Comparing Light and Dark Chamber Measurements of CH4 Fluxes in Drained and Rewetted Raised Bogs of Ireland

Stephen Barry
barry.stephen@tudublin.ie

Technological University Dublin

Kenneth Byrne
University of Limerick

Kenneth Crawford
Bord na Móna (Ireland)

Mike Clancy
University of Limerick

O'Doherty Clare
Bord na Móna (Ireland)

Grainne Heagney
Bord na Móna (Ireland)

Harry Kelly
Bord na Móna (Ireland)

McCorry Mark
Bord na Móna (Ireland)

Hannah Mealy
Bord na Móna (Ireland)

Brian Mollahan
Bord na Móna (Ireland)

Matthew Saunders
Trinity College Dublin

Amey Tilak
University of Limerick

Research Article

Keywords: Peatlands, Restoration, Methane fluxes, Manual closed chamber method, Raised bogs

Posted Date: June 12th, 2025

DOI: https://doi.org/10.21203/rs.3.rs-6810432/v1

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Wetlands Ecology and Management on October 13th, 2025. See the published version at https://doi.org/10.1007/s11273-025-10089-6.

Abstract

The important factors regulating methane (CH_4) fluxes in rewetted peatlands such as the vegetation types, water table depths (WTDs) and in-situ conditions (pH, redox, soil temperature and moisture) are widely reported, but the impact of light and dark conditions on CH_4 fluxes from multiple vegetation types are not widely reported. This field study investigated if the CH_4 fluxes from multiple vegetation communities (*Sphagnum* communities, *Eriophorum angustifolium*, *Molinia caerulea*, *Typha latifolia*, *Phragmites australis*, *Juncus effusus*, *Calluna vulgaris, Carex rostrata* and open water) responded differently to light and dark conditions. Triplicate simultaneous light and dark measurements of carbon dioxide (CO_2) and CH_4 fluxes were measured on the same day using the chamber method from the above-mentioned vegetation communities from five peatland sites located in the Irish midlands. The field measurements showed that the CH_4 fluxes were higher in light conditions compared to dark conditions for *Carex rostrata* (0.05 ±0.02 in light, 0.02 ±0.01 g CH_4 m^{-2} hr^{-1} in dark) and *Eriophorum angustifolium* (0.02 ±0.01 in light, 0.01 ±0.00 g CH_4 m^{-2} hr^{-1} in dark) compared to other vegetation communities. The mixed-effect model results indicated that differences between light and dark measurements were strongly related to CO_2 fluxes. When the vegetation was sequestering CO_2, CH_4 fluxes increased, alternatively, during the respiration, CH_4 fluxes decreased. Future work should examine the impact of vegetation specific phenological mechanisms that influence CH_4 fluxes in light and dark conditions using multiple years of field data.

Introduction

Natural or near-natural peatlands store vast amounts of carbon over millennial time scales and typically have a net radiative cooling effect (Strack et al. 2022). However, when they are drained and degraded they become large sources of carbon dioxide (CO_2). Globally, drained peatlands emit approximately 2 gigatons of CO_2 annually (Joosten et al. 2016) despite covering only 3% of the Earth's land surface (Leifeld & Menichetti 2018). Moreover, peatlands, which store 30% of the world's soil carbon, present a twofold scenario: a chance to maintain or enhance their carbon sink capacity, or a danger of further escalating carbon losses if degradation continues (Gorham 1991; Leifeld et al. 2019; Strack et al. 2022). Total global emissions from drained and degraded peatlands are estimated to be 57.4 Gt CO_2-eq in 2022 (UNEP 2023) which accounts to 1–4.5% of global emissions. The rewetting is the deliberate action of raising the groundwater table to the peat surface in the previously drained peatland (Ojanen & Minkkinen 2020; Tanneberger et al. 2021). The drained peatland is considered rewetted if the average annual WTD is equal to or shallower than 30 cm from the peat surface (IPCC 2014). However, peatland restoration is the process of actively or passively assisting the recovery of the degraded peatland back to the state that existed before the degradation (Khan et al. 2025). The global potential for peatland restoration estimated to be 1.1 to 2.6 Gt CO_2-eq per year (Strack et al. 2022). However, even with ambitious and careful restoration programmes, the benefits of peatland restoration will take time to achieve and are vulnerable to external pressures like poor water quality and climate change. For instance, Wilson et al. (2022) found that even if emissions are reduced in line with the low emission scenarios (SSP1-1.9), peatland restoration will have a warming effect until 2085. Importantly, Günther et al. (2020) concluded that the continued CO_2 emissions from degraded peatlands will result in greater radiative forcing than the CH_4 emissions, indicating the critical importance of peatland restoration.

Drained peatlands have been found to have small to no CH_4 fluxes (Aitova et al. 2023). However, rewetted peatlands have been found to experience elevated CH_4 fluxes (Evans & Gauci 2023). Three processes govern the CH_4 emissions from peat: production, storage, and transport (Rey 2014; Roland et al. 2015). CH_4 production occurs under the anoxic conditions, where methanogens break down carbohydrates into CH_4 (Lai 2009). Peat soils, with high moisture contents create anoxic conditions due to persistently shallow water table at the peat surface (Hobbs 1986). Restored peatlands that were previously subjected to industrial extraction and having a depth of less than 1.5 m, exhibited higher CH_4 emissions (Aitova et al. 2023) possibly due to increased alkalinity, which favored methanogen activity (Evans & Gauci 2023). However, not all the produced CH_4 reaches the atmosphere, as methanotrophs in the aerobic zone consume some CH_4 before it escapes to the atmosphere (Hanson & Hansen 1996). But in waterlogged conditions, limited pore space and reduced diffusion increases ebullition (sudden CH_4 bursts) or plant-mediated transport via aerenchyma tissues (Vroom et al. 2022). These pathways bypass the aerobic oxidation, increasing CH_4 emissions. Vegetation plays a crucial role in CH_4 fluxes by facilitating direct transport to the atmosphere, reinforcing the link between plant communities and CH_4 dynamics (Ge et al. 2024). CH_4 fluxes also depend upon the vegetation type (Chanton et al. 1993), nutrient status (Lai et al. 2009), biological processes (Hanson & Hansen 1996), hydrology (Evans et al. 2021), climatic conditions and landuse (Aitova et al. 2023). If an incomplete understanding of factors governing the production or emission of CH_4 exist, it is important to determine which specific environmental and biological variables most significantly impact these processes.

