

Early carbon recovery after cell-bunding rewetting is constrained by aerated microsites in a cutaway raised bog

Md Shamsuzzaman¹, Shane Regan², Ultan McCarthy³, Imelda Casey³, Ciara Farrell¹, Sate Ahmad⁴, Wahaj Habib⁵, Owen Naughton¹

¹Department of the Built Environment, South East Technological University, Carlow, Ireland

²Scientific Advice and Research Directorate, National Parks and Wildlife Service, Dublin, Ireland

³Department of Land Sciences, South East Technological University, Waterford, Ireland

⁴Restoration and Landscape Ecology Lab, School of Biology and Environmental Science, University College Dublin, Dublin, Ireland

⁵Department of Geography, Trinity College Dublin, Dublin, Ireland

Correspondence to: Shane Regan (shane.regan@npws.gov.ie)

Abstract. Rewetting is increasingly used to reduce greenhouse gas emissions from cutaway peatlands and support the recovery of carbon sequestration. While carbon responses of drained peatlands to rewetting are relatively well understood, few studies link ecosystem-scale carbon exchange with fluxes at restoration-created microsites during early recovery. This is particularly true for cell-bunding restoration, where whole-site fluxes are rarely linked to the microsites created by the restoration design. Here, we examined carbon dynamics at an Irish cutaway raised bog during the two years after cell-bunding rewetting. We combined ecosystem-scale eddy covariance measurements of CO₂ and CH₄ with CO₂ chamber measurements across bunds, vegetated peat, bare peat, and open water. The site remained a net CO₂-C source in both years, although net CO₂ losses declined by 39 % from 2024 to 2025. CH₄ emissions were approximately two orders of magnitude smaller than CO₂ emissions in carbon-mass terms. CO₂ exchange was strongly associated with meteorological and hydrological conditions, with lower net losses occurring during the cooler, wetter conditions of 2025. Chamber measurements revealed strong spatial heterogeneity. Bunds were persistent CO₂ hotspots. Flooded open water areas had very low emissions, whereas CO₂ efflux increased when these surfaces became temporarily exposed following water-table drawdown. Vegetated peat showed high respiration along with substantial growing-season CO₂ uptake. Overall, early post-rewetting CO₂-C dynamics at the site remained strongly influenced by aerated microsites. Restoration success should therefore be assessed using both ecosystem-scale fluxes and microsite-level measurements to capture spatial heterogeneity in carbon responses.

1 Introduction

Peatlands store large amounts of terrestrial carbon, but drainage, extraction and land-use change can convert them into persistent greenhouse-gas (GHG) sources (Page et al., 2011; Rydin and Jeglum, 2013). In degraded and milled peatlands, lower water tables accelerate aerobic decomposition, slow or halt new peat formation, and leave a patchy surface where hydrology, vegetation recovery and carbon exchange vary over short distances (Rydin and Jeglum, 2013; Waddington et al., 2010). Rewetting is now widely promoted as the primary restoration strategy, but its carbon effects are often slow and complex, especially during the first years after intervention (Parry et al., 2014; Schimmel et al., 2025; Wilson et al., 2016). The outcomes of rewetting drained peatlands depend on site-specific conditions and the restoration measures applied (Mander et al., 2024). The aim of rewetting is to restore wetter, near-natural hydrological conditions by raising water levels and adapting restoration design to site hydrology (Wilson et al., 2022; Christen et al., 2016).

Rewetting can reduce aerobic decomposition by raising water levels and increasing surface moisture, but exposed peat structures such as dams may remain aerated and continue to emit CO₂ (Waddington et al., 2010; Vybornova et al., 2019). Rewetting typically reduces CO₂ emissions but may increase CH₄ emissions relative to drained conditions, especially during the early stages of recovery (Escobar et al., 2022; Koskinen et al., 2016; Laine et al., 2019). The post-rewetting GHG trajectory therefore remains uncertain and can vary substantially among sites, reflecting differences in hydrology, restoration approach, pre-existing vegetation, residual peat properties and other environmental conditions (Schaller et al., 2022; Strack and Zuback,



2013; Turmel-Courchesne et al., 2023; Khan et al., 2025). In addition, peat subsidence caused by compaction and decomposition can persist after water levels are raised (Leifeld et al., 2011). Rewetting may also lead to the development of shallow lakes (Steffenhagen et al., 2012), while vegetation recovery can remain slow. This may delay the establishment of peatland species, CO₂ uptake and the resumption of carbon accumulation (Beyer et al., 2021; Koch et al., 2017). Short measurement windows after rewetting should therefore be interpreted as part of an early recovery trajectory rather than as firm evidence of the final restoration outcome.

A fundamental challenge in assessing restoration is that recovery often proceeds unevenly across a rewetted site (Haapalehto et al., 2011, 2017). Measures such as drain blocking and bund construction can improve water conditions at the site scale, but they can also create a mosaic of microsites that differ in microelevation, inundation, vegetation cover, and aeration (Ahmad et al., 2025; Parry et al., 2014; Pouliot et al., 2011; Rochefort et al., 2003). These fine-scale differences in water-table position, peat properties, and vegetation can strongly influence ecosystem respiration and carbon uptake; thus, fluxes measured at individual plots may not represent whole-site conditions (Rinne et al., 2007; Strack et al., 2006). Conversely, ecosystem-scale measurements provide an integrated flux for the whole footprint but may not reveal how individual microsites contribute to the observed carbon exchange (Kutzbach et al., 2004; Schrier-Uijl et al., 2010; Strack et al., 2006).

Eddy-covariance (EC) techniques are widely used to track high-frequency temporal variability in CO₂ exchange over relatively large areas (Aubinet et al., 1999; Baldocchi, 2003; Kroon et al., 2010). Recently rewetted peatlands can remain net CO₂ sources at the ecosystem scale, even where rewetting reduces emissions relative to drained conditions (Petrone et al., 2003; Holl et al., 2020). However, EC measurements alone cannot reveal which microsites contribute to these losses (Shahan et al., 2022). In contrast, flux chamber (FC) methods are particularly useful for quantifying fine-scale spatial variability in CO₂ and CH₄ fluxes and identifying dominant sources and sinks within heterogeneous landscapes (Pavelka et al., 2018; Shahan et al., 2022; Zhao et al., 2024). They can further examine how differences in peat properties and surface-cover types contribute to flux variation among microsites (Krauss et al., 2016). Combining EC and FC can therefore link ecosystem-scale carbon exchange with the spatial variability and local controls observed among individual microsites. Recent reviews emphasise that empirical data from rewetted peatlands, particularly holistic GHG assessments that consider both temporal trends and spatial heterogeneity, remain limited, and many key questions about post-rewetting climate impacts are still unresolved (Laudon et al., 2025).

Previous studies have used EC to investigate carbon exchange during recovery after peat extraction and rewetting, showing that restored sites may remain substantial CO₂ sources during the first years following rewetting (e.g., Holl et al., 2020; Petrone et al., 2003). FC likewise show considerable variation in carbon exchange among microsites in restored peatlands (e.g., Waddington et al., 2010). However, few studies have combined ecosystem-scale EC measurements with concurrent microsite-scale FC observations during the early recovery of rewetted post-extraction peatlands. This is particularly relevant at sites rewetted using cell bunding, where raised bunds, flooded cells, exposed peat and patches of recovering vegetation create a highly heterogeneous surface within a single EC footprint. An important unresolved question is therefore how ecosystem-scale carbon exchange relates to fluxes from contrasting microsites, and whether early post-rewetting carbon losses are distributed relatively evenly across the rewetted surface or concentrated in particular microsites created or maintained by the restoration design.

Here, we evaluate how cell-bunding rewetting of a cutaway peat-extraction site in Ireland alters early-stage carbon exchange by combining EC measurements of ecosystem-scale CO₂ and CH₄ exchange with FC of CO₂ fluxes across microsite types within the EC footprint. This combined approach links ecosystem-scale carbon exchange with the local factors that drive variation among microsites. More specifically, we (1) quantify seasonal and interannual variation in ecosystem-scale CO₂ and CH₄ exchange, (2) compare respiration and net exchange across the major microsite classes within the EC footprint, and (3) assess how microsite heterogeneity and fine-scale fluxes relate to ecosystem-scale carbon exchange during early post-rewetting recovery.



2 Methods

2.1 Study site and restoration context

All Saints Bog is a raised bog complex in central Ireland, approximately 5 km north northwest of Birr, County Offaly (Fig. 1) (53.151755° N, 7.967942° W). It is protected as a Special Area of Conservation under the EU Habitats Directive (92/43/EEC) due to the presence of Active and Degraded Raised Bog, Rhynchosporion communities, and bog woodland. The main uncut high bog occupies around 223 ha, while an adjacent approximately 40 ha cutaway former peat-extraction area on the north-eastern margin, hereafter referred to as the Study Site, forms the focus of this work. This area was milled for horticultural peat in the early 1990s and left with a gently sloping, drained surface, uneven topography, and sparse vegetation.

The peat surface was dissected by a regular pattern of shallow drains, spaced at roughly 15 m and 0.1–0.5 m deep. Peat across this area is between 0.7 and 2.9 m deep, thinning towards the northern margin, and overlies shelly marl and other fine-grained lacustrine and glacial deposits. Prior to restoration, hydrogeological investigations with piezometer pairs showed mainly downward gradients and water tables that were generally deeper than 0.5 m below the surface, consistent with a dry, oxidising peat horizon and dominance of surface runoff (Hydro-Environmental Services, 2020).

Restoration work, coordinated by the National Parks and Wildlife Service (NPWS), began in May 2022 and was completed in August 2023. Peat trench bunds and berms were constructed across the study site, aligned with local topography to create small hydrological cells, retain surface water, and promote rewetting. Unlike surface bunds, trench bunds are cut into the underlying peat to intercept shallow subsurface pathways. At the Study Site, the trench-bunds were cut 1.5–2.0 m below the ground surface and filled with compacted peat and followed topographic contour lines that corresponded with a 0.1 m drop in elevation gradient. Weirs and pipes were added at selected points in the cells to allow controlled overflow between cells. On the remaining high bog, drainage ditches were blocked with peat dams. Overall, these measures were designed to raise and stabilise water tables, promote wetter microsites, and enable the gradual re-establishment of peat-forming bog vegetation at the Study Site. Site conditions before and after rewetting are shown in Fig. 1e and f. Long-term water-table, soil-moisture and precipitation records spanning the pre-restoration, active-restoration and post-restoration periods are provided in Fig. S2.



Fig. 1. Study site and field measurements at All Saints Bog, Ireland: (a) Location of All Saints Bog within Ireland and orthomosaic aerial image of the rewetted peatland showing the eddy covariance (EC) footprint, EC tower, FC measurement plots, and water-table (WT) logger locations; (b) EC tower installed within the rewetted cutaway bog; (c) Dark chamber used for ecosystem respiration (R_{eco}) measurements; (d) Transparent chamber used for net ecosystem exchange (NEE) measurements; (e) Site conditions before rewetting in April 2021; (f) Site conditions after rewetting in September 2024.



2.2 Research design and microsite classification

Microsite classes and sampling plots were set up to capture spatial heterogeneity across the Study Site. The land cover was grouped into four main microsite classes that best represent conditions occurring on the Study Site: bare peat, bunds, vegetated peat, and open water (Table 1). These classes reflect differences in vegetation cover, hydrological conditions, and proximity to bunds and ditches, as well as their position relative to the main EC footprint. Open water plots were treated as a single microsite class, but observations were classified as open water when flooded and open water (exposed) when temporarily exposed, because exposure changed their CO₂ exchange dynamics. In July 2024, 84 plots were identified using a sector-based transect layout (Korkiakoski et al., 2023). Eight transects radiated from the EC tower at 45° intervals, with additional transects positioned within the prevailing wind sector (135°–270°) to increase sampling in the dominant wind directions (Fig. 1). Each transect had seven plots, with the first three located inside the EC footprint. Spacing between plots was about 25 m near the tower and increased as the transects extended into the wider fetch (Fig. 1).

During plot installation, basic microsite characteristics were recorded, focusing on peat conditions and the presence or absence of vegetation. High-resolution drone imagery, combined with field observations, was used to support microsite classification and map surface features. During each day-long respiration campaign, the hydrological status of each established plot as dry or wet was recorded at the time of flux measurement. ‘Dry’ plots had no standing water, with the water table at or below the peat surface, while ‘wet’ plots were flooded or waterlogged. These observations were used to identify temporary state changes, especially in open water plots that became exposed during drawdown periods and were classified as open water (exposed).

