LIMNOLOGY and OCEANOGRAPHY LETTERS

ASLO

Open Access

Limnology and Oceanography Letters 11, 2026, e70150

doi: 10.1002/lol2.70150

LETTER

Methane emissions from canals draining tropical peatlands: Constraining temporal variability and emissions pathways

Clarice R. Perryman [1]* **Jennifer C. Bowen** [1a] **Desi Silviani Putri Aulian Barry** [2] **Erin Dayanti** [3] **Yulita Andriyani** [2] **Ruby L. Gates** [1] **Nisa Novita** [4] **Gusti Z. Anshari** [2,3] **Alison M. Hoyt** [1]

[1]Department of Earth System Science, Stanford University, Stanford, California, USA; [2]Department of Soil Science, Tanjungpura University, Pontianak, Indonesia; [3]Magister of Environmental Science, Tanjungpura University, Pontianak, Indonesia; [4]Yayasan Konservasi Alam Nusantara, Jakarta, Indonesia

Scientific Significance Statement

Canals draining tropical peatlands may be a significant source of methane emissions, but to date there is a critical lack of information about the temporal variability and pathways of methane emissions from tropical canals. Here, we address these key uncertainties using a year-round dataset of methane emissions, including previously lacking direct measurements of methane ebullition, and dissolved methane from canals draining peatlands in Indonesia. Our results provide evidence that diffusion is the predominant pathway of canal methane emissions throughout the year, and that precipitation shapes temporal variation in diffusive methane emissions on monthly to weekly timescales by regulating the extent of water column methane oxidation.

Abstract

Drainage canals are potential hotspots of methane (CH_4) emissions from degraded peatlands in Southeast Asia. Estimates of CH_4 emissions from these canals remain scarce, and both the temporal variability and pathways of CH_4 emissions are uncertain. Here, we present a year-round study of CH_4 emissions from canals draining peatlands in Southeast Asia. We quantified diffusive and ebullitive fluxes and tracked canal CH_4 dynamics by measuring $\delta^{13}C$-CH_4. Diffusion was the primary pathway of CH_4 fluxes throughout the year, accounting for > 80% of net CH_4 emissions. Periods of low rainfall limited CH_4 oxidation and enhanced diffusive CH_4 emissions, particularly in canals blocked to rewet the adjacent peat soils. By synthesizing data from past studies, we find an apparent decrease in canal CH_4 emissions with time following peatland drainage. Our results highlight the importance of considering seasonal to decadal variation in efforts to include drainage canals in the global CH_4 budget.

*Correspondence: crperry@stanford.edu

[a]Present address: School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia, USA

Associate Editor: Paul del Giorgio

Special Issue: Methane in Freshwater, Brackish and Marine Environments

Inland waters emit ~110 Tg methane (CH_4) per year (Saunois et al. 2025), and half of these emissions are due to anthropogenic impacts like the construction of reservoirs, land use change, and eutrophication (Jackson et al. 2024). Ditches and canals constructed to drain wet soils are estimated to emit ~4 Tg CH_4 y^{-1} (Peacock et al. 2021), but these emissions are not yet included in global budgets. Methane emissions from tropical ditches and canals are estimated to be larger than those in the northern latitudes (Gan et al. 2024; Peacock et al. 2021), but to date there have been few efforts to quantify CH_4 emissions from tropical canals. Canals draining tropical peatlands represent ~11% of global drainage ditch area and ~33% of the total area of ditches in drained peatlands (Gan et al. 2024; Günther et al. 2020; Peacock et al. 2021). As such, constraining the magnitude and variability of CH_4 emissions from canals in tropical peatlands is a critical step toward including drainage ditch emissions in global budgets.