However, the incorporation of light levels into CH_4 flux models remains limited, representing a significant area of uncertainty. If CH_4 fluxes follow a diurnal pattern independent of commonly used predictors such as soil temperature and WTD, further investigation is warranted. Differences in CH_4 fluxes between daylight and night-time conditions, if unaccounted for in annual flux models, this can lead to inaccurate greenhouse gas (GHG) balances (Saunois et al. 2020). Failure to consider light conditions in chamber measurement programs may also affect emission inventories, potentially leading to over-or underestimation of emissions and contributing to discrepancies between atmospheric CH_4 concentrations and bottom-up inventories (Saunois et al. 2020). Observational studies focusing on this pattern have typically been conducted in single vegetation communities like *Phragmites australis* (Minke et al. 2014) or *Sphagnum* dominated communities (Lhosmot et al. 2023). Other studies have

focused on a small sample of vegetation communities, including *Phragmites australis*, wetland sedges, grasses, and herbs (Juutinen et al. 2004), *Eriophorum angustifolium* and *Eriophorum vaginatum* (Dooling et al. 2018), and *Sphagnum* mosses, evergreen shrubs, sedges, and forbs (Lai et al. 2012). Studies examining this have used manual closed chamber measurements with the study duration lasting few days (Dooling et al. 2018) or over two summers (Minke et al. 2014) or four months (Juutinen et al. 2004) and using a combination of automated chambers and flux towers over several years (Lai et al. 2012). These studies observed differences betweeen day and night flux measurements (Bäckstrand et al. 2008; Lai et al. 2012). However to date, most studies have not examined this from a seasonal perspective given the short duration of past studies.

Different mechanisms have been proposed to explain this including processes that affect CH_4 production (Doane & Rongzhong 2022) or transport processes (Chanton et al. 1993). Recently, photochemical reactions identified as potentially important sources of CH_4 production. A link between CH_4 fluxes and photochemistry specifically in agricultural settings and forestry, albiet under mostly mineral soils was reported (Doane & Rongzhong 2022). Photochemical reactions were found to increase the number of ketones produced in vegetation, decayed matter and peat. This was identified as the best predictor of CH_4 emission (Doane & Rongzhong 2022). While it is often assumed that the microbial activity and associated CH_4 emissions decline in winter, this photochemical reaction was found to continue regardless of temperature if sufficient light levels are present and resulted in the continued production of CH_4. Chanton et al. (1993) found that as the sunlight increased, it caused air to move through the plants, opening the stomata (tiny openings on the plant's surface). This ventilation process helped release the trapped methane from inside the plant stems, leading to an increase in methane emissions. Minke et al. (2014) found a significant negative correlation between CO_2 and CH_4 fluxes, though the strength of this correlation varied greatly between different plots. All recorded parameters showed a strong correlation with Photosynthetically Active Radiation (PAR), which regulates the CO_2-consuming process of photosynthesis. This study also observed that the CO_2 concentrations within the chamber are typically higher at night when PAR and photosynthesis were absent, while CH_4 emissions were low (Minke et al. 2014). In contrast, the study found that during the daytime, when PAR and photosynthesis are active, both CO_2 and CH_4 emissions increased. Although the effect of CO_2 was significant, this study further suggested that the PAR was likely the main factor driving the differences in CH_4 fluxes. This implies that the variations in CH_4 emissions are more directly related to light availability and the resulting photosynthetic activity, rather than CO_2 levels alone (Minke et al. 2014).

Additionally, some studies have been unable to detect any dirunal pattern (Mengyu et al. 2024) while other studies found that light oxidised CH_4 emissions, (Lhosmot et al. 2022). This field study investigates whether there is a significant difference in CH_4 flux measurements taken under light and dark conditions using the manual closed chamber method. By comparing flux measurements across nine vegetation communities from five peatland sites, the study aims to evaluate the influence of light and dark conditions on CH_4 fluxes. Additionally, it seeks to assess the scale of this effect by comparing its influence with environmental parameters, such as WTDs and soil temperature. Therefore this research aims to enhance our understanding of CH_4 flux variations between light and dark conditions across diverse wetland vegetation communities. In doing so, it seeks to determine whether this pattern is widespread across multiple vegetation communities. Additionally, this study will assess whether the effect of light and dark conditions is significant compared to other important environmental factors.

Methods

Site Description

The locations used in this study were former raised bogs located in Co. Offaly and Co. Kildare in the midlands of Ireland (Fig. 1). All the bogs were drained and subjected to peat extraction except the *Sphagnum fuscum* dominated site located in Mouds bog, Co. Kildare which was drained but not extracted. The vegetation communities at Blackriver, Ballycon and Derries were rewetted approximately 40, 20 and 10 years prior to this study respectively. The *Calluna vulgaris* and *Molinia* grasses monitored at Clonad and Mouds were former extraction sites that were revegetated. All the vegetation communities except at Mouds and Clonad (drained and revegetated) had shallow peat depths averaging less than 1.5 m (Table 1).

Nine vegetation communities commonly found in degraded shallow and deep peatlands, as well as those associated with rewetted sites, were selected for monitoring (Table 1). *Sphagnum* communities were aggregated together for the purposes of this study. Duplicate sites (e.g. vegetation communities sampled at two separate bog locations) were included to assess intra-site variation, except for *Phragmites australis* and Open Water. The peat depth was shallow at most vegetation communities, due to peat removal, while pH and presence of vegetation varied depending on hydrology and peat depth. *Calluna vulgaris* and *Molinia Caerulea* were found in dry areas, *Typha latifolia* and *Phragmites australis* dominated in wet areas, while basic conditions with shallow peat had variety of *Sphagnum* mosses (hereafter referred to as *Sphagnum* dominated communities) and *Eriophorum angustifolium* were found over a range of peat depths with varying nutrient statuses (Table 1).

Table 1
Site descriptions of selected locations used in this study. Chamber monitoring locations are located over nine different vegetation communities and land use status (rewetted, drained or drained and extracted)

Site	County	Area (Ha)	Vegetation Community	Rewetted	Rewetted Status	Extraction	pH	Mean WTD (cm)	Depth (cm)
Ballycon	Co. Kildare	281	*Sphagnum palustre*	Y	20 years ago,	1960–2001	6.5	-13	100
Ballycon	Co. Offaly	281	*Eriophorum angustifolium*	Y	20 years ago,	1960–2001	6.5	-13	100
Ballycon	Co. Offaly	281	*Molinia caerulea*	Y	20 years ago,	1960–2001	NA	>-50	50
Ballycon	Co. Offaly	281	*Typha latifolia*	Y	20 years ago,	1960–2001	6.5	8	100
Ballycon	Co. Offaly	281	*Phragmites australis*	Y	20 years ago,	1960–2001	6.6	10	100
Blackriver	Co. Kildare	6	*Eriophorum angustifolum*	Y	40 years ago,	Ceased in 1980s	5.1	2.7	50
Blackriver	Co. Kildare	6	*Juncus effusus*	Y	40 years ago,	Ceased in 1980s	5.1	-0.18	50
Blackriver	Co. Kildare	6	*Sphagnum papillosum*	Y	40 years ago,	Ceased in 1980s	5.1	-1.2	50
Clonad	Co. Offaly	447	*Calluna vulgaris*	N	Drained, extracted	1970–2019	4.3	-35	300
Clonad	Co. Offaly	447	*Molinia careulea*	N	Drained, extracted	1970–2019	4.9	-14.6	300
Mouds	Co. Kildare	411	*Calluna vulgaris*	N	Drained, extracted	Ceased in 2019	4.7	-40.2	250
Mouds	Co. Kildare	411	*Sphagnum fuscum*	N	Drained, not extracted	Unknow when drained	4.6	-19.8	> 300
Derries	Co. Offaly	371	*Typha latifolia*	Y	Rewetted 10 years ago	1960–2005	5.9	4.2	100
Derries	Co. Offaly	371	*Open water*	Y	Rewetted 10 years ago	1960–2005	5.6	5	100
Derries	Co. Offaly	371	*Carex rostrata*	Y	Rewetted 10 years ago	1960–2005	6.1	4.2	100

