables declined during summer, CH₄ production may have shifted to deeper, anaerobic soil layers, where diurnal temperature fluctuations are smaller because of the damping of temperature variations with depth (Figure A2d–f). This could delay the response of CH₄ production to diurnal temperature forcing. At the same time, the expansion of the aerobic zone may have increased the influence of temperature-dependent CH₄ oxidation on net emissions. If oxidation is weaker at night than during the day, it would dampen daytime emissions more strongly, shifting



the timing of peak net emissions towards later hours. Together, these processes may help explain the longer lag times observed in summer, although their relative contributions cannot be distinguished from net flux measurements alone.

625 A potential additional mechanism contributing to the observed diurnal CH₄ dynamics is the influence of vascular plants. Wetland sedges can affect CH₄ exchange through several pathways (e.g., Joabsson et al., 1999). Aerenchymatous tissues provide conduits for gas transport between the atmosphere and the soil, facilitating both the downward transport of oxygen to the rhizosphere, which can stimulate CH₄ oxidation in the rhizosphere, and the upward transport of CH₄ from anoxic soil layers to the atmosphere, thereby bypassing the aerobic oxidation zone. In addition, plants can promote methanogenesis
 630 through the supply of organic substrates, including root exudates, plant litter, and recently assimilated carbon transferred belowground.

In low-lying hollow areas of Siikaneva bog, plant-mediated transport has been shown to contribute substantially to total CH₄ emissions (Jentsch et al., 2024). The dominant vascular species at the study site, including *Scheuchzeria palustris*, *Carex limosa*, and *Rhynchospora alba*, are all known to have relatively high CH₄ transport capacities (Korrensalo et al.,
 635 2022). However, previous studies indicate that CH₄ transport in *S. palustris* and *C. limosa* occurs predominantly through passive diffusion rather than active, pressurized gas flow, resulting in little direct dependence on light conditions or stomatal activity (Shannon et al., 1996; Whiting and Chanton, 1992). Gas transport in *Rhynchospora alba* is likewise likely to be dominated by passive diffusion. Although this mechanism has not, to our knowledge, been investigated directly for this species, pressurized gas transport is generally restricted to a relatively small number of highly specialized wetland plants,
 640 particularly species adapted to persistently inundated conditions (Vroom et al., 2022). Consequently, diurnal variation in plant-mediated CH₄ transport itself is unlikely to be the primary cause of the observed diurnal patterns. This interpretation is further supported by the fact that similar nighttime maxima in CH₄ emissions were observed at the intermediate site, where gas-transporting sedges were largely absent.

In contrast, diurnal variation in carbon supply from plant photosynthesis may have contributed to the observed patterns.
 645 Recently assimilated carbon can be transferred belowground, where it stimulates microbial activity, including methanogenesis. Evidence for such a coupling has been provided by pulse-labeling studies demonstrating incorporation of recent photosynthates into CH₄ production within hours to one day, including within 2 h in Arctic tundra ecosystems (King et al., 2002), approximately 20 h in a boreal Finnish fen (Dorodnikov et al., 2011), and within 24 h in Arctic wet sedge tundra (King & Reeburgh, 2002). The strong relationship between ER and CH₄ flux variability observed at the bog site is
 650 consistent with this possibility, as increased availability of labile carbon may enhance both respiratory processes and CH₄ production after a similar delay. A similar mechanism was proposed by Dooling et al. (2018) and Mikkilä et al. (1995), who suggested that nighttime maxima in CH₄ emissions from a restored bog could result from a delay of approximately half a day between daytime photosynthetic carbon assimilation, subsequent utilization of photosynthates by methanogens, and the eventual transport of produced CH₄ to the atmosphere. While the present data does not allow for direct testing of this
 655 hypothesis, it indicates that plant-mediated carbon inputs may represent an additional pathway linking ecosystem



metabolism and short-term CH₄ dynamics, pointing towards frequent substrate-limitation of methanogenesis in the bog ecosystem.