Table 1. Microsite classes and key site characteristics, including surface description, hydrological condition, vegetation cover and hydrological variability. WT = water table position relative to the peat surface; positive values indicate water above the peat surface and negative values indicate water below the peat surface.

Microsite class	Surface description	Typical condition (WT)	Vegetation cover	State dynamics
Bare peat	Exposed, degraded peat surface	Non-flooded (WT ≤ 0 cm)	None	May become temporarily wet or waterlogged after rainfall
Bund	Constructed raised peat ridge	Very dry (typically WT ≤ −40 cm)	None	Remains mostly dry to moist
Vegetated peat	Eriophorum-dominated surface	Non-flooded (WT ≤ 0 cm)	Present	May become temporarily flooded during wetter periods
Open water	Shallow ponded depression	Flooded (WT > 0 cm)	None	Usually flooded, but becomes exposed when WT ≤ 0 cm

2.3 Eddy flux measurements

2.3.1 EC instrumentation and measurements

An eddy covariance (EC) system was installed by NPWS in January 2021 to measure ecosystem-scale fluxes of CO₂, CH₄, and H₂O at the Study Site (Fig. 1b). The tower was installed at a height of 2.5 m near the centre of the restored area and equipped with a sonic anemometer and two gas analysers (enclosed-path LI-7200 for CO₂ and H₂O and open-path LI-7700 for CH₄; LI-COR Biosciences). High-frequency (10 Hz) wind and gas data were recorded using an LI-7550 data logger with SMARTFlux and aggregated into 30-min averages. Ancillary measurements included photosynthetic photon flux density (PPFD), air temperature (Ta), relative humidity (RH), precipitation (R), soil temperature (Ts), soil water content (SWC) at 10 cm depth, and water table depth from automated pressure loggers near the tower. Vapour pressure deficit (VPD) was derived



from Ta and RH, and all meteorological variables were averaged to 30-min mean values to match the flux data. Positive NEE values indicate net CO₂ release to the atmosphere, whereas negative values indicate net CO₂ uptake by the ecosystem. Annual sums were calculated for calendar years.

2.3.2 EC data processing

Raw EC data were processed in EddyPro using standard procedures (Aubinet et al., 2012). Processing steps included spike removal (Mauder et al., 2013); double coordinate rotation to align wind vectors with the mean flow (Wilczak et al., 2001); time-lag compensation; spectral corrections for high- and low-pass filtering (Moncrieff et al., 1997; Fratini et al., 2012); and steady-state and turbulence tests (Foken and Wichura, 1996). Storage terms were added, and footprint estimates (Kormann and Meixner, 2001) were used to retain only half-hour periods with at least 70 % footprint contribution from the Study Site. Gap filling and flux partitioning were carried out in the REdDyProc framework (Reichstein et al., 2005; Wutzler et al., 2018).

Low turbulence periods were filtered using friction velocity (u^*) thresholds, CO₂ gaps were filled with the marginal distribution sampling (MDS) method, and NEE was partitioned into R_{eco} and GPP using the standard nighttime temperature-response approach (Reichstein et al., 2005). CH₄ gaps were filled with a two-stage approach combining linear interpolation for short gaps and machine learning (ML) models (Random Forest and XGBoost) for longer gaps, following recent work on ML-based gap filling for methane fluxes (e.g., Irvin et al., 2021; Wutzler et al., 2018). We applied the u^* -ensemble approach in REdDyProc and report the median u^* case as our best estimate, with low and high u^* scenarios defining the associated uncertainty range (Reichstein et al., 2005; Wutzler et al., 2018).

2.4 FC-based CO₂ flux measurements

2.4.1 Ecosystem respiration (R_{eco}) measurements

To quantify ecosystem respiration (R_{eco}), FC-based CO₂ flux monitoring was conducted across 83 microsite plots. Sampling occurred twice monthly from July 2024 to June 2025. A total of 1287 measurements were collected. During the winter months, sampling was reduced to 60 plots due to restricted daylight and site accessibility. CO₂ efflux measurements were carried out using an opaque soil respiration chamber (SRC-2) connected to an environmental gas monitor (EGM-5 IRGA; PP Systems, UK) (Fig. 1c). For CO₂ efflux measurements from open water plots, a floating collar system was used. A floating cork sheet fitted with a centrally positioned collar was placed on the water surface, and a rubber gasket was used between the SRC-2 and the collar to create an airtight seal. Each measurement lasted 130 s, with CO₂ concentrations recorded at 1 Hz intervals. Measurements were conducted between 08:00 and 17:00. Because the opaque chamber excluded photosynthesis during measurements, all recorded CO₂ effluxes were treated as total ecosystem respiration (R_{eco}). These FC measurements represent daytime campaign conditions and were not intended to produce a fully time-resolved annual budget.

2.4.2 Net ecosystem exchange (NEE) and gross primary production (GPP)

NEE measurements were conducted to assess CO₂ uptake at a subset of four vegetated plots dominated by *Eriophorum* spp. The plots were established in areas within the EC tower footprint that had become vegetated following restoration, with measurements beginning in January 2025. Measurements were restricted to vegetated peat surfaces because the focus was on active carbon uptake by vegetation; bare peat, bunds, and open water were excluded from this analysis. The campaign used a CPY-4 canopy assimilation chamber connected to an EGM-5 (PP Systems, UK) (Fig. 1c). Measurements followed the same protocol as the respiration campaigns, with CO₂ concentrations recorded at 1 Hz over a 130 s enclosure period. Immediately before or after each NEE measurement, the chamber was covered with a dark cloth to record R_{eco} at the same plots. These paired measurements allowed partitioning of GPP from R_{eco} and NEE ($GPP = R_{eco} - NEE$). The resulting fluxes describe carbon uptake at vegetated microsites and were not intended to represent ecosystem-scale NEE.

2.4.3 FC data processing

Changes in CO₂ concentration recorded within the chamber headspace during each chamber deployment were used to calculate CO₂ fluxes. A linear regression was fitted to the CO₂ concentration time series for each measurement, and the resulting slope was used to calculate the flux. Flux calculations accounted for the effective chamber volume, enclosed surface area, air



temperature, atmospheric pressure and water vapour pressure, with results expressed as $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$. Measurements with a CO_2 concentration change of 1 ppm or less were retained as near-zero fluxes. Those with larger concentration changes were retained only when the regression fit reached an R^2 of 0.90 or higher.

2.5 Environmental and ancillary measurements

Environmental parameters were recorded concurrently with each plot-wise CO_2 flux measurement. A Stevens HydraProbe sensor connected to the EGM-5 system was used to record soil temperature and soil moisture content adjacent to each plot at 5 cm depth below the peat surface. Measurements were taken at the time of each chamber deployment to ensure a direct temporal match with the observed gas exchange. Water table depth at each plot was measured manually from PVC phreatic tubes. Water table depth was referenced to the peat surface, with positive values indicating standing water and negative values indicating water below the peat surface.

Microsites across the study area were mapped using a drone survey (Mavic 3M; DJI, Shenzhen, China). The survey was conducted in April 2024, approximately eight months after completion of the restoration works. UAV imagery acquired on 26 April 2024 was classified into four land-cover classes (bund, vegetation, water and bare peat) using a PSPNet semantic segmentation model with a ResNet-101 backbone (Zhao et al., 2017). In June 2025, a field-based survey of microsite-specific vegetation characteristics was conducted to assist in interpreting the variation in CO_2 fluxes. The survey included identifying dominant plant species and performing visual estimates of percentage vegetation cover. These measurements were used to evaluate relationships between CO_2 fluxes, hydrological conditions, and thermal drivers across microsites. For descriptive environmental summaries, the study period was divided into three seasonal intervals: Nov–Feb, Mar–Jun, and Jul–Oct.

2.6 Flux upscaling

To relate plot-scale fluxes to ecosystem-scale EC fluxes, we upscaled FC observations using the areal cover of each microsite within the main EC footprint. The footprint boundary was defined from the EC footprint analysis, and land-cover fractions were derived from the classified UAV orthomosaic acquired on 26 April 2024 by calculating the proportional pixel area of each microsite class inside this boundary. The resulting land-cover fractions are reported in Sect. 3.2 and remained unchanged during the course of the study period. For each microsite class, we calculated the mean chamber flux over the overlapping period (17 July 2024–15 June 2025) and then computed an area-weighted footprint mean by multiplying these class means by their respective area fractions and summing across classes. This yielded a FC-based estimate of the footprint-average flux for comparison with EC-derived mean and cumulative fluxes over the same period. Given the biweekly sampling of FC measurements, this upscaled estimate should be interpreted as an approximate consistency check rather than an independent, fully time-resolved budget.

To further examine the influence of spatial heterogeneity on ecosystem-scale CO_2 exchange, the classified UAV land-cover map was also analysed by 10° wind sectors within the dominant EC footprint (0–84 m radius around the EC tower). Fractional cover of bund, bare peat, vegetation, and open water were calculated for each sector in ArcGIS Pro 3.2. Mean NEE for the post-restoration period was then calculated from quality-filtered EC observations ($u^* \geq 0.10 \text{ m s}^{-1}$) for each corresponding wind sector, allowing directional variation in ecosystem-scale CO_2 exchange to be compared with the corresponding footprint land-cover composition.

2.7 Statistical analysis

Two complementary statistical approaches were applied to EC and FC datasets. Mutual information (MI) analysis, recently used to identify environmental controls on ecosystem-scale carbon fluxes (Lindenberger et al., 2026), was applied to the continuous half-hourly EC time series (2024–2025) to identify key drivers of NEE and CH_4 . Generalized additive models (GAMs) were fitted to FC-derived data to examine plot-scale controls. MI quantifies the amount of shared information between two variables and can capture both linear and nonlinear dependence. Unlike simple correlation, MI does not assume a particular functional form or the direction of association, providing a more general way to explore links between fluxes and their potential drivers (Kraskov et al., 2004; Shannon, 1948). Here, MI was used as an exploratory ranking tool and was not interpreted as evidence of causality.



We implemented MI analysis in Python (v3.12.13) using the `mutual_info_regression` estimator from scikit-learn (Pedregosa et al., 2011), which is based on a k-nearest neighbour approach similar to that proposed by Kraskov et al. (2004). We first compiled a dataset for 2024–2025 containing NEE, CH₄ flux and a set of candidate drivers: sensible heat (H), latent heat (LE), net radiation (NETRAD), SWC, incoming shortwave radiation (SW_IN), PPFD, VPD, Ts, Ta, soil heat flux (SHF), RH, air pressure (Pa) and wind speed (WS). MI was then computed separately for NEE and CH₄ as target variables. For each target, we analysed two subsets: (i) the full 2-year record and (ii) a growing-season subset (May–September). Within each subset, we removed rows with missing values, rescaled the drivers to the 0–1 range using a `MinMaxScaler` function from scikit-learn (Pedregosa et al., 2011) and calculated MI between the target flux and each driver. The resulting MI scores were used to rank variables by their relative explanatory importance for NEE and CH₄ and to compare how driver influence changed between the full record and the growing-season.

We used spatial generalized additive models (GAMs) in R (package - `mgcv`; Wood, 2017) to examine which variables were associated with FC-derived Reco. GAMs are particularly suitable for this as they enable the inclusion of non-linear relationships between the dependent and the explanatory variables (Ahmad et al., 2025), such as the responses of ecosystem respiration to environmental conditions. R_{eco} was modelled as the response variable. The model was fitted using a Tweedie distribution with a log link and restricted maximum likelihood (REML), which accounted for the skewed and heteroscedastic flux data, including very low or near-zero R_{eco} values, without the need for transformation (Zauner et al., 2025). Smoothed terms of Ts, WT and day of year (DoY) were included as continuous predictors, while microsite type was included as a categorical factor. DoY was represented with a cyclic spline to capture seasonal variation. Plot locations (longitude and latitude) were included as a two-dimensional smooth to represent spatial variation, while elevation was retained as a linear term because its preliminary smooth was effectively linear (edf = 0.95). Shrinkage smoothers were used for continuous predictors so that non-informative terms could be penalised towards zero. Basis dimensions were set to $k = 10$ for univariate smooths and $k = 70$ for the spatial term. Model diagnostics indicated no major violations of model assumptions (Fig. S1).