Greenhouse Gas Flux Measurement Methodology

The experimental set-up for measuring greenhouse gas fluxes involved the installation of collars

(60 x 60cm) made of stainless steel. These were inserted 12 cm into the peat profile to create a gas-tight seal and remained in place throughout the study. Three steel collars were installed per vegetation community at each monitoring location. The monitoring frequency at each study site was twice per month during the growing season (April to September) and once per month over the non-growing season (October to March). During each site visit, CH_4 fluxes was measured three times from each collar: (i) using a clear chamber, (ii) clear chamber covered by a semi-transparent net and (iii) clear chamber covered by a non-transparent tarpaulin (Wilson et al. 2016) using a LICOR 7810 CH_4 and CO_2 gas analyser. The chamber measurements were taken in succession with a small break period

(2–3 min) to allow the sensor to re-calibrate to atmospheric conditions and to allow the chamber headspace to equilibrate with the atmospheric conditions. Temperature probes were installed at 5 cm depth (Wilson et al. 2022) to continuously monitor soil temperature. Boardwalks were constructed to minimize soil compaction and disturbance during measurements, particularly to reduce ebullition events driven by trampling during CH_4 measurements. Chambers were equipped with a small 5V fan for air mixing and PAR sensors are placed in the chamber during measurements. The closure time of the chambers was 90 seconds with 30 seconds mixing time and 60 seconds (1 min) monitoring time. Concentrations were recorded every 2 seconds and then averaged over a 6-second period. This process was repeated to collect a total of 10 measurements during the entire closure period. This approach was adopted to minimise temperature, pressure and changes of light within the headspace of the chamber. If PAR measurements changed significantly over the measurement period, the measurement was retaken. Fluxes were only accepted if an R^2 value of > 0.90 was detected. The flux of CH_4 was estimated simultaneously using Eq. 1:

Equation 1: $F_c = \frac{10VP_0(1-\frac{W_0}{1000})}{RS(T_0+273.15)} \frac{\partial C\prime}{\partial t}$ (LICOR, 2024)

Where V is the chamber Volume (m^3), P is the Air Pressure (Hpa), W_0 is the initial H_2O concentration (mmol/mol), R is the ideal gas constant (8.3144), T_0 is air temperature taken from an air temperature probe (Kelvin), ∂C' is the change in CH_4 concentration and ∂t is the time elapsed (seconds). CO_2 fluxes (Net Ecosystem Exchange) were measured simultaneously. Methane flux measurements were carried out from July 2023 to May 2024. Given that site set up was ongoing during this time, the number of flux measurements per site varied. These measurements were compiled into a single data base and organised according to vegetation community and whether the flux was taken in light or dark conditions. Water table levels were obtained via manual dip measurements, internal chamber PAR values using SQ-520: Full-Spectrum Smart Quantum Sensor, pH using a YSI pH probe and soil temperature using a Hobo soil temperature probe.

Analysis of differences between light and dark CH chamber measurements

To assess differences in CH_4 flux between light and dark conditions, Mann-Whitney U tests and a linear mixed-effect model (Lindstrom & Bates 1988) were employed. Given the non-normal distribution of the data, the Mann-Whitney U test compared rankings between groups, while the mixed-effect model accounted for fixed effects (light/dark) and random effects (vegetation communities) to analyse CH_4 flux variability. Preliminary tests, including the Shapiro-Wilk test for normality and Levene's test for heteroscedasticity, were conducted, with QQ plots and residuals examined using PYTHON 3.1.1 (Figures S1-S9; Supplementary material). The Mann-Whitney U test provided p-values to assess significance, and Cohen's d test quantified effect size. As CH_4 fluxes are influenced by multiple factors such as temperature, water table, CO_2 flux, and pH, the mixed-effect model was essential for capturing these interactions. Cross-validation was performed by partitioning the dataset into multiple subsets to evaluate predictive performance. Model outputs included intercepts (baseline CH_4 flux) and coefficients indicating effect magnitude and direction, where a positive coefficient for "Dark to Light" suggested increased CH_4 flux under light conditions. Model accuracy was assessed using Mean Square Error (MSE), with lower values indicating better performance (Lohse et al. 2023).

Results

This study found that the vegetation communities such as the *Carex rostrata* and *Eriophorum angustifolium* exhibited higher CH_4 fluxes in light conditions compared to dark conditions, while the other vegetation communities did not show any observable differences between light and dark CH_4 fluxes (Fig. 2). However, on average, the *Carex rostrata* exhibited the largest difference (0.03 g CH_4 m^{-2} hr^{-1}, p-value < 0.05) followed by *Eriophorum angustifolium* (0.01 g CH_4 m^{-2} hr^{-1}, p-value < 0.05). But the *Juncus effusus exhibited the* opposite trend i.e., the CH_4 fluxes were higher in dark conditions compared to the light conditions, albiet with a non-significant effect. The box plots of each individual vegetation highlight the differences between the light and dark measurements (Fig. 3). The *Carex rostrata* and *Eriophorum angustifolium* had notable differences in CH_4 flux values (median and upper quartile) (Fig. 3) while other species such as *Calluna Vulgaris, Juncus effusus, Molinia Caerulea* and *Sphagnum* communities showed minor to no differences in CH_4 fluxes between light and dark conditions (Fig. 3).

Table 2 shows the results of Shapiro-Wilk Test and Levene's test. The CH_4 flux data was found to be non-normally distributed across all nine vegetation communities (e.g. p-values were < 0.05) and this was supported by the QQ plots (Figures S1-S9; Supplementary material) and histograms and Kernal Density Estimates (KDEs) (Figure S10; Supplementary material). Outliers retained in the dataset given that the ebullition is an important process within bogs that results in large and abrupt CH_4 fluxes (Bieniada & Strack 2021). Heteroscedasticity was detected in *Carex rostrata* and *Eriophorum angustifolium* (e.g. p-values were < 0.05) meaning that the parametric tests on these vegetation communities may be biased and invalid. However, given the non-normality, the Mann-Whitney U statistic was used to determine if there was a significant difference between light and dark CH_4 flux measurements (Table 3). The results showed a significant difference in light and dark measurements for *Carex rostrata* and *Eriophorum angustifolium* compared to other vegetation communities (Table 4).