4.4 Implications of diurnal variability for CH₄ budget estimates

The pronounced diurnal variability observed across all three sites has important implications for the quantification of ecosystem CH₄ budgets. Manual chamber measurements are commonly conducted during daytime hours and often implicitly assume that these observations are representative of daily mean fluxes. The results presented here indicate that this assumption may not always be valid, as CH₄ fluxes exhibited consistent diurnal patterns whose magnitude varied seasonally and among sites. However, the implications of these patterns for daily and annual CH₄ budgets depend on whether the observed nighttime enhancement reflects genuine biological variability, chamber-induced effects, or a combination of both.

If the observed diurnal patterns are primarily biological, daytime-only measurements could systematically bias estimates of daily CH₄ exchange. At the upland forest site, where CH₄ uptake was generally stronger during nighttime, restricting measurements to daytime would tend to underestimate atmospheric CH₄ uptake. In contrast, at the bog site, where CH₄ emissions were generally stronger during nighttime, daytime-only measurements would tend to underestimate daily CH₄ emissions. At the intermediate site, daytime-only measurements would particularly overlook net nighttime emissions during spring and summer. Similar potential biases associated with temporally restricted measurements have been reported for peatlands and upland tundra ecosystems (Duan et al., 2025; Mikkilä et al., 1995; Voigt et al., 2023). To illustrate the potential magnitude of this effect, we estimated cumulative CH₄ exchange over the measurement period using either all available chamber measurements or daytime measurements only. Nighttime was defined as 18:30–06:00 throughout the year, corresponding to equal numbers of chamber measurements in the two periods. For each day, mean CH₄ flux was calculated separately using all measurements and using daytime measurements only, and the resulting daily means were summed over the measurement period. Compared with estimates based on all measurements, using daytime measurements only reduced the estimated magnitude of CH₄ uptake by 12 % at the upland forest, increased the estimated magnitude of uptake by 38 % at the intermediate site, and reduced estimated CH₄ emissions by 42 % at the bog site.

The interpretation changes, however, if nighttime enhancement is partly caused by chamber-induced modification of atmospheric turbulence. In this case, nighttime chamber measurements may overestimate instantaneous nocturnal fluxes by enhancing mixing across concentration gradients that would otherwise persist under stable atmospheric conditions. However, this does not necessarily imply that the integrated daily CH₄ exchange is overestimated. Under natural conditions, gases accumulating near the surface during periods of low turbulence may still be released when atmospheric mixing increases, suggesting that chamber-induced enhancement may partly alter the timing rather than the total magnitude of CH₄ exchange.

Koskinen et al. (2014) showed that the nighttime artefact in respiration measurements could be reduced by minimizing fan speed and selecting an appropriate period after chamber closure for flux calculation. They further suggested that, where



nighttime artefacts cannot be adequately avoided, nighttime fluxes may need to be excluded and daytime measurements used for budget estimation. While this approach reduces the risk of including artificially enhanced nocturnal fluxes, it may also remove genuine nighttime exchange or fail to account for gas that would be released later under naturally increasing turbulence. Consequently, excluding nighttime measurements does not necessarily provide an unbiased estimate of daily CH_4 exchange. Another possibility would be to develop models of peat gas storage (e.g., Nickerson and Risk, 2009) that can be used to evaluate how chamber-induced mixing influences the timing and magnitude of measured fluxes and to assess the resulting uncertainty in budget estimates.

Consequently, automated measurements provide important advantages for resolving diurnal variability but do not necessarily provide an unambiguous basis for calculating daily CH_4 budgets. The key uncertainty is not simply whether nighttime enhancement should be included or excluded, but whether the observed diurnal cycle accurately represents ecosystem-scale gas exchange or is partly modified by the measurement system. This distinction is particularly important when interpreting apparent nighttime enhancement, because chamber-induced mixing may alter the temporal distribution of CH_4 exchange even when the integrated daily flux remains largely unchanged.