To compare ecosystem-scale carbon fluxes between 2024 and 2025, daily NEE, Reco, GPP, and CH₄-C fluxes were aggregated to daily totals and matched by calendar day. This pairing enabled direct comparison between corresponding days in the two years. Differences between years were evaluated using two-sided Wilcoxon signed-rank tests because the observations represented matched pairs and did not consistently satisfy the assumptions of parametric tests. Statistical significance was assessed at $\alpha = 0.05$.

3 Results

3.1 Environmental and site conditions

Environmental conditions measured at the EC tower showed that mean annual Ta decreased from 13 ± 4 °C in 2024 to 11 ± 4 °C in 2025, while mean annual Ts remained at 12 °C. SWC stayed high overall (71 ± 9 % in 2024 and 74 ± 5 % in 2025), although 2024 showed a clear dry summer condition, with SWC dropping to 60 ± 7 % and WT deepening to -33 ± 5 cm in Jul–Oct. In contrast, higher annual R in 2025 (848 mm vs 676 mm) led to a shallower and more stable WT (annual mean -20 ± 4 cm vs -25 ± 8 cm), limiting summer drying despite similar seasonal temperatures. Overall, site conditions remained cool and wet in both years, with 2025 being cooler and wetter than 2024.

Table 2. Seasonal (Nov–Feb, Mar–Jun, Jul–Oct) and annual values of Ta (air temperature), Ts (soil temperature), SWC (soil water content), WT (water table depth; negative values indicate levels below the peat surface), and R (total rainfall) at the Study Site in 2024 and 2025 (daily mean $\pm$ SD and total rainfall).

Year	Period	Ta (°C)	Ts (°C)	SWC (%)	WT (cm)	R (mm)
2024	Nov–Feb	10 ± 3	8 ± 3	75 ± 3	-25 ± 9	282
	Mar–Jun	12 ± 3	13 ± 3	77 ± 3	-18 ± 2	214
	Jul–Oct	15 ± 2	15 ± 3	60 ± 7	-33 ± 5	180



	Annual	13 ± 4	12 ± 4	71 ± 9	-25 ± 8	676
2025	Nov–Feb	7 ± 3	6 ± 2	76 ± 2	-17 ± 3	340
	Mar–Jun	12 ± 3	13 ± 4	74 ± 2	-18 ± 3	205
	Jul–Oct	15 ± 3	17 ± 4	72 ± 6	-23 ± 3	303
	Annual	11 ± 4	12 ± 6	74 ± 5	-20 ± 4	848

3.2 Environmental conditions across microsites

Spatially, the Study Site was strongly heterogeneous with a mosaic of bare peat, vegetated peat, open water pools, and bunds. Among these microsites, strong variability in hydrological conditions was observed across different seasons. Water tables in open water microsites remained near or above the peat surface (Fig. 2). During drier conditions, mostly in summer, WT dropped and remained below the peat surface. As a result, the peat surface at these open water microsites became exposed. In contrast, the bund remained consistently drier with the deepest WT. Hydrological conditions (WT and SWC) were broadly similar across bare peat, temporarily exposed open water areas, and vegetated peat. Together, these measurements show that the restored surface remained wet overall but retained strong microsite-scale hydrological contrasts.

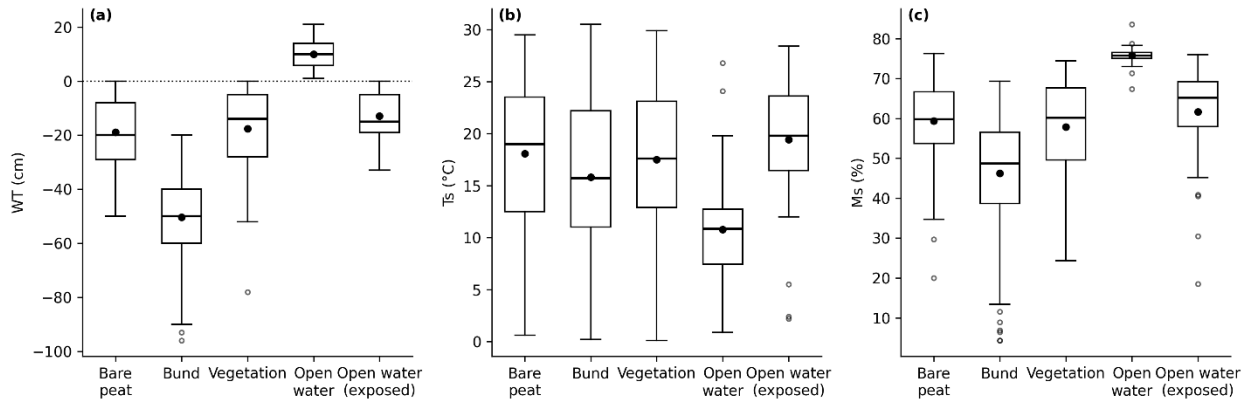


Fig. 2. Hydrological and soil microclimate contrasts among microsites (water table (WT) depth, soil temperature (Ts), and soil moisture (Ms)) at the Study Site from July 2024 to June 2025.

3.3 Footprint land cover and microsite distribution

Within the main EC footprint (0–84 m), land cover was dominated by bare peat (64 %). Bunds, vegetated peat and open water pools contributed 25 %, 8 % and 3 %. Within the wider EC fetch (0–250 m), bare peat still covered roughly half of the surface. Most of the vegetated peat occurred outside the main footprint, where it made up just over one-fifth of the area, with bunds and open water forming the remainder. Across the full 0–250 m fetch, bare peat and bund surfaces therefore occupied most of the source area, whereas vegetated peat and open water pools were confined to a relatively small share of the footprint. This distribution helps interpret the EC fluxes, because the main footprint was dominated by bare peat and bund surfaces rather than vegetated peat or open water.

3.4 EC fluxes

The Study Site remained a net source of CO₂ throughout the study period (2024–2025), with clear seasonal and interannual differences in flux dynamics (Fig. 3). The annual cumulative NEE varied substantially between years, with 236 g C m⁻² in



2024 and a decline to 145 g C m^{-2} in 2025. This reduction coincided with a decrease in R_{eco} from 387 g C m^{-2} in 2024 to 335 g C m^{-2} in 2025 and an increase in GPP from 151 g C m^{-2} in 2024 to 190 g C m^{-2} in 2025. Despite a nearly 26 % increase in GPP and a 13 % decrease in R_{eco} , the ecosystem remained a net CO_2 source.

Interannual differences were also evident in the monthly patterns of CO_2 fluxes (Fig. 3). In 2024, the highest GPP (23 g C m^{-2}) was recorded in May, indicating maximum uptake. However, late summer (August) was characterised by higher CO_2 emissions, with R_{eco} (44 g C m^{-2}) and NEE (26 g C m^{-2}). Peak GPP increased further to 29 g C m^{-2} in June 2025, while peak R_{eco} declined slightly to 42 g C m^{-2} in July. Across this year, NEE varied within a narrower range compared to 2024, ranging from 10 g C m^{-2} in September to 14 g C m^{-2} in February. This indicates relatively stronger growing-season CO_2 uptake and lower peak carbon losses in 2025.

These interannual contrasts were also evident in the daily flux statistics. Daily NEE, R_{eco} and GPP often deviated from normality according to Shapiro–Wilk tests of the paired differences (for example, NEE: $p = 0.0005$; R_{eco} : $p = 0.0004$; GPP: $p = 0.316$). Therefore, daily fluxes were paired by calendar day and compared between 2024 and 2025 using two-sided Wilcoxon signed-rank tests. All three flux components differed significantly between years (365 paired days), with the strongest difference observed for NEE ($W = 5581$, $p < 0.001$), followed by R_{eco} ($W = 13502$, $p < 0.001$) and GPP ($W = 19380$, $p < 0.001$). Overall, the lower annual NEE in 2025 appeared to reflect a more consistent shift in daily fluxes rather than differences limited to a few months.

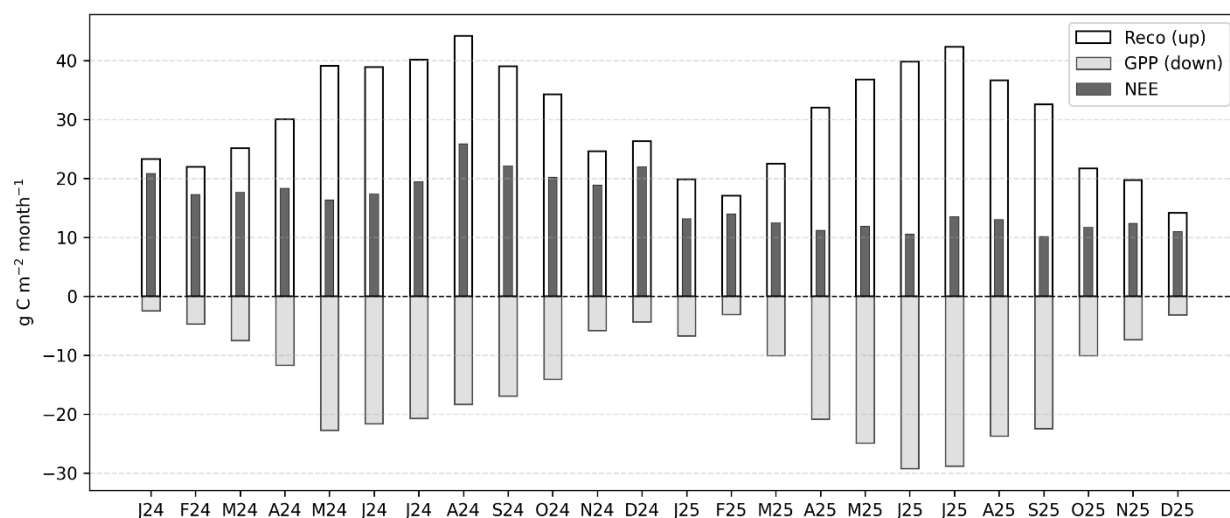


Fig. 3. Monthly sums of ecosystem respiration (R_{eco}), gross primary production (GPP), and net ecosystem exchange of CO_2 (NEE) for 2024–2025 ($\text{g C m}^{-2} \text{ month}^{-1}$). R_{eco} is shown as positive fluxes, while GPP is plotted as negative values to represent CO_2 uptake. NEE reflects the net balance of these components. Positive NEE and R_{eco} indicate CO_2 release, while negative NEE and GPP indicate CO_2 uptake.

Methane emissions from the Study Site were very small relative to CO_2 fluxes and changed only slightly between years. Annual $\text{CH}_4\text{-C}$ release increased from 3.30 g C m^{-2} in 2024 to 3.65 g C m^{-2} in 2025, whereas annual NEE and R_{eco} were one to two orders of magnitude larger over the same period. Monthly $\text{CH}_4\text{-C}$ sums showed a modest seasonal pattern, with higher emissions during mid- to late summer and lower values in spring (Fig. 4): maximum monthly fluxes reached 0.39 g C m^{-2} in July 2024 and 0.56 g C m^{-2} in August 2025, while the lowest values occurred in April of both years (0.18 and 0.13 g C m^{-2} , respectively).

At the daily scale, CH₄-C fluxes also showed a small but detectable interannual shift. Daily CH₄-C fluxes were paired by calendar day and compared between 2024 and 2025 using a two-sided Wilcoxon signed-rank test. The test confirmed a statistically significant difference between the two years ($W = 27,286$, $p = 0.002$; $n = 365$ paired days). However, because CH₄-C fluxes remained small overall, these differences appear to have had only a minor effect on the net annual carbon balance compared with the much larger and more variable CO₂ exchanges.