Table 2
Sample size of chamber measurements included in the study at each vegetation community and provides an assessment of normality and heteroscedasticity

	No. of Chamber Measurements		Shapiro-Wilk Test		Levene's Test	
Vegetation Communities	Dark	Light	W-statistic	p-value	W-statistic	p-value
Carex rostrata	35	25	0.71	0.00	6.31	0.01
Eriophorum angustifolium	53	36	0.63	0.00	6.81	0.01
Calluna vulgaris	37	19	0.62	0.00	0.41	0.52
Juncus effusus	29	24	0.46	0.00	0.99	0.32
Molinia Caerulea	46	30	0.85	0.00	1.28	0.26
Open Water	22	17	0.30	0.00	0.13	0.72
Phragmites australis	10	13	0.82	0.00	3.61	0.07
Sphagnum Communities	83	40	0.69	0.00	0.97	0.33
Typha latifolia	12	15	0.77	0.00	0.12	0.74

Table 3
Assesses if there is a significant difference between vegetation communities. The t-statistic assumes normality while the Mann-Whitney U statistic does not

Vegetation Communities	Mann-Whitney U statistic	p-value
Carex rostrata	603.00	0.01
Eriophorum angustifolium	1217.00	0.03
Calluna vulgaris	332.00	0.74
Juncus effusus	324.00	0.67
Molinia Caerulea	765.00	0.43
Open Water	147.00	0.26
Phragmites australis	75.00	0.56
Sphagnum Communities	1674.50	0.94
Typha latifolia	109.00	0.36

The mixed-effect model provided additional information as compared to the non-parametric tests. It also showed that *Carex Rostrata* and *Eriophorum angustifolium* had significant differences in CH_4 fluxes. Table 4 shows that when switched from dark to light conditions the fluxes increased by 0.0201 g CH_4 m^{-2} hr^{-1} for *Carex Rostrata* and 0.0153 g CH_4 m^{-2} hr^{-1} for *Eriophorum angustifolium*. An opposite trend was observed for *Juncus effusus and Typha latifolia* where fluxes decreased in light conditions (-0.0135 & -0.0104 g CH_4 m^{-2} hr^{-1} respectively). The presence of outliers best explained these differences. The overlapping confidence intervals also suggests a less clearly defined role between light and dark conditions. Moreover, the influence of pH and WTD were found to have an equally important effect on CH_4 fluxes. pH was found to influence CH_4 fluxes from *Juncus Effusus* and open water with higher pH values (more alkaline conditions) associated with higher fluxes (Figures S11, S12 and S13; Supplementary material). *Typha latifolia* also showed that higher pH values influenced CH_4 fluxes (-0.0102 g CH_4 m^{-2} hr^{--1}), in addition to the switch between dark to light conditions (-0.01043 g CH_4 m^{-2} hr^{-1}) and water table level (+ 0.0141 g CH_4 m^{-2} hr^{-1}). CO_2 fluxes were also found to strongly influence CH_4 fluxes in *Carex Rostrata*, *Eriophorum angustifolium*, Open Water, *Sphagnum* Communities and *Typha Latifolia* (Table 4). In nearly all vegetation communities, this was found to be a negative effect, implying that while these vegetation communities sequester CO_2, CH_4 emissions increase simultaneously. Conversely, during respiration, CH_4 emissions decrease. In the *Sphagnum* communities and Open water, the opposite trend was observed.

Table 4
Presents the intercept, coefficients, and cross-validation mean squared error (MSE) for various vegetation communities, considering factors such as dark to light transitions, water table (WT), pH, soil temperature, and photosynthetically active

Vegetation Communities	Intercept	Dark to Light	WT	pH	Soil Temp	PAR	CO2	CV MSE
Carex Rostrata	-0.15086	0.02010	-0.00260	0.03392	-0.00372	0.00000	-0.02134	0.00164
Eriophorum angustifolium	-0.03823	0.01536	0.00202	0.00568	0.00197	-0.00002	-0.02650	0.00081
Calluna vulgaris	0.00003	-0.00005	0.00000	0.00002	0.00000	0.00000	-0.00012	0.00000
Juncus effusus	-0.14121	-0.01357	0.00073	0.02787	0.00109	0.00001	-0.00786	0.00061
Molinia Caerulea	0.00077	0.00001	0.00001	-0.00009	0.00005	0.00000	-0.00015	0.00000
Open Water	0.05148	-0.00335	0.00008	-0.00947	0.00011	0.00000	0.07981	0.00009
Phragmites australis	-0.00667	-0.00025	0.00006	0.00036	0.00055	-0.00000	-0.00049	0.00001
Sphagnum communities	-0.00087	0.00029	0.00000	0.00002	0.00015	-0.00000	0.01203	0.00000
Typha latifolia	0.08231	-0.01043	0.01411	-0.01023	-0.00637	0.00006	-0.04793	0.00355

Discussion

The mixed-effect model found that the *Carex rostrata* and *Eriophorum angustifolium* had the largest differences between light and dark conditions. The effect of light and dark conditions was significant and found to have a more profound impact than the water table, soil temperature and PAR on CH_4 fluxes (Table 4). In contrast, the *Juncus effusus* was found to have higher fluxes in the dark conditions compared to the light conditions. However, research to date on CH_4 fluxes under varying light conditions has yielded mixed results. For instance, some studies found higher CH_4 fluxes in light conditions compared to the dark conditions (Minke et al. 2014), while other studies found no differences between CH_4 fluxes in light and dark conditions (Mengyu et al. 2024) while some studies showed higher CH_4 fluxes in dark conditions compared to light conditions (Dooling et al. 2018; Lhosmot et al. 2022). All three scenarios were replicated in this study albeit for different vegetation communities. This indicates a high degree of heterogeneity in CH_4 fluxes among peatland species in response to varying light and dark conditions.

To understand why this might be the case, it is important to distinguish whether the observed differences arise from CH_4 production or CH_4 transport. This distinction helps to determine whether the vegetation is actively producing CH_4 or primarily facilitating its movement to the atmosphere. This distinction is not only important for accurately estimating CH_4 fluxes, but also for informing management decisions in restored bog and fens, such as water table regulation and vegetation control. Previous research has reported both scenarios, where differences between light and dark measurements were due to the changes in the CH_4 production rate (Dooling et al. 2018) or changes in the rate of CH_4 transport (Minke et al. 2014). Processes that account for increases in the CH_4 fluxes are due to increasing rates of CH_4 production via root exudates (Dooling et al. 2018) or via photochemical reactions linked with the production of keytones (Doane & Rongzhong 2022). Studies found that either atmospheric turbulence (Lai et al. 2012) or stomatal conductivity which was affected by higher CO_2 concentrations (Minke et al. 2014) were the main drivers of CH_4 fluxes between light and dark conditions. While turbulence was not measured here, given that the light and dark measurements were taken concurrently, it's unlikely that the atmospheric turbulence can account for differences in this study.