These considerations are also relevant when comparing ecosystems along hydrological gradients. If the observed diurnal patterns are biological, daytime sampling may reduce the apparent contrast between wetland sources and upland sinks by underestimating both nighttime emissions from wet sites and nighttime uptake at well-drained sites. Consistent with this, the difference in cumulative CH_4 exchange between the upland forest and bog over the measurement period was $364.3 \text{ mg CH}_4 \text{ m}^{-2}$ when all measurements were considered, but only $253.8 \text{ mg CH}_4 \text{ m}^{-2}$ when daytime measurements were used to estimate daily fluxes, corresponding to a 30 % reduction in the magnitude of the contrast between the two sites. Even if part of the nighttime enhancement is influenced by chamber-induced mixing, these calculations demonstrate that the treatment of nocturnal fluxes can strongly affect estimated ecosystem differences. Moreover, because the magnitude and direction of diurnal variability differed among sites and seasons, the potential effects of temporally restricted sampling are unlikely to be constant across ecosystems or throughout the year.

Together, these findings highlight the importance of accounting for diurnal variability when scaling chamber measurements to daily, seasonal, or annual CH_4 budgets. Automated high-frequency measurements provide the most direct means of capturing such variability, but where these are not feasible, sampling strategies should be designed to account for potential diurnal variability rather than assuming that daytime measurements represent daily mean fluxes. Future work should aim to better distinguish between biological controls on diurnal CH_4 exchange and methodological effects associated with chamber deployment, particularly under stable nocturnal atmospheric conditions. More generally, the results demonstrate that short-term CH_4 dynamics represent a potentially important source of uncertainty in ecosystem and landscape-scale CH_4 budget estimates.



5. Conclusions

Methane exchange differed strongly along the hydrological gradient, with the upland forest acting as a persistent CH₄ sink, the bog as a substantial CH₄ source, and the intermediate site occupying a transitional position between these end members. These contrasting flux regimes highlight the dominant role of hydrology in regulating the balance between CH₄ production and oxidation and demonstrate that substantial differences in CH₄ exchange can occur across relatively short spatial distances within peatland landscapes.

Pronounced diurnal variability in CH₄ fluxes was observed at all three sites, but both the direction and seasonal expression of these patterns differed along the hydrological gradient. At the bog and upland forest sites, CH₄ exchange was generally enhanced during nighttime, whereas the intermediate site exhibited more complex seasonal behaviour, including shifts between daytime uptake and nocturnal emissions. The strong sensitivity of diurnal CH₄ dynamics to seasonal changes in hydrological conditions at the intermediate site suggests that ecosystems near the transition between CH₄ sources and sinks may exhibit particularly dynamic short-term responses.

The results further indicate that the processes governing diurnal CH₄ variability are not necessarily the same as those controlling seasonal patterns or mean CH₄ exchange. In particular, the observed relationships between CH₄ fluxes, ecosystem respiration, and environmental conditions suggest that changes in CH₄ oxidation rates can contribute substantially to short-term variability in net CH₄ emissions even at sites where methanogenic production dominates overall CH₄ exchange. Moreover, the observed relationships between CH₄ fluxes and ecosystem respiration point to close interactions between carbon cycling and CH₄ turnover that are not fully captured by considering seasonal flux patterns alone.

At the same time, the possibility that part of the observed diurnal variability reflects chamber-induced alterations of near-surface turbulence highlights the need for careful interpretation of diurnal patterns derived from chamber measurements. Regardless of whether the observed cycles are primarily biological, methodological, or a combination of both, the results demonstrate that restricting measurements to daytime periods can substantially influence estimated CH₄ budgets and alter apparent differences among ecosystems along hydrological gradients.

Overall, this study shows that CH₄ exchange in northern peatland landscapes is characterized not only by strong spatial and seasonal variability but also by pronounced variability over the course of a day. Accounting for these short-term dynamics is important both for improving process-level understanding of CH₄ cycling and for designing measurement strategies that accurately represent ecosystem-scale CH₄ exchange across heterogeneous boreal landscapes.



750 Appendix



Figure A1: Seasonal photographs of the three microsites along the hydrological gradient from upland forest to bog. Images illustrate the chamber installations and seasonal variation in vegetation structure, site conditions, and snow cover throughout the measurement period.