Several key uncertainties remain about CH_4 emissions from canals draining tropical peatlands, including their temporal variability, transport pathways, and the impact of the land use history. Past efforts to characterize the seasonality of canal emissions find conflicting results about whether CH_4 emissions are larger during periods of high (Manning et al. 2019) or low (Jauhiainen and Silvennoinen 2012; Kent 2019) precipitation. Furthermore, while ebullition is a major pathway of aquatic CH_4 emissions, including from ditches draining northern peatlands (Hendriks et al. 2024; Vermaat et al. 2011), to date only one study has investigated CH_4 ebullition from canals draining tropical peatlands (Kasak et al. 2025). Lastly, while CH_4 emissions from tropical peat soils vary with land use history (Cooper et al. 2020; Hergoualc'h and Verchot 2014), the impact of land use history on canal CH_4 emissions remains uncertain.

Here, we address key uncertainties about the temporal variability and pathways of CH_4 emissions from canals draining tropical peatlands in Southeast Asia. Canal emissions are particularly important to landscape-scale CH_4 budgets of Southeast Asian peatlands, as canals are present in over two-thirds of the peatlands in this region (Dadap et al. 2021). While canals represent <5% of the area of drained peatlands (Drösler et al. 2014), on a per area basis canal CH_4 emissions are substantially larger than emissions from drained peat soils (Manning et al. 2019). As such, on a landscape-level CH_4 emissions from canals can counterbalance reductions in peat soil CH_4 emissions after drainage (Deshmukh et al. 2020; Wong et al. 2025). To evaluate the temporal variability and pathways of canal CH_4 emissions, we conducted year-round sampling of canals draining peat soils in a smallholder mixed agriculture area in West Kalimantan, Indonesia. We quantified diffusive and ebullitive CH_4 emissions and tracked changes in the stable isotope composition of CH_4 in canal waters ($\delta^{13}C$-CH_4) to understand how CH_4 dynamics in canals vary across time.

Methods

We investigated the temporal variability and pathways of CH_4 emissions from five canal reaches in a smallholder mixed agriculture area in Limbung Village, Kubu Raya Regency, West Kalimantan, Indonesia (Fig. 1; Supporting Information Table S1). Peatlands in this region were deforested and drained for conversion to agricultural land in the 1970s (Anshari et al. 2022). Two of the sites were blocked by dams in 2021 to raise the groundwater level of the adjacent peat soils (Blocked-1 and Blocked-2) and two of the sites were free-flowing (Flowing-1 and Flowing-2). Another site was also free-flowing but had intermittent flow, such that while the canal bottom was never completely dry there were periods during which water did not cover the entire canal bottom (Intermittent). Flowing-1 and Flowing-2 had abundant aquatic vegetation and average water velocity of ~0.10 m s^{-1}. Sites Blocked-1, Blocked-2, and Intermittent lacked vegetation and often had non-detectable flow velocities.

Canal CH_4 emissions were estimated biweekly over a 16-month period between July 2023 and October 2024 (Supporting Information Table S2). At each site, we collected surface water samples in 12 mL Exetainer™ (Labco Ltd.) vials without headspace and acidified samples in the field to a pH < 2 using 1.5 M hydrochloric acid. Alongside sample collection, we measured the depth of water in the canal and the distance from the peat surface to the canal water surface (i.e., peatland water table depth), as well as water temperature, pH (HANNA HI8424), and dissolved oxygen (Milwaukee MW600). Water samples collected in the Exetainer vials were analyzed for CH_4 concentration and $\delta^{13}C$-CH_4 using a Picarro G2210-*i* following headspace equilibration (Supporting Information Text S1). Following analysis, we calculated dissolved CH_4 concentrations using the *neonDissGas* package (Cawley et al. 2020).