Vegetation species such as *Carex rostrata, Eriophorum angustifolium, Juncus effusus, Phragmites australis* and *Typha latifolia*, all possess aerenchyma tissues allowing transport of CH_4 from peat-surface to atmosphere. However, not all species containing *aerenchyma* exhibited differences between light and dark measurements such as *Phragmites australis* and *Typha latifolia*. *Phragmites australis* was found to have low CH_4 fluxes in general which was surprising given it was an aerenchyma species. Alternatively, *Typha latifolia* exhibited the highest CH_4 fluxes in both light and dark conditions. This provides evidence that production may not be responsible for observed differences between light and dark conditions. If light levels were important in determining the production of CH_4, a pronounced effect should be observable in all vegetation communities with high CH_4 fluxes. However, this was not the case. No difference was detected for *Typha latifolia* suggesting that the light levels were not influencing CH_4 production. This contrasts with the findings of other studies which found the CH_4 production to be the main reason for differences between light and dark CH_4 fluxes (Dooling et al. 2018; Doane & Rongzhong 2022).

Minke et al. (2014) found that because of the dense network of interlinked rhizomes, the CH_4 emissions may be rerouted to rhizomes which may be located outside of the closed chamber due to the pressure gradients created by the manual closed chamber method. Therefore, both CH_4 fluxes and the differences observed between light and dark measurements may be obscured by enhanced transport between the stands. This further supports the importance of understanding the role of transport mechanisms of gases within vegetation communities. Given the observed association between CH_4 and CO_2 fluxes, our study results are consistent with Minke et al. (2014), where field measurements showed that the CH_4 fluxes increased when the CO_2 concentrations decreased and vice versa. Chanton and Whitney (1994) found this pattern to be related to

decreased stomatal conductance at high CO_2 concentrations. One important difference between our study and that of Minke et al. (2014), was that PAR and relative humidity were found to strongly control CH_4 fluxes in Minke et al. (2014) while the PAR was not observed to control CH_4 fluxes in our study. Of note, both Minke et al. (2014) and this study agreed that little differences were observed in CH_4 fluxes from *Phragmites australis* in light or dark conditions. The results of this study support Chanton and Whitney (1994) findings that the stomatal conductivity could be controlling CH_4 fluxes. This aligns with Noyce et al. (2014) who have found that the removal of above-ground biomass in the case of *Carex rostrata* reduced CH_4 fluxes by 40–70%, indicating that the transport may be the main factor controlling CH_4 fluxes. Therefore, considering light levels could improve the precision of CH_4 flux estimation. As our results show evidence of differences in light and dark measurements for two vegetation communities, this may result in underestimation or over estimation of CH_4 fluxes. The implications of this study mean that the inclusion of light and dark measurements in future chamber measurement programs is advisable and subsequent modelling approaches should seek to incorporate light and dark response curves and CO_2 fluxes in addition to water table and soil temperature (Wilson et al. 2016).

Conclusion

This study utilized statistical techniques (Mann Whitney U test, mixed-effects model) to determine if there were any potential differences in CH_4 fluxes from different wetland vegetation types (*Sphagnum* communities, *Eriophorum angustifolium*, *Molinia caerulea*, *Typha latifolia*, *Phragmites australis*, *Juncus effusus*, *Calluna vulgaris*, and *Carex rostrata*) subjected to light and dark conditions over a one-year period. The mixed-effect model showed that only two wetland vegetation species (*Carex rostrata* and *Eriophorum angustifolium*) exhibited different CH_4 fluxes in light and dark conditions and this effect was greater than the impact exerted by measured in-situ environmental variables such as pH, redox and soil temperature. However, it is important to note that the limitations of this study include the presence of outliers, the abnormal distribution of the vegetation communities and heteroscedasticity, meaning that some statistical analyses need to be interpreted with caution. However, all statistical tests show the same result-a difference between light and dark measurements for two vegetation species (*Eriophorum angustifolium* and *Carex rostrata*). As the study was conducted over a single year, it does not account for interannual variability, so future research should seek to conduct multiple year measurements. While this study identifies differences in CH_4 fluxes between light and dark conditions, it does not elucidate the underlying mechanisms driving these differences. Without direct measurements of plant specific phenological characteristics, soil microbial activity or pore water CH_4 concentrations to explain the observed patterns, the underlying drivers remain somewhat speculative. To identify the driving mechanism/s impacting the plant-specific CH_4 fluxes, future field monitoring programs can measure plant biomass, amount of permeable root surface (taking proxy measurements of root length), presence and diversity of methanogens and methanotrophs within the plant shoots along with the measurements of in-situ environmental parameters (pore-water CH_4 concentrations, WTDs, pH and soil temperature).

Declarations

Acknowledgements

We appreciate the critical reviews provided by the journal referees and the journal editor/co-editor.

Funding

This work was supported by the Department of Environment, Climate and Communications under the Peatland Climate Action Scheme. Amey Tilak was funded by the Irish Environmental Protection Agency (EPA) and the Department of Agriculture, Food and Marine respectively (grant number for CH_4 project: 2021-CE-1060). The EPA Research Program 2021-2030 is a Government of Ireland initiative funded by the Department of Communications, Climate Action, and Environment. This research program is administered by the Environment Protection Agency (EPA), which has the statutory function of coordinating and promoting environmental research. M Clancy was funded by Science Foundation Ireland (grant number SFI 20/SPP/3705). KA Byrne acknowledges funding from Science Foundation Ireland (grant number SFI 20/SPP/3705) and the University of Limerick.

Author information and affiliations

School of Architecture, Building and Environment, Technological University Dublin, Bolton Street,
Dublin 1, Ireland
Stephen Barry

Bord na Mona, Leabeg, Boora Ave, Co. Offaly, Ireland
Kenneth Crawford, Clare O'Doherty, G Heagney, Harry Kelly, Mark McCorry, Hannah Mealy, Brian Mollahan

Department of Biological Sciences & Bernal Institute, Faculty of Science and Engineering,
University of Limerick, Limerick, Ireland
Mike Clancy, Amey S. Tilak and Kenneth A. Byrne

School of Natural Sciences, Botany Discipline, Trinity College, Dublin, Ireland
Matthew Saunders

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Harry Kelly, Clare O'Doherty, Hannah Mealy, Brian Mollahan, Amey Tilak, Mike Clancy, Ken Byrne, Matt Saunders and Stephen Barry, ecology surveys were carried out by Mark McCorry. The first draft of the manuscript was written by Stephen Barry and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability The datasets generated during and/or analysed during the current study are available from the first and corresponding authors on reasonable request.

Corresponding author

Stephen Barry barry.stephen@tudublin.ie

Ethics declaration

Competing interests
The authors have no relevant financial or non-financial interests to disclose.