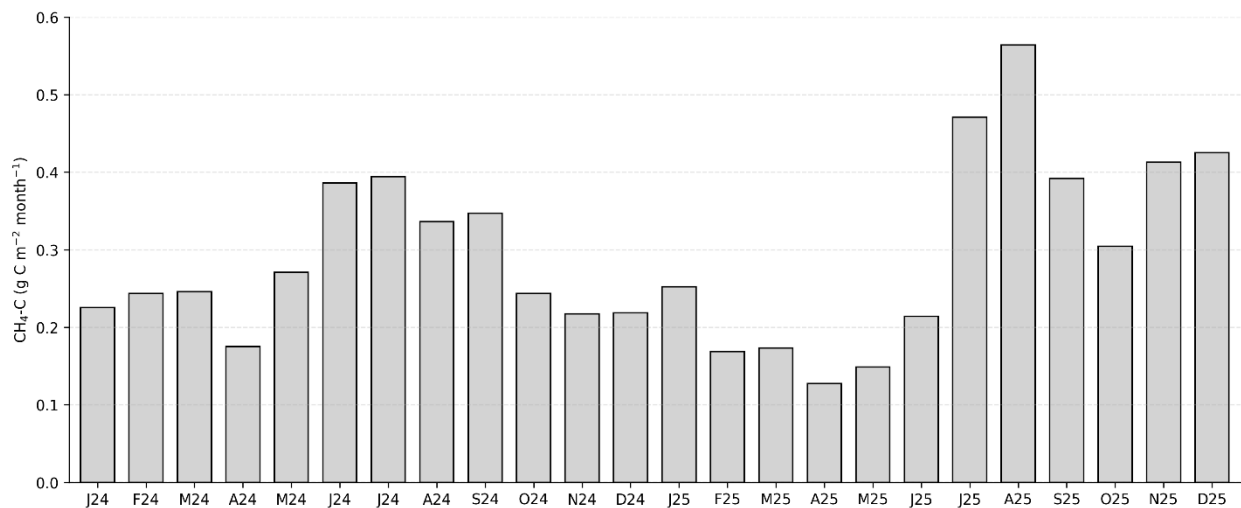


Fig. 4. Monthly sums of CH₄-C fluxes for 2024–2025 (g C m⁻² month⁻¹) derived from gap-filled half-hourly data. Fluxes exhibit modest seasonal variation, with relatively higher emissions during warmer months.

3.5 Directional footprint composition and NEE

Mean NEE varied substantially among wind directions and broadly reflected differences in land-cover composition within the dominant EC footprint (Fig. 5). Wind sectors dominated by bunds and bare peat generally exhibited higher CO₂ emissions, whereas sectors containing greater proportions of vegetation and open water showed lower NEE. Mean NEE ranged from 0.21 μmol m⁻² s⁻¹ (350–360°) to 0.70 μmol m⁻² s⁻¹ (120–130°), representing approximately a 3.4-fold variation across wind sectors. Directional variation in NEE was associated with differences in land-cover composition across footprint sectors. Sectors containing greater proportions of bunds and bare peat generally had higher NEE, whereas those containing more vegetation and open water tended to have lower NEE.

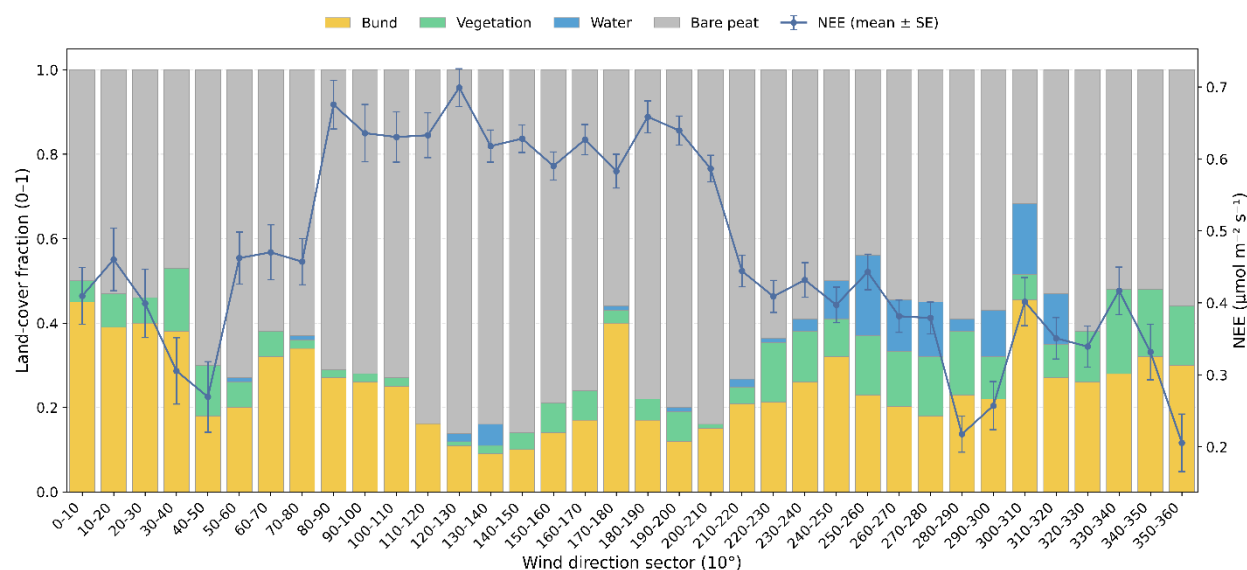


Fig. 5. Directional variation in land-cover composition within the dominant eddy covariance footprint and corresponding mean net ecosystem exchange (NEE). Stacked bars show the proportional cover of bund, vegetation, open water and bare peat within each 10° wind sector (0–84 m radius around the EC tower). The blue line shows the corresponding mean NEE ($\pm$ SE; $u^* \geq 0.10 \text{ m s}^{-1}$).

3.6 Environmental controls

MI analysis showed that NEE and CH_4 were associated with multiple environmental variables rather than a single dominant control (Fig. 6). During the 2024–2025 period, SWIN (0.21), NETRAD (0.20), and H (0.13) exhibited the highest MI scores for NEE, indicating that short-term fluctuations in NEE were mainly related to radiation and surface energy fluxes. During summer, these variables showed higher MI values, with NETRAD (0.29), SWIN (0.29), and H (0.26) ranking highest. The consistent importance of these variables indicates a stronger relationship between energy inputs and NEE during the growing-season. For CH_4 , the full record showed that the highest MI scores were for SWC (0.16), T_s (0.11), and VPD (0.11). During the growing-season, SWC (0.09), RH (0.09), and T_a (0.06) had the highest MI values. Overall, MI values for CH_4 were lower than those for NEE across all variables. This suggests that short-term CO_2 exchange was mainly associated with photosynthetic and energy-balance conditions, whereas CH_4 variation was more closely tied to wetness and atmospheric moisture.

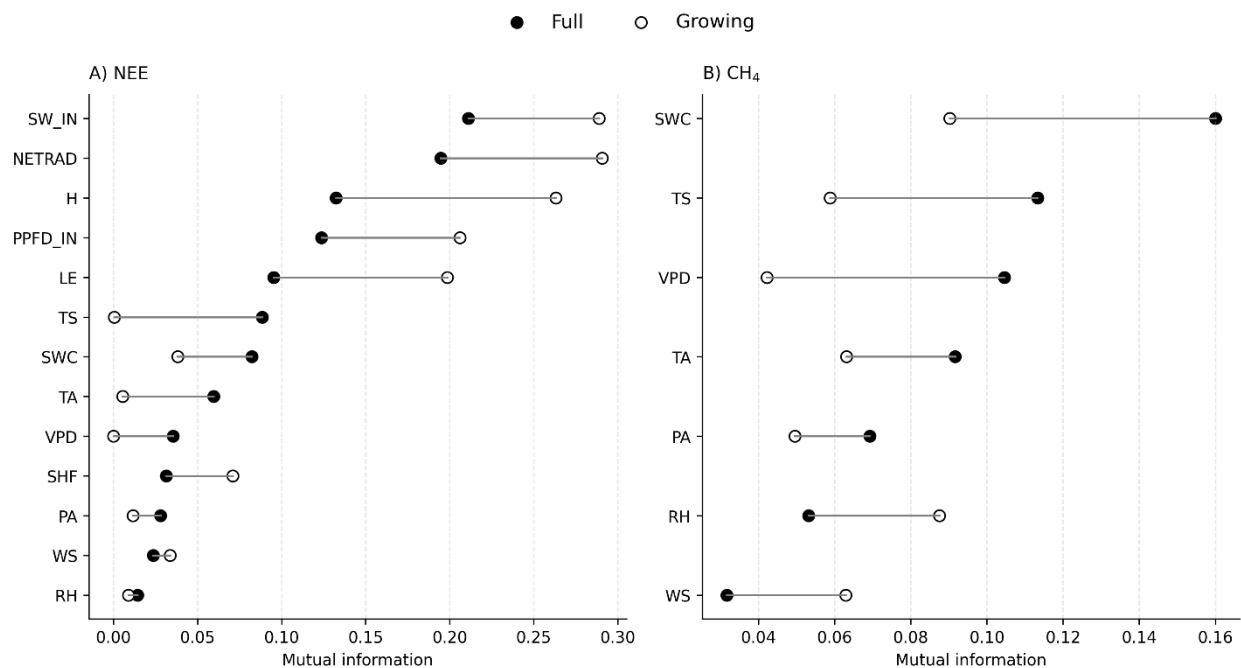


Fig. 6. Mutual information (MI) between environmental variables and (a) net ecosystem exchange of CO₂ (NEE) and (b) CH₄ flux for the study period 2024–2025. Higher MI values indicate a stronger statistical association between a given driver and the flux, but do not imply causation. Filled circles show MI values calculated from the full dataset (all available half-hourly observations), and open circles show values for the growing-season subset (May–September). Horizontal lines connect corresponding values for each variable to illustrate differences between the two datasets.

3.7 FC-based CO₂ fluxes

3.7.1 Dark chamber (R_{eco})

Seasonal patterns in FC-derived R_{eco} varied among microsites (Table S1). Respiration rates were generally highest during Jul–Oct and lowest during Nov–Feb, with winter declines especially marked in bare peat and vegetated microsites. Bare peat showed relatively modest seasonal variation, with median R_{eco} around 0.24–0.28 μmol m⁻² s⁻¹ during J–O and M–J before declining to 0.05 μmol m⁻² s⁻¹ in N–F. In winter, the respiration of bunds was relatively higher. The vegetated peat had the highest overall R_{eco}, with medians of around 1.1 μmol m⁻² s⁻¹ during the growing-season and about 0.25 μmol m⁻² s⁻¹ in winter. Flooded open water microsites consistently showed the lowest respiration rates, whereas temporarily exposed open water areas exhibited moderately higher R_{eco} under aerated conditions.

R_{eco} also differed significantly among microsites overall (Kruskal–Wallis: H = 146.82, p < 0.001; Fig. 7). Median R_{eco} increased from bare peat (0.24 μmol m⁻² s⁻¹) to bunds (0.40 μmol m⁻² s⁻¹) and was highest in vegetated peat (0.75 μmol m⁻² s⁻¹). Open water microsites were sampled under both flooded (“Open water”) and temporarily exposed (“Open water (exposed)”) conditions, representing the same plots after surface water had receded. Flooded open water showed very low median R_{eco} (0.07 μmol m⁻² s⁻¹), whereas exposed open water had much higher values (0.36 μmol m⁻² s⁻¹), similar to bunds. The same plots therefore shifted from very low CO₂ efflux when flooded to higher efflux when exposed, showing that short-term water table drawdown can rapidly change microsite function. Post-hoc Dunn tests indicated that vegetated peat and bunds had significantly higher R_{eco} than bare peat and flooded open water (all p ≤ 0.003), while bare peat also exceeded flooded open water (p = 0.038). No significant difference was found between the bund and exposed open water, indicating similar respiration rates under aerated conditions.