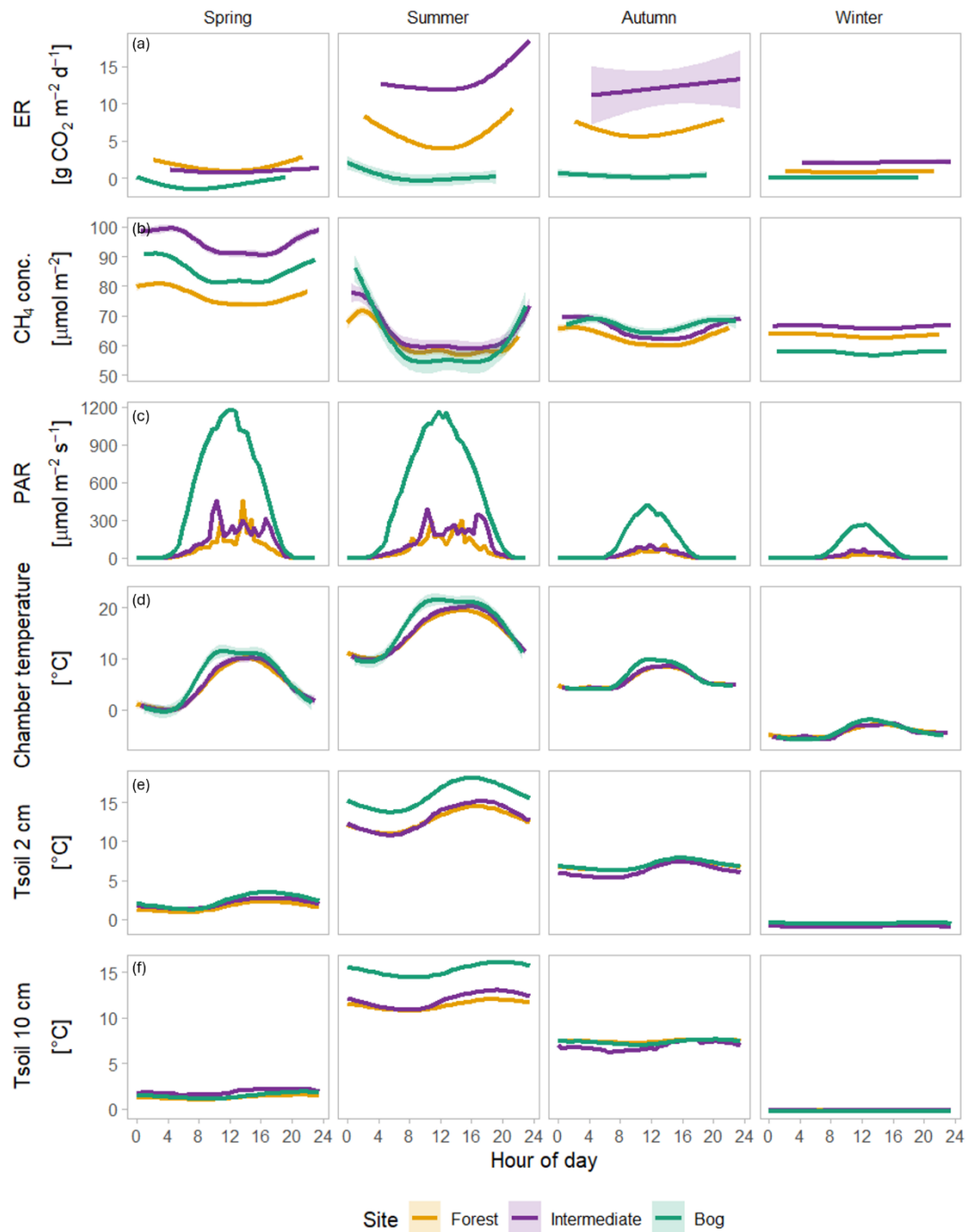




Figure A2: Diurnal patterns in environmental variables. Smoothed mean diurnal cycles of ecosystem respiration (ER, i.e. CO₂ flux measured in the opaque chamber) (a), ambient CH₄ concentrations (b), PAR (c), air temperature inside the chamber (d), and soil temperatures at 2 (e) and 10 cm depth (f) by site and season.