References

1. Aitova E, Morely T, Wilson D, Renou-Wilson F (2023) A review of greenhouse gas emissions and removals from Irish peatlands. Mires and Peat 1-17. http://mires-and-peat.net/pages/volumes/map29/map2904.php
2. Bäckstrand K, Crill P, Mastepanov M, Christensen T, Bastviken D (2008) Total hydrocarbon flux dynamics at a subarctic mire in northern Sweden. *J Geophys Res* 113, G03026. https://doi.org/10.1029/2008JG000703
3. Bord na Móna (BnM) (2024) *Peatlands Climate Action Scheme*. Retrieved from https://www.bnmpcas.ie/: https://www.bnmpcas.ie/#:~:text=Learn%20More%20%3E-,Climate%20Action%20Benefits,rich%20vegetation%20in%20suitable%20conditions. Accessed on May 22nd 2024.
4. Breiman L (2001) Random Forests. *Machine Learning*, 45: 5-32. https://doi.org/10.1023/A:1010933404324
5. Chandra N, Patra P, Fujita R, Höglund-Isaksson L, Umezawa T, Goto D, Morimoto S, Vaugh B.H, Röckmann T (2024) Methane emissions decreased in fossil fuel exploitation and sustainably increased in microbial source sectors during 1990-2020. *Communications Earth & Environment* 5-147. https://doi.org/10.1038/s43247-024-01286-x
6. Chanton J, Whiting G, Happell J, Ghislan G (1993) Contrasting rates and diurnal patterns of methane emission from emergent aquatic macrophytes. *Aquatic Botany*, 46(2): 111-128. https://doi.org/10.1016/0304-3770(93)90040-4
7. Chapin C, Bridgham S, Pastor J (2004) pH and nutrient effects on above-ground net primary production in a Minnesota, USA bog and fen. *Wetlands* 24: 186-201. https://doi.org/10.1672/0277-5212(2004)024[0186:PANEOA]2.0.CO;2
8. Doane T, Rongzhong Y (2022) Photochemical Soil Methane Emission. *ACS Earth and Space Chemistry* 6 (7): 1742-1749. https://doi.org/10.1021/acsearthspacechem.2c00055
9. Dooling G, Chapman P, Baird A, Shepherd M, Kohler T (2018) Daytime-only measurements underestimate CH_4 emissions from a restored bog. *Écoscience* 259-270. https://doi.org/10.1080/11956860.2018.1449442
10. Dunfield P, Knowles R, Dumont R, Moore T (1993) Methane production and consumption in temperate and subarctic peat soils: Response to temperature and pH. *Soil Biol, Biochem* 321-326. https://doi.org/10.1016/0038-0717(93)90130-4
11. European Environment Agency (2024) *European Climate Risk Assessment.* Copenhagen: European Environment Agency.
12. Evans C, Gauci V (2023) *Wetlands and Methane - Technical Paper.* UK: Wetlands International.
13. Evans CD, Peacock M, Baird AJ, Artz RRE, Burden A, Callaghan N, Chapman PJ, Cooper HM, Coyle M, Craig E, Cumming A, Dixon S, Gauci V, Grayson RP, Helfter C, Heppell CM, Holden J, Jones DL, Kaduk J, Levy P, Matthews R, McNamara NP, Misselbrook T, Oakley S, Page SE, Rayment M, Ridley LM, Stanley KM, Williamson JL, Worrall F, Morrison R (2021) Overriding water table control on managed peatland greenhouse gas emissions. Nature 593: 548-552. https://doi.org/10.1038/s41586-021-03523-1.
14. Evans C, Artz R, Moxley J, Smyth M-A, Taylor E, Archer N, Burden A, Williamson J, Donnelly D, Thomson A, Buys G, Malcolm H, Wilson D, Renou-Wilson F, Potts J (2017) Implementation of an emission inventory for UK peatlands. Report to the Department for Business, Energy and Industrial Strategy, Centre for Ecology and Hydrology, Bangor.88pp. Accessed Dec 05 2024. https://uk-air.defra.gov.uk/reports/cat07/1904111135_UK_peatland_GHG_emissions.pdf
15. Goode K, Ries D, McClernon K (2024) Characterizing climate pathways using feature importance on echo state networks. *Statistical Analysis and Data Mining*, 17. https://doi.org/10.1002/sam.11706

16. Gorham E (1991) Northern peatlands: role in the carbon cycle and probably responses to climate warming. *Ecological Applications* 182-185. https://doi.org/10.2307/1941811
17. Günther A, Barthelmes A, Huth V, Joosten H, Jurasinski G, Koebsch F, Couwenberg J (2020) Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. Nat Commun 11 : 1644. https://doi.org/10.1038/s41467-020-15499-z
18. Hanson R, Hansen T (1996) Methanotrophic bacteria. *Microbial Review* 60(2): 439-471. https://doi.org/10.1128/mr.60.2.439-471.1996
19. Hobbs N (1986) Mire morphology and the properties and behaviour of some British and foreign peats. *Quarterly Journal of Engineering Geology*, 19(1):7-80. https://doi.org/10.1144/GSL.QJEG.1986.019.01.02
20. IPCC (2013) *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press: T.F. Stocker, D. Qin, G.-K. Plattner, et al. (Eds.)).
21. Joosten, H., Sirin, A., Couwenberg, J., Laine, J., & Smith, P. (2016). The role of peatlands in climate regulation. In A. Bonn, T. Allott, M. Evans, H. Joosten, & R. Stoneman (Eds.), Peatland Restoration and Ecosystem Services: Science, Policy and Practice (pp. 63-76). Cambridge University Press. https://doi.org/10.1017/CBO9781139177788.005
22. Juutinen S, Alm J, Larmola T, Saarnio S, Martikainen P, Silvola J (2004) Stand-specific diurnal dynamics of CH_4 fluxes in boreal lakes: Patterns and controls. *Journal of Geophysical Research* 1-11. https://doi.org/10.1029/2004JD004782
23. Lai D (2009) Methane Dynamics in Northern Peatlands: A Review. Pedosphere, 19(4): 409-421. https://doi.org/10.1016/S1002-0160(09)00003-4
24. Lai D, Roulet N, Humpreys E, Moore, T, Dalva M (2012) The effect of atmospheric turbulence and chamber deployment period on autochamber CO_2 and CH_4 flux measurements in anombrotrophic peatland. *Biogeosciences*, 3305-3322. https://doi.org/10.5194/bg-9-3305-2012.
25. Le Mer, J, Roger P (2001) Production, oxidation, emission and consumption of methane by soils: A review. European Journal of Soil Biology 37(1): 25-50. https://doi.org/10.1016/S1164-5563(01)01067-6
26. Leifeld J, Menichetti, L (2018) The underappreciated potential of peatlands in global climate change mitigation strategies. Nature Communications 9. https://doi.org/10.1038/s41467-018-03406-6
27. Leifeld J, Wüst-Galley C, Page, S (2019) Intact and managed peatland soils as a source and sink of GHGs from 1850 to 2100. Nature Climate Change 9:945-947. https://doi.org/10.1038/s41558-019-0615-5
28. Lhosmot A, Jacotot A, Steinmann M, Binet P, Toussaint M, Gogo S, Gilbert D, Coffinet S, Laggoun-Deffarge F, Bertrand G (2023) Biotic and Abiotic Control Over Diurnal CH_4 Fluxes in a Temperate Transitional Poor Fen Ecosystem. Ecosystems 26: 951-968. https://doi.org/10.1007/s10021-022-00809-x
29. LI-COR (2024) LI-7810 $CH_4/CO_2/H_2O$ Trace Gas Analyzer. Retrieved https://www.licor.com/ on May 18th 2024. https://www.licor.com/env/products/soil-flux/LI-7810
30. Lindstrom M, Bates D (1988) Newton-Raphson and EM algorithms for linear mixed-effects models for repeated-measures data. Journal of the American Statistical Association 1014-1022. https://doi.org/10.1080/01621459.1988.10478693.
31. Lohse K, Kozlowski A, Strube M (2023) Model Specification in Mixed-Effects Models: A Focus on Random Effects. Communications in Kinesiology 1(5) https://doi.org/10.51224/cik.2023.52
32. Mengyu G, Korrensalo A, Putkinen A, Laiho R., Kohl L, Pihlatie M, Lohila A, Makiranta, P, Siljanen H, Tuittila, E-T, Koskinen M (2024) CH_4 transport in wetland plants under controlled environmental conditions-untangling the impacts of phenology. Research Square, 1-33. https://doi.org/10.1101/2023.10.08.561392
33. Minke M, Augustin J, Hagemann U, Joosten H (2014) Similar methane fluxes measured by transparent and opaque chambers point at belowground connectivity of Phragmites australisbeyond the chamber footprint. *Aquatic Botany*, 63-71. https://doi.org/10.1016/j.aquabot.2013.11.006
34. Noyce G, Varner, R, Bubier J, Frolking S (2014) Effect of Carex rostrata on seasonal and inter annual variability in peatland methane emissions. J. Geophys. Res. Biogeosci, 24-34. https://doi.org/10.1002/2013JG002474
35. RAMSAR (2018). *75% of Earth's land areas are degraded; wetlands have been hit hardest, with 87% lost globally in the last 300 years*. Retrieved https://www.ramsar.org/news/75-earths-land-areas-are-degraded-wetlands-have-been-hit-hardest-87-lost-globally-last-300
36. Renou-Wilson F, Moser G, Fallon D, Farrell C, Müller C, Wilson D (2019) Rewetting degraded peatlands for climate and biodiversity benefits: Results from two raised bogs. Ecological Engineering 547-560. https://doi.org/10.1016/j.ecoleng.2018.02.014
37. Rey A (2014) Mind the gap: non-biological processes contributing to soil CO_2 efflux. Global Change Biology 1752-1761. https://doi.org/10.1111/gcb.12821
38. Roland M, Vicca S, Bahn M, Ladreiter-Knauss T, Schmitt M, Janssens IA (2015) Importance of nondiffusive transport for soil CO_2 efflux in a temperate mountain grassland. J. Geophys. Res. Biogeosci., 502-512. https://doi.org/10.1002/2014JG002788