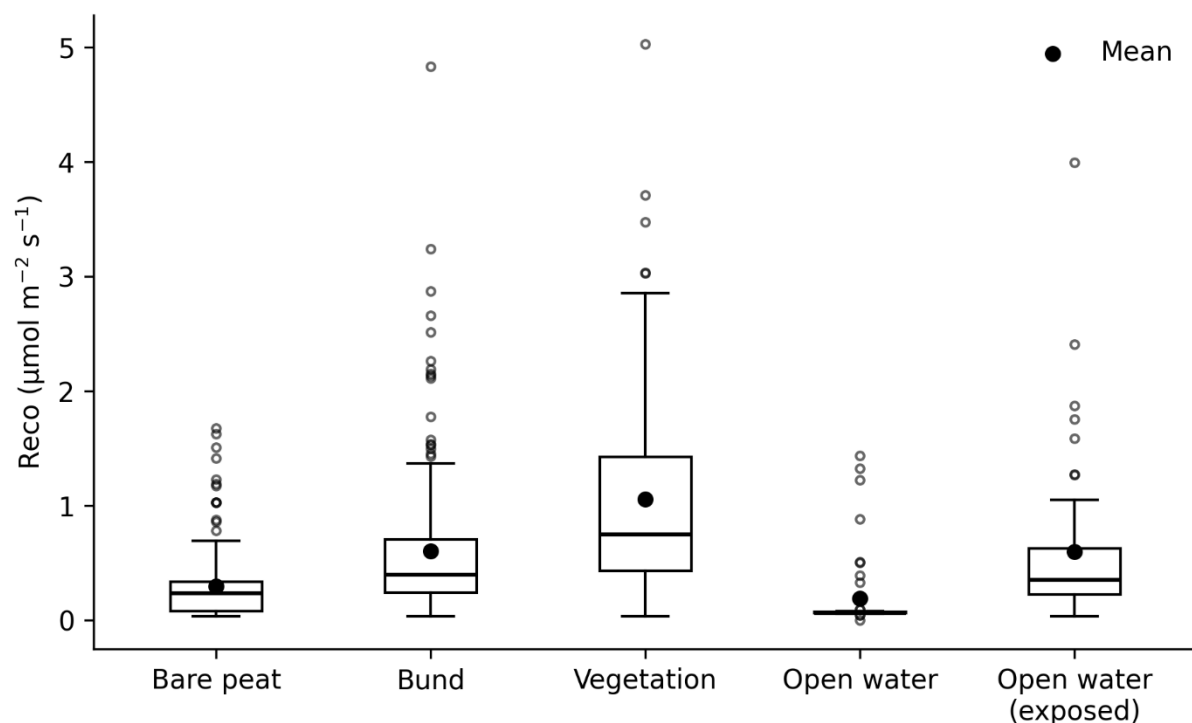


Fig. 7. Distribution of FC-derived ecosystem respiration (R_{eco}) across microsite types during the study period (17 July 2024–15 June 2025), including bare peat, bund, vegetation, open water, and open water (exposed). Boxes show the median and interquartile range; whiskers indicate the spread of the data; circles represent individual observations; and black dots indicate the mean value for each microsite.

3.7.2 Light chamber (NEE)

The fluxes showed a clear seasonal shift from winter to spring at the vegetated microsites (Fig. 8). Net exchange during January and February was low and close to zero (NEE between -0.01 and $-0.17 \mu\text{mol m}^{-2} \text{s}^{-1}$), indicating the ecosystem started to uptake CO_2 . There was an increase observed in both R_{eco} and GPP from March to May. These changes were significantly higher, where R_{eco} rose from 0.51 to $3.34 \mu\text{mol m}^{-2} \text{s}^{-1}$, while GPP increased from 0.52 to $6.81 \mu\text{mol m}^{-2} \text{s}^{-1}$. The stronger increase in GPP led to progressively more negative NEE, with a maximum uptake in May ($-3.47 \mu\text{mol m}^{-2} \text{s}^{-1}$) and weaker uptake in June ($-1.58 \mu\text{mol m}^{-2} \text{s}^{-1}$). The mean R_{eco} , GPP and NEE across January–June was 1.57 , 3.04 and $-1.48 \mu\text{mol m}^{-2} \text{s}^{-1}$, confirming that the vegetated microsite acted as a CO_2 sink in the early post-restoration period. These results show that vegetated microsites can act as daytime CO_2 sinks during active growth, but their limited footprint means they do not represent whole-site NEE.

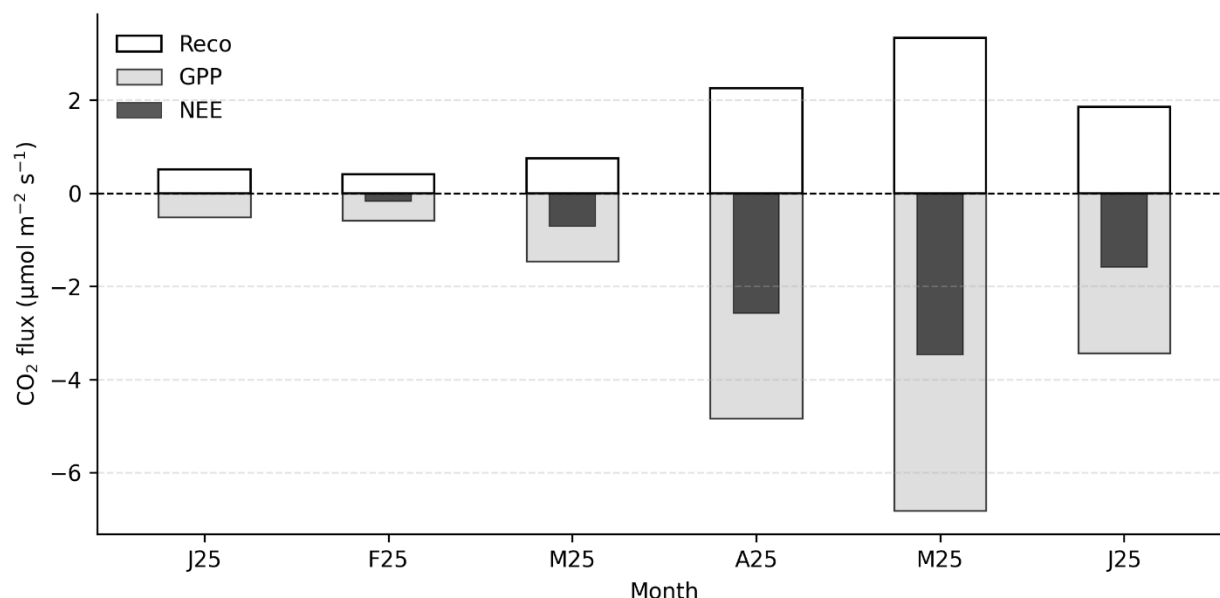


Fig. 8. Monthly mean FC-based Reco, GPP and NEE at the vegetated microsite plots (Jan–Jun 2025). Values represent plot-scale fluxes from vegetated surfaces only and do not reflect site-scale NEE.

3.7.3 Nonlinear responses of FC-derived CO₂

The GAM explained 66 % of the deviance in R_{eco} and had an adjusted R^2 of 0.55. Smooth terms for T_s , WT , DoY , and plot location were all significant predictors of R_{eco} (all $p < 0.001$). Peat surface elevation and microsite type also contributed significantly to the model. R_{eco} increased with rising T_s across the observed range ($p < 0.001$; Fig. 9a). WT had a significant nonlinear relationship with R_{eco} ($p < 0.001$). Predicted R_{eco} was greatest at deeper water-table levels (around -100 cm) and declined as the water table rose toward, and above, the peat surface (Fig. 9b). Seasonal effects were also evident, with higher R_{eco} during summer and lower values during winter ($p < 0.001$; Fig. 9c). The spatial smooth for plot location was highly significant ($p < 0.001$), indicating substantial spatial heterogeneity across the site (Fig. 9d). The microsite type was also important, with larger fluxes in bunds and vegetated microsites, but little effect on open water microsites. R_{eco} decreased slightly with increasing peat surface elevation ($p < 0.01$), although the effect size was relatively small.

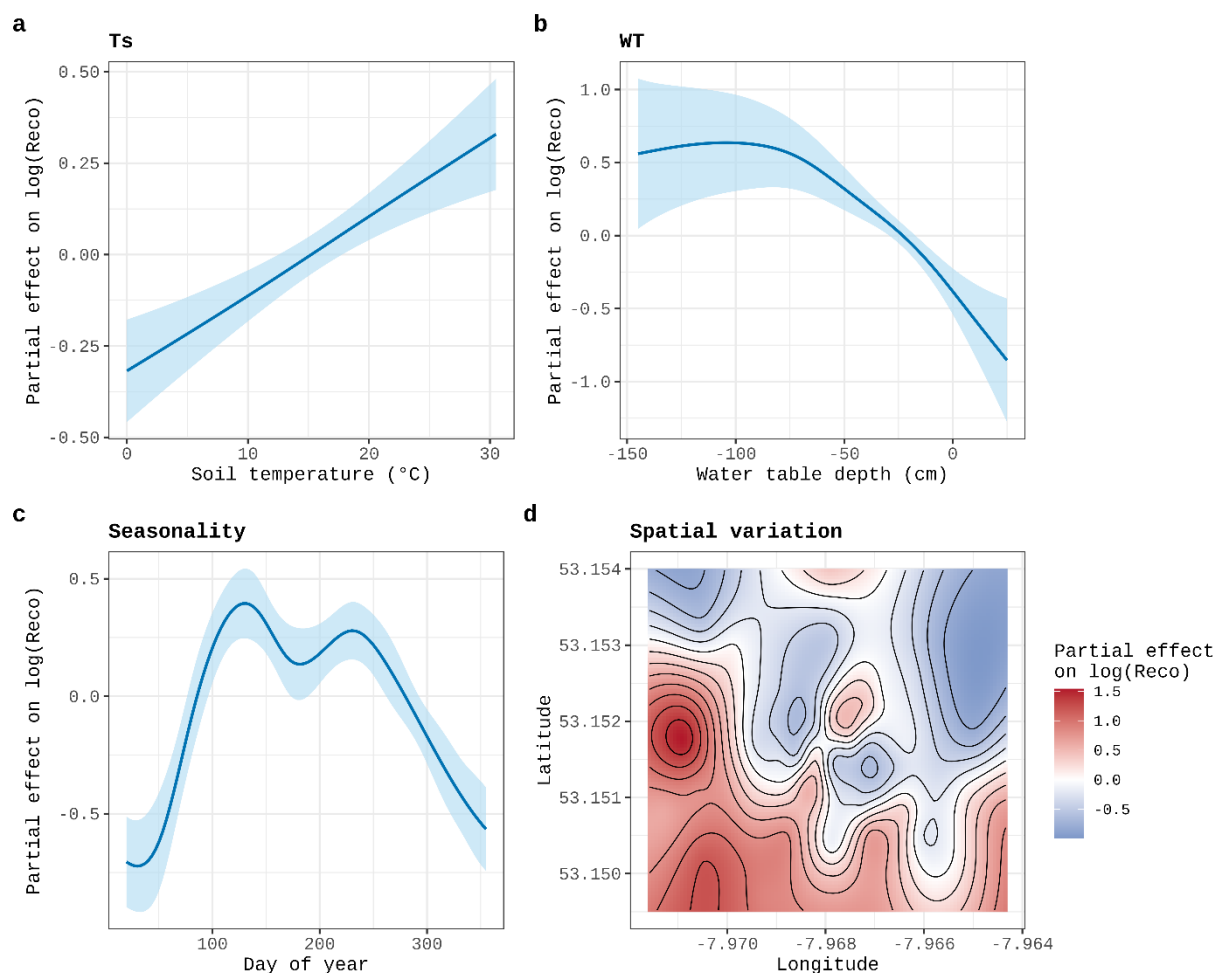


Fig. 9. Partial effects of environmental predictors on ecosystem respiration (R_{eco}) derived from a generalized additive model (GAM). Effects are shown on the log scale (model link function). Panels show responses to (a) soil temperature (Ts), (b) water table (WT) depth, (c) day of year (DoY), and (d) spatial variation. Shaded areas represent 95% confidence intervals.

3.8 Plot-scale to ecosystem-scale

During 17 July 2024–15 June 2025, mean daytime (10:00–16:00) ecosystem respiration (R_{eco}) derived from eddy covariance averaged $1.06 \pm 0.34 \mu\text{mol m}^{-2} \text{s}^{-1}$ (mean $\pm$ SD, $n = 4008$), with a corresponding median of $1.04 \mu\text{mol m}^{-2} \text{s}^{-1}$. In contrast, footprint-weighted dark-chamber R_{eco} , calculated by scaling microsite-specific means according to their proportional cover within the 70 % EC footprint, averaged $0.43 \pm 0.02 \mu\text{mol m}^{-2} \text{s}^{-1}$ (mean $\pm$ SE). Overall, the FC-based estimate was approximately 59 % lower than the EC-derived R_{eco} over the same period. This mismatch indicates that the chamber campaigns reproduced the relative ranking of microsites but underestimated the magnitude of ecosystem-scale respiration measured by EC. Differences in temporal resolution, footprint characteristics and incomplete sampling of short-lived emissions hotspots are likely to contribute to this discrepancy.