To estimate diffusive CH_4 fluxes, we determined gas transfer velocities (k, in m d^{-1}) using a floating chamber and manual headspace gas sampling (Supporting Information Text S2). We collected floating chamber fluxes on three dates in September and October 2024 alongside water samples for the measurement of dissolved CH_4 concentrations. We also used data reported in Perryman et al. (2024) from May 2023 for sites Blocked-1, Blocked-2, and Flowing-1. We calculated *k* using Eq. 1:

$$CH_4\,\text{Flux} = k\left(CH_{4-\text{canal}} - CH_{4-\text{eq}}\right) \quad (1)$$

As we did not observe expected relationships between *k* and factors like wind speed or canal discharge (Supporting Information Fig. S1), we used the mean *k* value by flow regime (flowing vs. stagnant, Supporting Information Fig. S1) to estimate diffusive fluxes across the study period. As sites

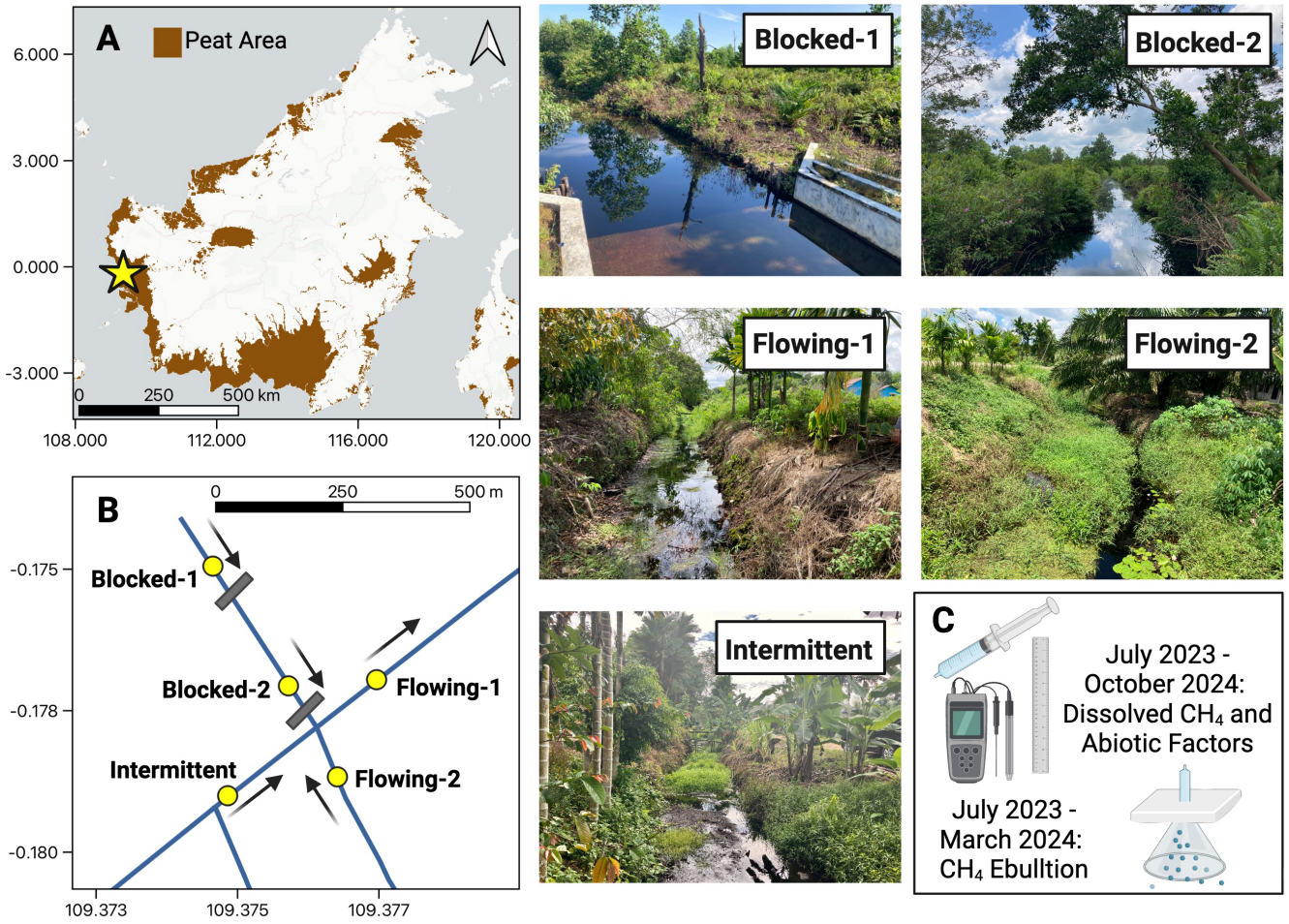

Fig. 1. (**A**) Location of study sites in West Kalimantan, Indonesia (yellow star) relative to peatland areas (brown; Greifswald Mire Centre 2022) across Borneo. (**B**) Study site map showing locations of all canal sampling sites (yellow dots) and water flow directions (black arrows). Gray boxes represent dams blocking canal flow. Photos of each sampling site (Blocked-1, Blocked-2, Flowing-1, Flowing-2, and Intermittent) are shown to the right of panels A and B. (**C**) Graphical summary of data collection from July 2023 to October 2024.

Blocked-1, Blocked-2, and Intermittent generally had non-detectable flow velocities, these sites were all considered stagnant. We calculated fluxes using the mean $k \pm$ standard error to characterize the uncertainty in our diffusive flux estimates.

To estimate CH_4 ebullition, we installed duplicate "bubble traps" made from ~200 cm^2 inverted funnels in Blocked-1 and Flowing-1 in July 2023 and in Blocked-2 and Intermittent in October 2023. We sampled gas accumulated in the traps at least weekly until March 2024 and stored gas samples in pre-evacuated Exetainer vials until analysis via GC-FID (Shimadzu GC-2014). We calculated ebullitive fluxes from the concentration of CH_4 in bubble samples, bubble volume, the length of time gas accumulated, and the area of the bubble traps following Wik et al. (2013).