39. Saunois M, Stavert, AR, Poulter B, Bousquet P, Canadell JG, Jackson RB, Raymond PA, Dlugokencky EJ, Houweling S, Patra PK, Ciais P, Arora VK, Bastviken D, Bergamaschi P, Blake DR, Brailsford G, Bruhwiler L, Carlson KM, Carrol M, Castaldi S, Chandra N, Crevoisier C, Crill PM, Covey K, Curry CL, Etiope G, Frankenberg C, Gedney N, Hegglin MI, Höglund-Isaksson L, Hugelius G, Ishizawa M, Ito A, Janssens-Maenhout G, Jensen KM, Joos F, Kleinen T, Krummel PB, Langenfelds RL, Laruelle GG, Liu L, Machida T, Maksyutov S, McDonald KC, McNorton J, Miller PA, Melton JR, Morino I, Müller J, Murguia-Flores F, Naik V, Niwa Y, Noce S, O'Doherty S, Parker RJ, Peng C, Peng S, Peters GP, Prigent C, Prinn R, Ramonet M, Regnier P, Riley WJ, Rosentreter JA, Segers A, Simpson IJ, Shi H, Smith SJ, Steele LP, Thornton BF, Tian H, Tohjima Y, Tubiello FN, Tsuruta A, Viovy N, Voulgarakis A, Weber TS, van Weele M, van der Werf GR, Weiss RF, Worthy D, Wunch D, Yin Y, Yoshida Y, Zhang W, Zhang Z, Zhao Y, Zheng B, Zhu Q, Zhu Q, Zhuang Q (2020) The Global Methane Budget 2000-2017, Earth Syst. Sci. Data, 12, 1561-1623, https://doi.org/10.5194/essd-12-1561-2020

40. Serrano-Silva N, Sarria-Guzmán Y, Dendooven L, Luna-Guido M (2014) Methanogenesis and Methanotrophy in Soil: A Review. Pedosphere 24(3): 291-307. https://doi.org/10.1016/S1002-0160(14)60016-3

41. Simpon G (2018) Modelling Palaeoecological Time Series Using Generalised Additive Models. Frontiers in Ecology and Evolution 6:149. https://doi.org/10.3389/fevo.2018.00149

42. Strack M, Davidson S, Hirano T, Dunn C (2022) The Potential of Peatlands as Nature-Based Climate Solutions. Current Climate Change Reports 71-82. https://doi.org/10.1007/s40641-022-00183-9

43. Swenson M, Regan S, Bremmers D, Lawless J, Saunders M, Gill L (2019) Carbon balance of a restored and cutover raised bog: implications for restoration and comparison to global trends. Biogeosciences 16:713-731. https://doi.org/10.5194/bg-16-713-2019

44. Tanneberger F, Appulo L, Ewert S, Lakner S, O'Brolcháin N, Peters J, Wichtmann W (2020) The Power of Nature-Based Solutions: How Peatlands Can Help Us to Achieve Key EU Sustainability Objectives. Advanced Sustainable Systems, Vol 5. https://doi.org/10.1002/adsu.202000146

45. UNEP (2023) *Emissions Gap Report 2023*. UNEP. https://www.unep.org/resources/emissions-gap-report-2023

46. Whalen C (2005) Biogeochemistry of methane exchange between natural wetlands and the atmosphere. Environmental Engineering Science, 22(1): 73-94. https://doi.org/10.1089/ees.2005.22.73

47. Wilson D, Farrell C, Fallon D, Moser G. Müller C, Renou-Wilson F (2016) Multiyear greenhouse gas balances at a rewetted temperate peatland. Global Change Biology, 4080-4095. https://doi.org/10.1111/gcb.13325

48. Wilson D, Mackin F, Tuovinen J-P, Moser G, Farrell C, Renou-Wilson F (2022) Carbon and climate implications of rewetting a raised bog in Ireland. Global Change Biology, 6349-6365. https://doi.org/10.1111/gcb.16359