4 Discussion

4.1 Ecosystem-scale CO₂ and CH₄

The Study Site was rewetted between May 2022 and August 2023, and over the initial post-rewetting period the site remained a net CO₂ source. The magnitude of this source declined, however, consistent with reduced ecosystem respiration and enhanced gross primary production between 2024 and 2025. The annual net carbon balance (CO₂ and CH₄) fell from roughly 240 g C m⁻² yr⁻¹ in 2024 to about 150 g C m⁻² yr⁻¹ in 2025, marking a clear step down in net losses even though the system is still far from being a carbon sink. Seasonal patterns also point to lower peak summer respiration and relatively stronger growing-season CO₂ uptake in 2025 compared with 2024. CH₄ emissions were consistently positive but small in carbon mass terms (ca. 3–4 g C m⁻² yr⁻¹), less than 3 % of the total carbon emissions from the Study Site. Compared with studies describing rewetted peatlands as net carbon sinks after longer recovery periods, our two-year record represents an early stage of recovery rather than a final outcome.

Eddy-covariance studies from rewetted former peat-extraction bogs remain limited. At a recently rewetted section of a cutover bog in north-west Germany, annual CO₂ emissions were lower than in the adjacent mined section, while CH₄ emissions increased following rewetting (Holl et al., 2020). The rewetted section nevertheless remained a net CO₂ source during the measurement period. Similar to this study, carbon losses at the Study Site are driven primarily by CO₂ exchange rather than CH₄. The relatively low CH₄ emissions may reflect a nutrient-poor, unstable water regime (i.e., water table fluctuations differ in different areas of the site), limited cover of vascular plants that facilitate CH₄ transport, such as *Eriophorum angustifolium*, and reduced methanogenic capacity following long-term drainage or disturbance (Bao et al., 2021; Buzacott et al., 2024; Finn et al., 2020; Green and Baird, 2012; Kwon et al., 2017).

Restoration works at the Study Site were completed in August 2023, so the study captures an early transition period in which hydrological conditions are stabilising and vegetation is slowly recovering. Lower CO₂ emissions in 2025 likely reflected a combination of cooler, wetter conditions, higher water tables, and stronger growing-season carbon uptake. Gross primary production increased by 28 % in 2025, indicating that recovering vegetation contributed to greater CO₂ uptake, although this was not yet sufficient to offset ecosystem respiration across the rewetted surface.

The MI analysis further showed that short-term ecosystem CO₂ exchange was most strongly associated with radiation and energy-related variables, particularly during the growing season, consistent with energy availability regulating photosynthesis and CO₂ uptake. CH₄ fluxes were more closely associated with soil water content, temperature, and atmospheric moisture, reflecting the importance of wetness and thermal conditions for anaerobic CH₄ production and release. Directional footprint analysis also showed higher NEE in sectors with greater bare peat and bund cover, and lower NEE where vegetated peat and open water were more extensive. Together, these results indicate that ecosystem-scale carbon exchange at this Study Site reflects both seasonal meteorological conditions and the spatial distribution of wet and aerated microsites.

4.2 Microsite controls on CO₂ exchange

Cell-bunding at this Study Site developed a mosaic of raised bunds, bare peat, vegetated peat, and flooded cells rather than a uniformly rewetted surface. These microsites differed in elevation, vegetation cover, and water-table position, and FC-derived R_{eco} varied accordingly. Bunds remained relatively dry and aerated above the rewetted cells and were CO₂ hotspots during the study period, likely because aerobic decomposition continued in the exposed peat. Elevated peat dams have also been reported as CO₂ sources after rewetting, although the available evidence largely comes from sites several years after restoration rather than the immediate post-rewetting phase considered here (Vybornova et al., 2019).

High R_{eco} from vegetated peat did not have the same implication as high R_{eco} from bunds, as the vegetated microsites also showed marked CO₂ uptake during active growth, indicating that respiration occurred alongside photosynthetic uptake. Recovering peatland vegetation can increase both autotrophic respiration and CO₂ uptake as plant cover develops (Tuittila et al., 2000; Nugent et al., 2018). The open water plots further showed that CO₂ exchange was not determined by microsite class alone. R_{eco} was low while plots were inundated but increased when the peat surface became exposed as water levels fell. Since both conditions were measured in the same plots, the shift points to a response to changing water-table position and peat aeration. This pattern accords with evidence that saturation limits aerobic peat respiration, whereas drying can increase CO₂ efflux (Strack et al., 2006; Strack and Zuback, 2013).



These microsite patterns indicate that early post-rewetting CO₂ exchange remained strongly controlled by peat surface elevation, vegetation development, and water-table position. Elevated bare peat structures can continue to lose CO₂ after rewetting, whereas wetter microsites may show lower efflux and vegetated microsites may show CO₂ uptake during active growth. The directional association between land-cover composition and NEE is consistent with the FC-based patterns. Sectors with greater proportions of bunds and bare peat generally had higher NEE, whereas sectors with more vegetation and open water tended to have lower NEE.

4.3 EC-FC comparison and spatial heterogeneity

The combined use of EC and FC highlights strong spatial heterogeneity in carbon exchange across this rewetted Study Site. The EC system recorded continuous ecosystem-scale fluxes over a broad, shifting footprint, whereas FC picked up strong differences among microsites that were placed amongst the dominant land-cover classes in the site, namely bunds, vegetated peat, bare peat and open water areas. EC-derived Reco averaged $1.10 \pm 0.35 \text{ g C m}^{-2} \text{ d}^{-1}$ (mean $\pm$ SD, $n = 4008$), with a corresponding median of $1.08 \text{ g C m}^{-2} \text{ d}^{-1}$, whereas upscaled FC-derived Reco averaged $0.45 \pm 0.02 \text{ g C m}^{-2} \text{ d}^{-1}$ (mean $\pm$ SE). The difference (ca. 59 %) indicates that upscaling point field measurements to the ecosystem scale do not capture the full heterogeneity of ecohydrological dynamics that are invariably present across any peatland site.

Despite the grouping of land-cover classes, and a dense FC network, upscaled FC-derived Reco is much lower than that calculated using EC. However, the FC results are extremely insightful with respect to 1) identifying ‘hot-spots’ of CO₂ emissions, such as the peat-bunds, 2) specific information on the seasonal dynamics at microsites, such as the vegetated and periodically flooded sites, and 3) how directional variation in land-cover composition controls eddy covariance NEE. Thus, EC integrates fluxes across the footprint and provides the more integrated measure of ecosystem-scale exchange, whilst chambers identify the microsites and hydrological conditions that are likely to drive those fluxes and contribute to the carbon exchanges.

4.4 Management implications

The findings of this study suggest that the spatial pattern of wet and aerated microsites across the cell-bunded cutaway surface strongly influences early restoration outcomes. Water-table position, surface condition, and vegetation composition regulate respiration, photosynthesis, and net carbon exchange in rewetted peatlands (Strack et al., 2006; Wilson et al., 2022). The main management question is therefore not only whether the restoration retains water, but also whether it keeps a sufficiently large proportion of the peat surface wet to limit aerobic decomposition and CO₂ loss. Persistent CO₂ emissions from bunds and temporarily exposed peat show that relatively small areas of aerated, non-flooded peat can influence the site’s early carbon balance. This may partly reflect local differences in surface elevation around the restoration-created bunds, with flooded conditions frequently observed in lower-lying areas near bund edges while higher peat surfaces and bund tops remain exposed.

The overflow pipes and weirs in the trench-bund system retain water in individual cells and allow water to move between cells once it reaches the outlet level. At the Study Site, uneven rewetting may reflect the cambered peat surface left by peat extraction rather than bund spacing alone. Flooded conditions were mainly observed in the lower parts of cells, while higher peat surfaces remained exposed and aerated. This suggests that bunds should be kept as close as possible to the surrounding ground level and properly compacted. Where practical, reprofiling or levelling the peat surface may also help achieve more even rewetting. In Northern Ireland, restoration of industrially extracted raised bogs included laser-levelling, cell-bunding, staged rewetting and the addition of donor *Sphagnum* material. Extensive *Sphagnum* lawns and peatland vascular plants subsequently became established at these sites (Everson et al., 2026).

Seasonal water-table stability is most likely to be important for further vegetation growth. Flooded areas released less CO₂, but emissions increased when water levels fell and the peat surface became exposed. Monitoring using repeated drone surveys, potentially supported by Sentinel-2 imagery, should identify which cells become exposed, when exposure occurs, and how long it persists. *Sphagnum* inoculation may be most appropriate in locations with stable, near-surface water levels through summer, but without persistent flooding, since both drought and prolonged inundation can limit establishment (Tuittila et al., 2004; Rochefort et al., 2003). Wet cells and *Eriophorum*-dominated patches indicate local recovery, but peat-forming bog vegetation, such as *Sphagnum*, has not yet developed extensively across the site. Continued holistic monitoring of hydrology,



520 vegetation, and FC is needed to establish whether wet vegetation expands and emissions from dry, aerated peat and contour
 bunds decline over time.

5 Conclusions

525 At the Study Site, rewetting of a cutaway raised bog by cell trench bunding reduced net CO₂ losses and improved hydrological
 conditions. The site nevertheless remained a net carbon source during the first two years after intervention. Ecosystem-scale
 measurements indicated that R_{eco} still exceeded GPP. CH₄ emissions were small relative to CO₂ and contributed only a minor
 fraction of the overall carbon balance. Together, these findings indicate an early post-rewetting phase in which carbon losses
 are already declining but have not yet shifted to a sustained sink.

530 The combined EC–FC approach, together with footprint-based analysis of land-cover composition, showed that spatial
 heterogeneity strongly influences carbon exchange at the study site. Bunds and intermittently flooded edges acted as persistent
 CO₂ hotspots. Flooded open water areas exhibited very low CO₂ emissions. Vegetated peat combined relatively high respiration
 with substantial growing-season uptake. These results suggest that early post-rewetting carbon losses are concentrated in
 relatively small, aerated patches that are likely under-represented in simple upscaling schemes. This pattern is consistent with
 reports from other degraded or rewetted peat extraction areas, where flux heterogeneity and vegetation type exert a strong
 control on ecosystem-scale carbon balance.

535 Further gains in carbon balance at this site will likely depend on maintaining high water tables and expanding peat-forming
 vegetation. Targeted measures such as *Sphagnum* inoculation in consistently wet cells may help to speed up peat-forming
 cover. Adjustments to bund size and layout could also limit the extent of elevated, well-aerated surfaces. Together, these
 actions may promote a more stable net carbon sink. More broadly, the results demonstrate that pairing ecosystem-scale and
 540 microsite-scale measurements provides a useful framework for evaluating early restoration outcomes in structurally
 heterogeneous cutaway bogs. They also indicate that early restoration assessment should not rely on whole-site fluxes alone,
 because microsite structure may determine whether improved hydrology translates into recovery of a net carbon sink function.



Data availability

The data supporting this study were collected as part of an ongoing monitoring program funded by the National Parks and Wildlife Service (NPWS) in Ireland. The dataset will be archived in a publicly accessible repository prior to publication. Data are available from the corresponding author upon reasonable request during peer review.

Financial support

This study was funded by the Irish Research Council under the Government of Ireland Postgraduate Scholarship Program (GOIPG/2024/4885).

Competing interests

The authors declare no conflicts of interest.

Authorship contribution

Md Shamsuzzaman: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review and editing. **Shane Regan:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review and editing. **Ultan McCarthy:** Supervision, Writing – review and editing. **Imelda Casey:** Supervision, Writing – review and editing. **Ciara Farrell:** Data curation. **Sate Ahmad:** Writing – review and editing. **Wahaj Habib:** Data curation, Writing – review and editing. **Owen Naughton:** Conceptualization, Methodology, Investigation, Funding acquisition, Project administration, Resources, Supervision, Writing – review and editing.

Acknowledgements

We are especially grateful to the National Parks and Wildlife Service (NPWS), Ireland. They provided the land access and the eddy covariance tower infrastructure and environmental data that made this research possible. We also want to thank the Research Office at South East Technological University (SETU) for their institutional support. Additionally, we appreciate the cooperation of Bord na Móna, who carried out the restoration work for NPWS. Their willingness to share restoration schedules and activity data was essential for linking our carbon flux measurements to the actual work happening on-site.