Figure A3: Daily mean CH₄ fluxes in 2022 measured by the four replicate chambers for upland forest (a), intermediate (b), and bog (c) sites. The grey vertical lines indicate the seasons. Negative values denote CH₄ uptake.

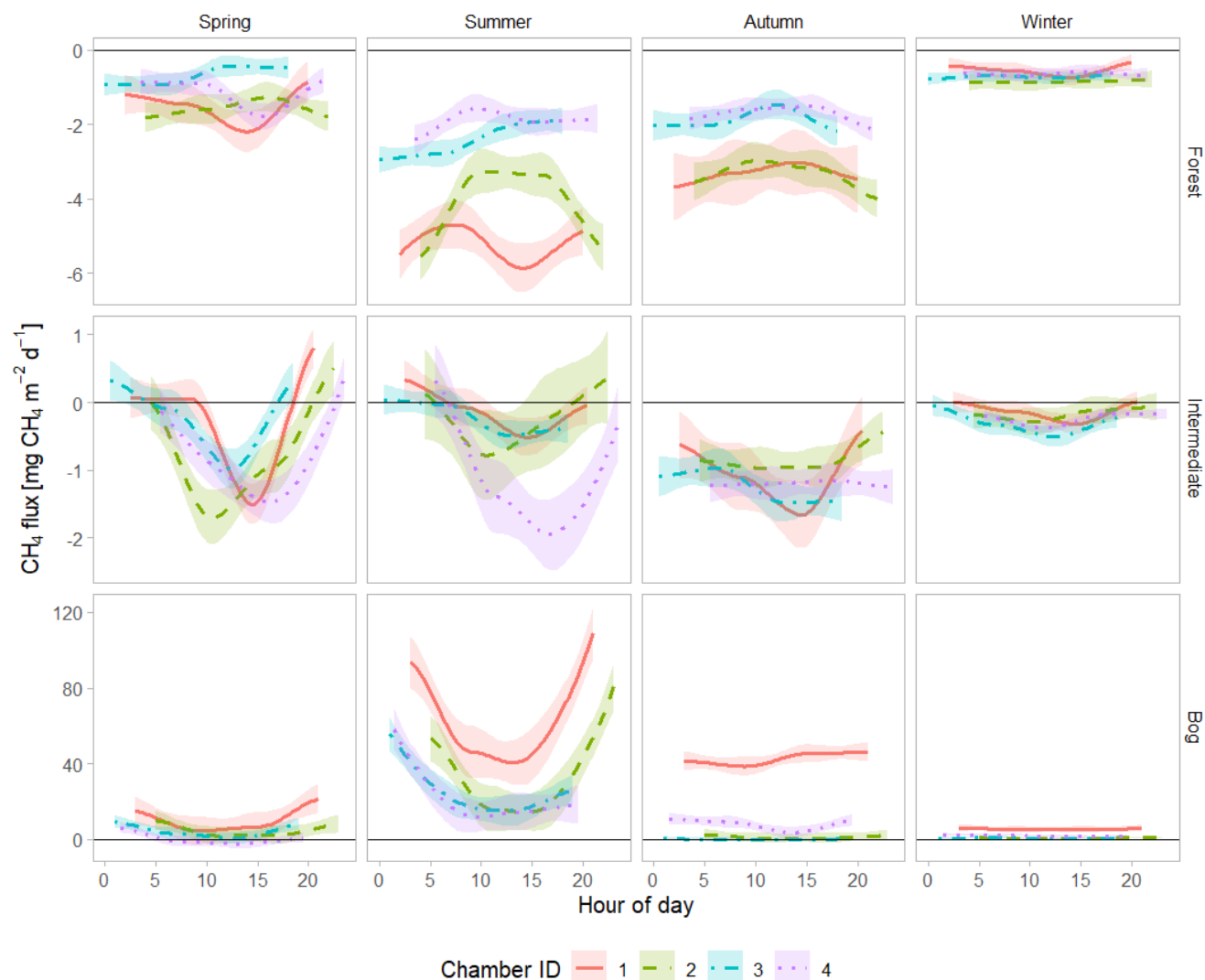


Figure A4: Diurnal variation in CH_4 fluxes along the moisture gradient by chamber and season. Fluxes are shown as seasonal means with 99 % confidence intervals derived from generalized additive model smoothing. Diurnal patterns are based on 4 measurements per chamber and day. Differences in the apparent timing of daily peak fluxes between chambers in this figure arise at least partly from the different timing of measurements during the day (Figure A5, Table A1).