Figures

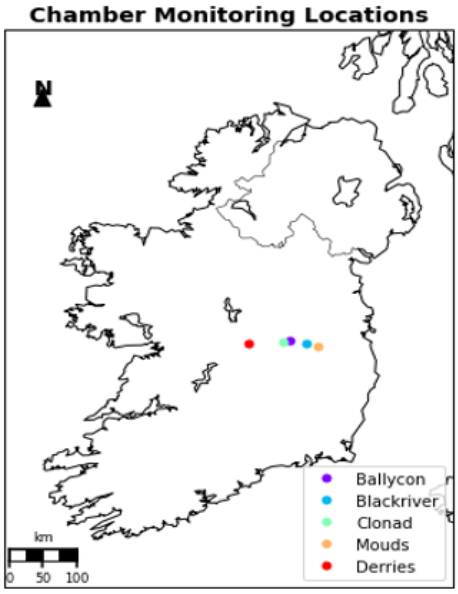

Figure 1

Location of peatlands in this study, where nine vegetation communities were monitored for CO_2 and CH_4 fluxes. The latitude and longitude of Ballycon bog is 53.282412, -7.194488, Blackriver bog is 53.261918, -6.977151, Clonad is

53.272977, -7.280195, Mouds bog is 53.251345, -6.793346 and finally Derries is 53.254687, -7.756066

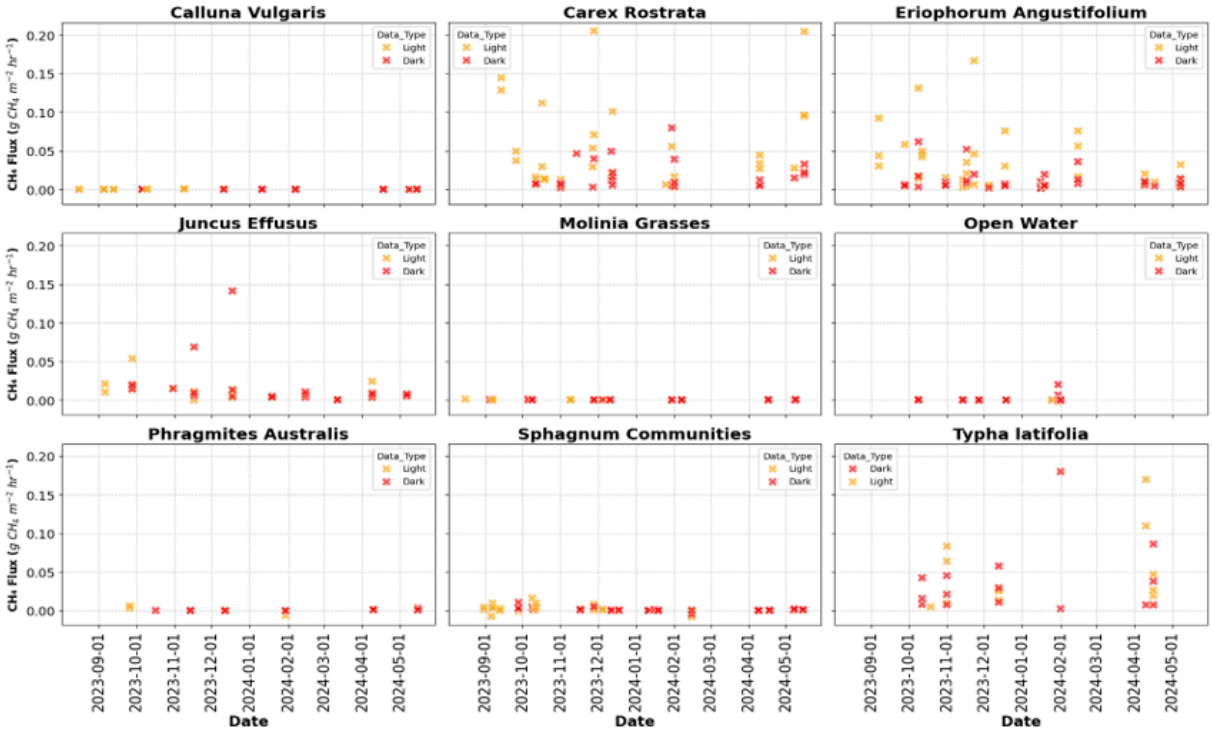

Figure 2

CH_4 flux measurements collected using manual closed chamber measurement technique between August 2023 and May 2024

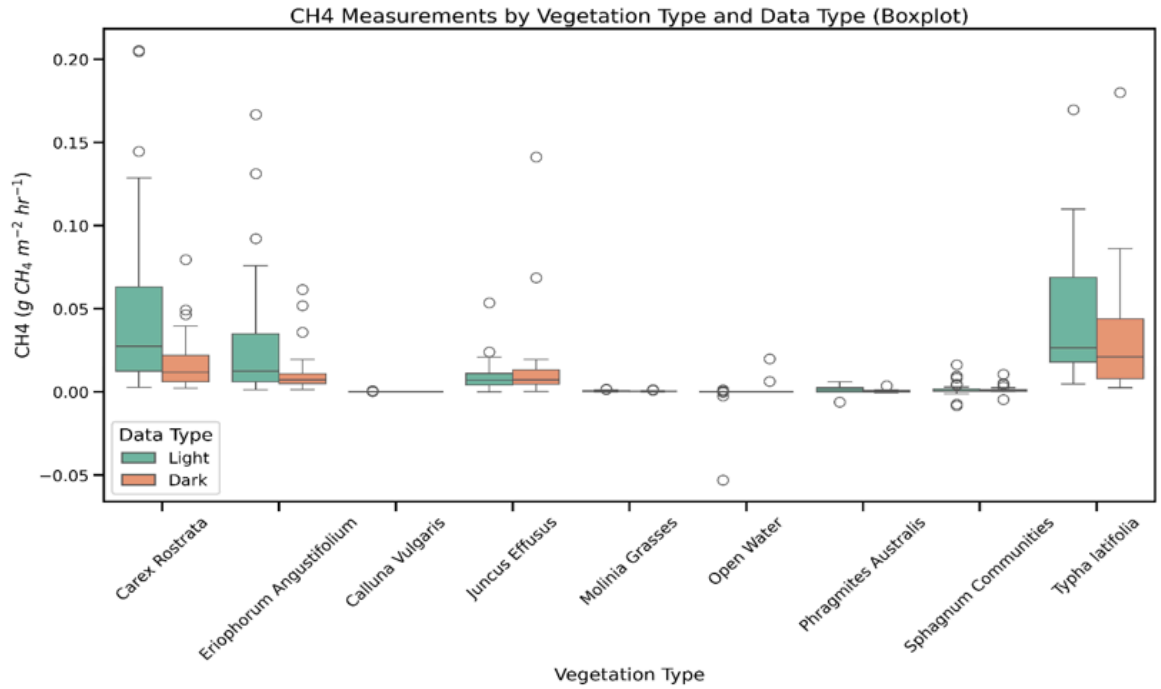

Figure 3

Highlights that the vegetation communities like *Carex rostrata* and *Eriophorum angustifolium* had notable differences in median and upper quartile values while other species like *Calluna Vulgaris, Juncus effusus, Molinia Caerulea* and *Sphagnum* communities showed only minor or no differences between light and dark conditions

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplementarymaterial1.docx