References

- 565 Ahmad, S., Wang, M., Bates, A., Martini, F., Regan, S., Saunders, M., Liu, H., McElwain, J., and Gill, L.: Flatlining fens? Small-scale variations in peat properties and microtopography as indicators of ecosystem homogenisation, *Ecol. Indic.*, 172, 113317, <https://doi.org/10.1016/j.ecolind.2025.113317>, 2025.
- Aubinet, M., Grelle, A., Ibrom, A., Rannik, Ü., Moncrieff, J., Foken, T., Kowalski, A. S., Martin, P. H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grünwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., and Vesala, T.: Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology, in: *Advances in Ecological Research*, Vol. 30, edited by: Fitter, A. H. and Raffaelli, D. G., Academic Press, 113–175, [https://doi.org/10.1016/S0065-2504\(08\)60018-5](https://doi.org/10.1016/S0065-2504(08)60018-5), 1999.
- 570 Aubinet, M., Vesala, T., and Papale, D. (Eds.): *Eddy covariance: A practical guide to measurement and data analysis*, Springer, <https://doi.org/10.1007/978-94-007-2351-1>, 2012.
- 575 Baldocchi, D. D.: Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: Past, present and future, *Global Change Biol.*, 9, 479–492, <https://doi.org/10.1046/j.1365-2486.2003.00629.x>, 2003.
- Bao, T., Jia, G., and Xu, X.: Wetland heterogeneity determines methane emissions: A pan-Arctic synthesis, *Environ. Sci. Technol.*, 55, 10152–10163, <https://doi.org/10.1021/acs.est.1c01616>, 2021.
- 580 Beyer, F., Jansen, F., Jurasinski, G., Koch, M., Schröder, B., and Koebsch, F.: Drought years in peatland rewetting: Rapid vegetation succession can maintain the net CO₂ sink function, *Biogeosciences*, 18, 917–935, <https://doi.org/10.5194/bg-18-917-2021>, 2021.
- Buzacott, A. J. V., Kruijt, B., Bataille, L., van Giersbergen, Q., Heuts, T. S., Fritz, C., Nouta, R., Erkens, G., Boonman, J., van den Berg, M., van Huissteden, J., and van der Velde, Y.: Drivers and annual totals of methane emissions from Dutch peatlands, *Global Change Biol.*, 30, e17590, <https://doi.org/10.1111/gcb.17590>, 2024.
- 585 Christen, A., Jassal, R. S., Black, T. A., Grant, N. J., Hawthorne, I., Johnson, M. S., Lee, S.-C., and Merckens, M.: Summertime greenhouse gas fluxes from an urban bog undergoing restoration through rewetting, *Mires Peat*, 17, 03, <https://doi.org/10.19189/MaP.2015.OMB.207>, 2016.
- Escobar, D., Belyazid, S., and Manzoni, S.: Back to the future: Restoring northern drained forested peatlands for climate change mitigation, *Front. Environ. Sci.*, 10, 834371, <https://doi.org/10.3389/fenvs.2022.834371>, 2022.
- 590 Everson, J., McCann, A., Walls, P., and Reid, N.: Restoration of exploited lowland raised bogs recovered plant and invertebrate taxa richness and peatland specialists within a decade, *J. Environ. Manage.*, 403, 129191, <https://doi.org/10.1016/j.jenvman.2026.129191>, 2026.
- Finn, D. R., Ziv-El, M., van Haren, J., Park, J. G., del Aguila-Pasquel, J., Urquiza-Muñoz, J. D., and Cadillo-Quiroz, H.: Methanogens and methanotrophs show nutrient-dependent community assemblage patterns across tropical peatlands of the Pastaza-Marañón Basin, Peruvian Amazonia, *Front. Microbiol.*, 11, 746, <https://doi.org/10.3389/fmicb.2020.00746>, 2020.
- 595 Foken, T. and Wichura, B.: Tools for quality assessment of surface-based flux measurements, *Agr. Forest Meteorol.*, 78, 83–105, [https://doi.org/10.1016/0168-1923\(95\)02248-1](https://doi.org/10.1016/0168-1923(95)02248-1), 1996.
- Fratini, G., Ibrom, A., Arriga, N., Burba, G., and Papale, D.: Relative humidity effects on water vapour fluxes measured with closed-path eddy-covariance systems with short sampling lines, *Agr. Forest Meteorol.*, 165, 53–63, <https://doi.org/10.1016/j.agrformet.2012.05.018>, 2012.
- 600 Green, S. M. and Baird, A. J.: A mesocosm study of the role of the sedge *Eriophorum angustifolium* in the efflux of methane, including that due to episodic ebullition, from peatlands, *Plant Soil*, 351, 207–218, <https://doi.org/10.1007/s11104-011-0945-1>, 2012.



- 605 Haapalehto, T. O., Vasander, H., Jauhiainen, S., Tahvanainen, T., and Kotiaho, J. S.: The effects of peatland restoration on water-table depth, elemental concentrations, and vegetation: 10 years of changes, *Restor. Ecol.*, 19, 587–598, <https://doi.org/10.1111/j.1526-100X.2010.00704.x>, 2011.
- Haapalehto, T., Juutinen, R., Kareksela, S., Kuitunen, M., Tahvanainen, T., Vuori, H., and Kotiaho, J. S.: Recovery of plant communities after ecological restoration of forestry-drained peatlands, *Ecol. Evol.*, 7, 7848–7858, <https://doi.org/10.1002/ece3.3243>, 2017.
- 610 Holl, D., Pfeiffer, E.-M., and Kutzbach, L.: Comparison of eddy covariance CO₂ and CH₄ fluxes from mined and recently rewetted sections in a northwestern German cutover bog, *Biogeosciences*, 17, 2853–2874, <https://doi.org/10.5194/bg-17-2853-2020>, 2020.
- Hydro-Environmental Services: Hydrogeological investigation of All Saints Bog SAC and Arragh More Bog NHA, Co. Offaly: hydrogeological assessment report, Report No. P1488-0, draft report prepared for the National Parks and Wildlife Service, 2020.
- 615 Irvin, J., Zhou, S., McNicol, G., Lu, F., Liu, V., Fluët-Chouinard, E., Ouyang, Z., Knox, S. H., Lucas-Moffat, A., Trotta, C., Papale, D., Vitale, D., Mammarella, I., Alekseychik, P., Aurela, M., Avati, A., Baldocchi, D., Bansal, S., Bohrer, G., Campbell, D. I., Chen, J., Chu, H., Dalmagro, H. J., Delwiche, K. B., Desai, A. R., Euskirchen, E., Feron, S., Göckede, M., Heimann, M., Helbig, M., Helfter, C., Hemes, K. S., Hirano, T., Iwata, H., Jurasinski, G., Kalhori, A., Kondrich, A., Lai, D. Y. F., Lohila, A., Malhotra, A., Merbold, L., Mitra, B., Ng, A., Nilsson, M. B., Noormets, A., Peichl, M., Rey-Sanchez, A. C., Richardson, A. D., Runkle, B. R. K., Schäfer, K. V. R., Sonnentag, O., Stuart-Haëntjens, E., Sturtevant, C., Ueyama, M., Valach, A. C., Vargas, R., Vourlitis, G. L., Ward, E. J., Wong, G. X., Zona, D., Alberto, M. C. R., Billesbach, D. P., Celis, G., Dolman, H., Friborg, T., Fuchs, K., Gogo, S., Gondwe, M. J., Goodrich, J. P., Gottschalk, P., Hörtnagl, L., Jacotot, A., Koebisch, F., Kasak, K., Maier, R., Morin, T. H., Nemitz, E., Oechel, W. C., Oikawa, P. Y., Ono, K., Sachs, T., Sakabe, A., Schuur, E. A. G., Shortt, R., Sullivan, R. C., Szutu, D. J., Tuittila, E.-S., Varlagin, A., Verfaillie, J. G., Wille, C., Windham-Myers, L., Poulter, B., and Jackson, R. B.: Gap-filling eddy covariance methane fluxes: Comparison of machine learning model predictions and uncertainties at FLUXNET-CH₄ wetlands, *Agr. Forest Meteorol.*, 308–309, 108528, <https://doi.org/10.1016/j.agrformet.2021.108528>, 2021.
- 620 Khan, A. S., Guêné-Nanchen, M., and Rochefort, L.: Unfolding a peatland’s story: Assessing the restoration outcomes and driving factors from a disturbed minerotrophic peatland in Eastern Canada, *Ecol. Eng.*, 212, 107496, <https://doi.org/10.1016/j.ecoleng.2024.107496>, 2025.
- Koch, M., Koebisch, F., Hahn, J., and Jurasinski, G.: From meadow to shallow lake: Monitoring secondary succession in a coastal fen after rewetting by flooding based on aerial imagery and plot data, *Mires Peat*, 19, 1–17, <https://doi.org/10.19189/MaP.2015.OMB.188>, 2017.
- 635 Korkiakoski, M., Ojanen, P., Tuovinen, J.-P., Minkkinen, K., Nevalainen, O., Penttilä, T., Aurela, M., Laurila, T., and Lohila, A.: Partial cutting of a boreal nutrient-rich peatland forest causes radically less short-term on-site CO₂ emissions than clear-cutting, *Agr. Forest Meteorol.*, 332, 109361, <https://doi.org/10.1016/j.agrformet.2023.109361>, 2023.
- Kormann, R. and Meixner, F. X.: An analytical footprint model for non-neutral stratification, *Bound.-Lay. Meteorol.*, 99, 207–224, <https://doi.org/10.1023/A:1018991015119>, 2001.
- 640 Koskinen, M., Maanavilja, L., and Nieminen, M.: High methane emissions from restored Norway spruce swamps in southern Finland over one growing season, *Mires Peat*, 17, 02, <https://doi.org/10.19189/MaP.2015.OMB.202>, 2016.
- Kraskov, A., Stögbauer, H., and Grassberger, P.: Estimating mutual information, *Phys. Rev. E*, 69, 066138, <https://doi.org/10.1103/PhysRevE.69.066138>, 2004.
- 645 Krauss, K. W., Holm, G. O., Jr., Perez, B. C., McWhorter, D. E., Cormier, N., Moss, R. F., Johnson, D. J., Neubauer, S. C., and Raynie, R. C.: Component greenhouse gas fluxes and radiative balance from two deltaic marshes in Louisiana: Pairing