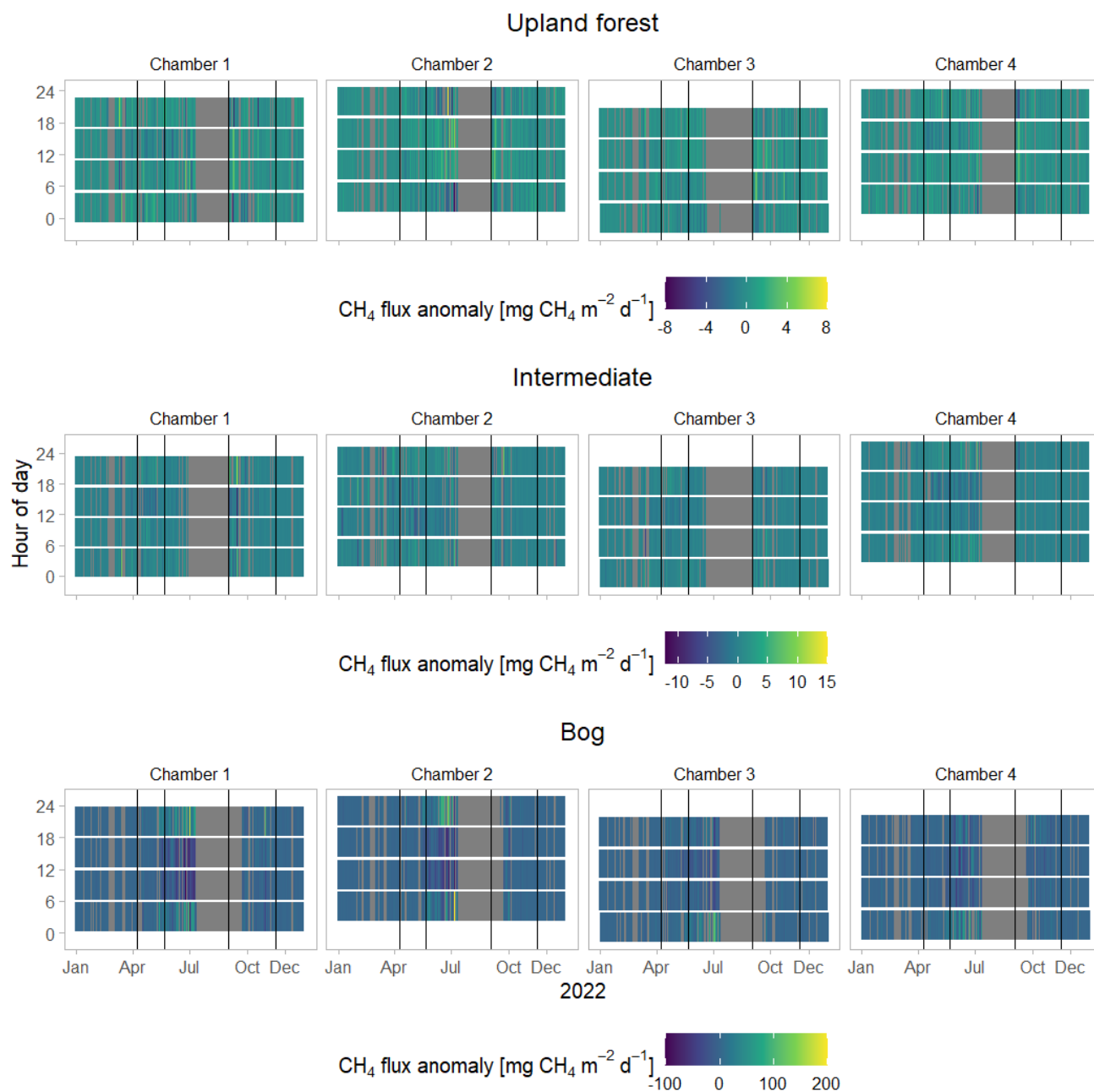


Figure A5: Diurnal variation in CH₄ fluxes along the moisture gradient by chamber for each measurement day. Colours indicate the CH₄ flux anomaly, i.e. the deviation of each chamber measurement from the chamber-specific daily mean. Grey areas indicate missing data. Black vertical lines delineate the seasons.