- chamber techniques and eddy covariance, *J. Geophys. Res.-Biogeo.*, 121, 1503–1521, <https://doi.org/10.1002/2015JG003224>, 2016.
- 650 Kroon, P. S., Hensen, A., Jonker, H. J. J., Ouwersloot, H. G., Vermeulen, A. T., and Bosveld, F. C.: Uncertainties in eddy covariance flux measurements assessed from CH₄ and N₂O observations, *Agr. Forest Meteorol.*, 150, 806–816, <https://doi.org/10.1016/j.agrformet.2009.08.008>, 2010.
- Kutzbach, L., Wagner, D., and Pfeiffer, E. M.: Effect of microrelief and vegetation on methane emission from wet polygonal tundra, Lena Delta, Northern Siberia, *Biogeochemistry*, 69, 341–362, <https://doi.org/10.1023/B:BIOG.0000031053.81520.db>, 2004.
- 655 Kwon, M. J., Beulig, F., Ilie, I., Wildner, M., Küsel, K., Merbold, L., Mahecha, M. D., Zimov, N., Zimov, S. A., Heimann, M., Schuur, E. A. G., Kostka, J. E., Kolle, O., Hilke, I., and Göckede, M.: Plants, microorganisms, and soil temperatures contribute to a decrease in methane fluxes on a drained Arctic floodplain, *Global Change Biol.*, 23, 2396–2412, <https://doi.org/10.1111/gcb.13558>, 2017.
- 660 Laine, A. M., Mehtätalo, L., Tolvanen, A., Frohking, S., and Tuittila, E.-S.: Impacts of drainage, restoration and warming on boreal wetland greenhouse gas fluxes, *Sci. Total Environ.*, 647, 169–181, <https://doi.org/10.1016/j.scitotenv.2018.07.390>, 2019.
- Laudon, H., Ågren, A. M., Hasselquist, E. M., Nilsson, M. B., Peichl, M., Tong, C., and Meyer, A.: Rewetting drained forested peatlands: A cornerstone of climate mitigation or a climate gamble?, *Ambio*, 54, 2092–2104, <https://doi.org/10.1007/s13280-025-02220-x>, 2025.
- 665 Leifeld, J., Müller, M., and Fuhrer, J.: Peatland subsidence and carbon loss from drained temperate fens, *Soil Use Manage.*, 27, 170–176, <https://doi.org/10.1111/j.1475-2743.2011.00327.x>, 2011.
- Lindenberger, A., von der Thannen, M., Rauch, H. P., Baldocchi, D., Pindus, M., Szutu, D., Verfaillie, J., and Kasak, K.: Contrasting carbon dynamics in grazed and flood-prone grasslands on mineral and degraded peat soils, *Agric. Ecosyst. Environ.*, 409, 110531, <https://doi.org/10.1016/j.agee.2026.110531>, 2026.
- 670 Mander, Ü., Espenberg, M., Melling, L., and Kull, A.: Peatland restoration pathways to mitigate greenhouse gas emissions and retain peat carbon, *Biogeochemistry*, 167, 523–543, <https://doi.org/10.1007/s10533-023-01103-1>, 2024.
- Mauder, M., Cuntz, M., Drüe, C., Graf, A., Rebmann, C., Schmid, H. P., Schmidt, M., and Steinbrecher, R.: A strategy for quality and uncertainty assessment of long-term eddy-covariance measurements, *Agr. Forest Meteorol.*, 169, 122–135, <https://doi.org/10.1016/j.agrformet.2012.09.006>, 2013.
- 675 Moncrieff, J. B., Massheder, J. M., de Bruin, H., Elbers, J., Friborg, T., Heusinkveld, B., Kabat, P., Scott, S., Søgaard, H., and Verhoef, A.: A system to measure surface fluxes of momentum, sensible heat, water vapour and carbon dioxide, *J. Hydrol.*, 188–189, 589–611, [https://doi.org/10.1016/S0022-1694\(96\)03194-0](https://doi.org/10.1016/S0022-1694(96)03194-0), 1997.
- Nugent, K. A., Strachan, I. B., Strack, M., Roulet, N. T., and Rochefort, L.: Multi-year net ecosystem carbon balance of a restored peatland reveals a return to carbon sink, *Global Change Biol.*, 24, 5751–5768, <https://doi.org/10.1111/gcb.14449>, 2018.
- 680 Page, S. E., Rieley, J. O., and Banks, C. J.: Global and regional importance of the tropical peatland carbon pool, *Global Change Biol.*, 17, 798–818, <https://doi.org/10.1111/j.1365-2486.2010.02279.x>, 2011.
- Parry, L. E., Holden, J., and Chapman, P. J.: Restoration of blanket peatlands, *J. Environ. Manage.*, 133, 193–205, <https://doi.org/10.1016/j.jenvman.2013.11.033>, 2014.
- 685 Pavelka, M., Acosta, M., Kiese, R., Altimir, N., Brümmer, C., Crill, P., Darenova, E., Fuß, R., Gielen, B., Graf, A., Klemetsson, L., Lohila, A., Longdoz, B., Lindroth, A., Nilsson, M., Marañón Jiménez, S., Merbold, L., Montagnani, L., Peichl, M., Pihlatie, M., Pumpanen, J., Serrano Ortiz, P., Silvennoinen, H., Skiba, U., Vestin, P., Weslien, P., Janous, D., and



- Kutsch, W.: Standardisation of chamber technique for CO₂, N₂O and CH₄ fluxes measurements from terrestrial ecosystems, *Int. Agrophys.*, 32, 569–587, <https://doi.org/10.1515/intag-2017-0045>, 2018.
- 690 Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., Blondel, M., Prettenhofer, P., Weiss, R., Dubourg, V., VanderPlas, J., Passos, A., Cournapeau, D., Brucher, M., Perrot, M., and Duchesnay, É.: Scikit-learn: Machine learning in Python, *J. Mach. Learn. Res.*, 12, 2825–2830, 2011.
- Petrone, R. M., Waddington, J. M., and Price, J. S.: Ecosystem-scale flux of CO₂ from a restored vacuum harvested peatland, *Wetlands Ecol. Manage.*, 11, 419–432, <https://doi.org/10.1023/B:WETL.0000007192.78408.62>, 2003.
- 695 Pouliot, R., Rochefort, L., and Karofeld, E.: Initiation of microtopography in revegetated cutover peatlands, *Appl. Veg. Sci.*, 14, 158–171, <https://doi.org/10.1111/j.1654-109X.2010.01118.x>, 2011.
- Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grünwald, T., Havránková, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.-M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., and Valentini, R.: On the separation of net ecosystem exchange into assimilation and ecosystem respiration: Review and improved algorithm, *Global Change Biol.*, 11, 1424–1439, <https://doi.org/10.1111/j.1365-2486.2005.001002.x>, 2005.
- 700 Rinne, J., Riutta, T., Pihlatie, M., Aurela, M., Haapanala, S., Tuovinen, J.-P., Tuittila, E.-S., and Vesala, T.: Annual cycle of methane emission from a boreal fen measured by the eddy covariance technique, *Tellus B*, 59, 449–457, <https://doi.org/10.1111/j.1600-0889.2007.00261.x>, 2007.
- 705 Rochefort, L., Quinty, F., Campeau, S., Johnson, K., and Malterer, T.: North American approach to the restoration of Sphagnum-dominated peatlands, *Wetlands Ecol. Manage.*, 11, 3–20, <https://doi.org/10.1023/A:1022011027946>, 2003.
- Rydin, H. and Jeglum, J. K.: *The biology of peatlands*, 2nd edn., Oxford University Press, Oxford, UK, 2013.
- Schaller, C., Hofer, B., and Klemm, O.: Greenhouse gas exchange of a NW German peatland, 18 years after rewetting, *J. Geophys. Res.-Biogeo.*, 127, e2020JG005960, <https://doi.org/10.1029/2020JG005960>, 2022.
- 710 Schimmel, H., Braun, M., and Amelung, W.: 40 years of restoration: Temporal effects on nitrogen levels and carbon stability of post-extracted bogs, *Geoderma*, 459, 117391, <https://doi.org/10.1016/j.geoderma.2025.117391>, 2025.
- Schrier-Uijl, A. P., Kroon, P. S., Hensen, A., Leffelaar, P. A., Berendse, F., and Veenendaal, E. M.: Comparison of chamber- and eddy covariance-based CO₂ and CH₄ emission estimates in a heterogeneous grass ecosystem on peat, *Agr. Forest Meteorol.*, 150, 825–831, <https://doi.org/10.1016/j.agrformet.2009.11.007>, 2010.
- 715 Shahan, J., Chu, H., Windham-Myers, L., Matsumura, M., Carlin, J., Eichelmann, E., Stuart-Haentjens, E., Bergamaschi, B., Nakatsuka, K., Sturtevant, C., and Oikawa, P.: Combining eddy covariance and chamber methods to better constrain CO₂ and CH₄ fluxes across a heterogeneous restored tidal wetland, *J. Geophys. Res.-Biogeo.*, 127, e2022JG007112, <https://doi.org/10.1029/2022JG007112>, 2022.
- 720 Shannon, C. E.: A mathematical theory of communication, *Bell Syst. Tech. J.*, 27, 379–423, <https://doi.org/10.1002/j.1538-7305.1948.tb01338.x>, 1948.
- Strack, M., Waddington, J. M., Rochefort, L., and Tuittila, E.-S.: Response of vegetation and net ecosystem carbon dioxide exchange at different peatland microforms following water table drawdown, *J. Geophys. Res.-Biogeo.*, 111, G02006, <https://doi.org/10.1029/2005JG000145>, 2006.
- 725 Strack, M. and Zuback, Y. C. A.: Annual carbon balance of a peatland 10 yr following restoration, *Biogeosciences*, 10, 2885–2896, <https://doi.org/10.5194/bg-10-2885-2013>, 2013.



- Steffenhagen, P., Zak, D., Schulz, K., Timmermann, T., and Zerbe, S.: Biomass and nutrient stock of submersed and floating macrophytes in shallow lakes formed by rewetting of degraded fens, *Hydrobiologia*, 692, 99–109, <https://doi.org/10.1007/s10750-011-0833-y>, 2012.
- 730 Tuittila, E.-S., Vasander, H., and Laine, J.: Impact of rewetting on the vegetation of a cut-away peatland, *Appl. Veg. Sci.*, 3, 205–212, <https://doi.org/10.2307/1478999>, 2000.
- Tuittila, E.-S., Vasander, H., and Laine, J.: Sensitivity of C sequestration in reintroduced *Sphagnum* to water-level variation in a cutaway peatland, *Restor. Ecol.*, 12, 483–493, <https://doi.org/10.1111/j.1061-2971.2004.00280.x>, 2004.
- 735 Turmel-Courchesne, L., Davies, M. A., Guêné-Nanchen, M., Rochefort, L., and Strack, M.: Rewetting increases vegetation cover and net growing-season carbon uptake under fen conditions after peat extraction in Manitoba, Canada, *Sci. Rep.*, 13, 20588, <https://doi.org/10.1038/s41598-023-47879-y>, 2023.
- Vybornova, O., van Asperen, H., Pfeiffer, E.-M., and Kutzbach, L.: High N₂O and CO₂ emissions from bare peat dams reduce the climate mitigation potential of bog rewetting practices, *Mires Peat*, 24, 04, <https://doi.org/10.19189/MaP.2017.SNPG.304>, 2019.
- 740 Waddington, J. M., Strack, M., and Greenwood, M. J.: Toward restoring the net carbon sink function of degraded peatlands: Short-term response in CO₂ exchange to ecosystem-scale restoration, *J. Geophys. Res.-Biogeo.*, 115, G01008, <https://doi.org/10.1029/2009JG001090>, 2010.
- Wilczak, J. M., Oncley, S. P., and Stage, S. A.: Sonic anemometer tilt correction algorithms, *Bound.-Lay. Meteorol.*, 99, 127–150, <https://doi.org/10.1023/A:1018966204465>, 2001.
- 745 Wilson, D., Farrell, C. A., Fallon, D., Moser, G., Müller, C., and Renou-Wilson, F.: Multiyear greenhouse gas balances at a rewetted temperate peatland, *Global Change Biol.*, 22, 4080–4095, <https://doi.org/10.1111/gcb.13325>, 2016.
- Wilson, D., Mackin, F., Tuovinen, J.-P., Moser, G., Farrell, C., and Renou-Wilson, F.: Carbon and climate implications of rewetting a raised bog in Ireland, *Global Change Biol.*, 28, 6349–6365, <https://doi.org/10.1111/gcb.16359>, 2022.
- Wood, S. N.: Generalized additive models: An introduction with R, 2nd edn., Chapman and Hall/CRC, Boca Raton, FL, USA, <https://doi.org/10.1201/9781315370279>, 2017.
- 750 Wutzler, T., Lucas-Moffat, A., Migliavacca, M., Knauer, J., Sickel, K., Šigut, L., Menzer, O., Reichstein, M., and Moffat, A. M.: Basic and extensible post-processing of eddy covariance flux data with REddyProc, *Biogeosciences*, 15, 5015–5030, <https://doi.org/10.5194/bg-15-5015-2018>, 2018.
- 755 Zauner, J., Guidolin, C., and Spitschan, M.: How to deal with darkness: Modeling and visualization of zero-inflated personal light exposure data on a logarithmic scale, *J. Biol. Rhythms*, 40, 480–490, <https://doi.org/10.1177/07487304251336624>, 2025.
- Zhao, H., Shi, J., Qi, X., Wang, X., and Jia, J.: Pyramid scene parsing network, in: Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 6230–6239, <https://doi.org/10.1109/CVPR.2017.660>, 2017.
- 760 Zhao, J., Weldon, S., Barthelmes, A., Swails, E., Hergoualc’h, K., Mander, Ü., Qiu, C., Connolly, J., Silver, W. L., and Campbell, D. I.: Global observation gaps of peatland greenhouse gas balances: Needs and obstacles, *Biogeochemistry*, 167, 427–442, <https://doi.org/10.1007/s10533-023-01091-2>, 2024.