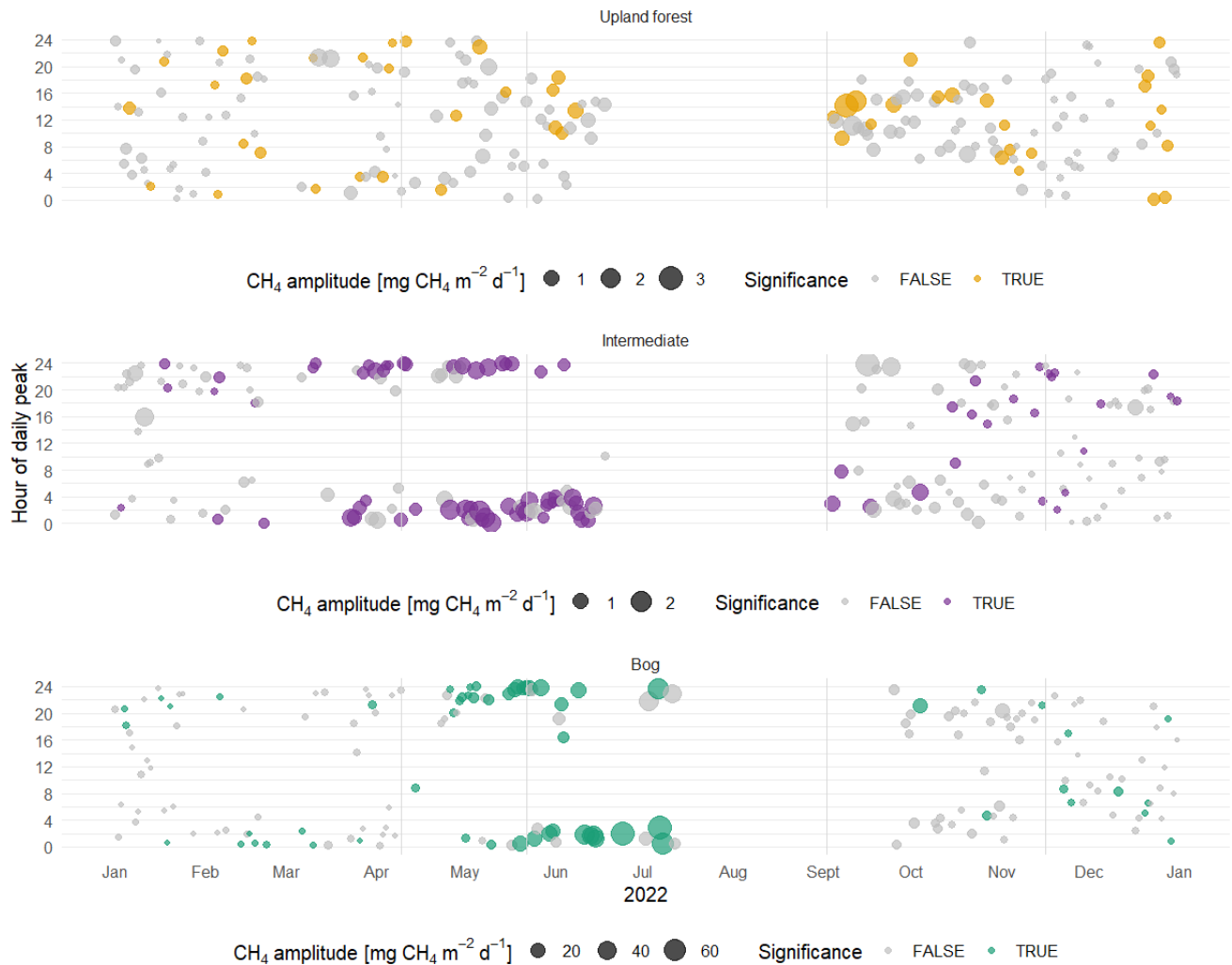


Figure A6: Strength of diurnal pattern (amplitude) and timing of peak CH₄ fluxes over the year derived from daily harmonic fits. Coloured points represent days with a significant diurnal pattern (harmonic fit with R²>0.3 and p<0.05). Vertical grey lines indicate shifts between seasons.

Table A1: Chamber closing times in Finnish standard time (UTC+2).

Site	Chamber	Closing times			
Upland forest	1 (transparent)	2:00	8:00	14:00	20:00
	2 (transparent)	4:00	10:00	16:00	22:00
	3 (transparent)	6:00	12:00	18:00	24:00
	4 (opaque)	3:30	9:30	15:30	21:30



Intermediate	1 (transparent)	2:30	8:30	14:30	20:30
	2 (transparent)	4:30	10:30	16:30	22:30
	3 (transparent)	0:30	6:30	12:30	18:30
	4 (opaque)	5:30	11:30	17:30	23:30
Bog	1 (transparent)	3:00	9:00	15:00	21:00
	2 (transparent)	5:00	11:00	17:00	23:00
	3 (transparent)	1:00	7:00	13:00	19:00
	4 (opaque)	1:30	7:30	13:30	19:30

Table A2: CH₄ flux data coverage after quality filtering in 2022 by site, chamber, and season.

	Year	Spring	Summer	Autumn	Winter
Upland forest	72 %	87 %	39 %	84 %	82 %
Chamber 1 (transparent)	73 %	85 %	43 %	83 %	82 %
Chamber 2 (transparent)	73 %	88 %	43 %	85 %	81 %
Chamber 3 (transparent)	69 %	87 %	28 %	84 %	82 %
Chamber 4 (opaque)	73 %	87 %	44 %	84 %	82 %
Intermediate	71 %	87 %	37 %	84 %	81 %
Chamber 1 (transparent)	70 %	87 %	33 %	84 %	81 %
Chamber 2 (transparent)	73 %	87 %	44 %	84 %	82 %
Chamber 3 (transparent)	68 %	88 %	27 %	84 %	81 %
Chamber 4 (opaque)	73 %	85 %	44 %	84 %	82 %
Bog	67 %	83 %	43 %	61 %	81 %
Chamber 1 (transparent)	68 %	83 %	44 %	60 %	81 %
Chamber 2 (transparent)	68 %	81 %	44 %	61 %	81 %
Chamber 3 (transparent)	67 %	85 %	42 %	61 %	81 %
Chamber 4 (opaque)	68 %	83 %	42 %	61 %	82 %

780 Code and data availability

The chamber flux and ancillary data set is available at <https://doi.org/10.1594/PANGAEA.993356> (Jentsch et al., 2026) and the soil and weather data collected at the upland forest site can be obtained from <https://doi.org/10.1594/PANGAEA.995282> (Boike et al., 2026).



Author contributions

785 CCT and LvD designed the measurement setup and installed the chamber system. JB provided and installed the soil and meteorological station at the upland forest site. AH and LvD processed the chamber data with contributions from KJ. KJ defined the focus of the manuscript and performed the data analyses. KJ wrote the manuscript with contributions by LvD to the methods chapter. All authors reviewed the manuscript. CCT supervised the project.

Competing interests

790 The authors declare that they have no conflict of interest.

Disclaimer

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Use of artificial intelligence

ChatGPT (OpenAI; GPT-5.5) was used to assist with language editing and improve the clarity, readability, and flow of the manuscript. The authors reviewed, revised, and verified all text modified with this tool and take full responsibility for the content of the publication.

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