To assess the potential for plant-mediated transport, we conducted a synoptic survey of CH_4 fluxes using a floating chamber in canal reaches with and without aquatic vegetation. A 3.4 L/240 cm^2 opaque floating chamber was placed atop areas within the canals with open water, emergent vegetation, or floating vegetation (Supporting Information Table S3). We made flux measurements using a LICOR 7810 in canals Flowing-1, Flowing-2, and five other canals within a ~1 km radius in April 2024. Fluxes were calculated using *FluxCalR* (Zhao 2019).

Finally, we compiled past estimates of CH_4 emissions and dissolved CH_4 concentration from canals across Southeast Asia to assess the impact of land use and drainage history. We identified 5 studies reporting CH_4 emissions and 4 reporting dissolved CH_4 concentrations with adequate drainage history and land use information (Supporting Information Tables S4 and S5). Drainage history was defined as the number of years between peatland conversion and data collection, as reported by authors. For fluxes, we recorded mean fluxes by site following Peacock et al. (2021). If a study reported CH_4 emissions

from more than one site from the same land use, we report a mean for each site. Our synthesis focused on diffusive CH_4 emissions, as to date only 2 studies (Kasak et al. 2025 and this study) report CH_4 ebullition. All data were converted to consistent units of mg CH_4 m^{-2} d^{-1} and μM CH_4.

All meteorological data presented here are from the Supadio International Airport Meteorological Station, located ~ 5 km from our study sites, from the Indonesia Meteorology, Climatology, and Geophysical Agency (https://www.bmkg.go.id/). We conducted all data analysis and visualization in R v.4.4.1 using the *dplyr, ggplot2*, and *patchwork* packages (Pedersen 2020; Wickham 2016; Wickham et al. 2021). Dissolved CH_4 concentration and fluxes were $\log_{10}$ transformed to improve normality prior to statistical analysis. We used the Kruskal–Wallis *H*-Test and Kendall's Rank Correlation to test for (1) differences between canal reaches and (2) potential correlations between variables, respectively. All data and metadata are available via Zenodo (Perryman 2025). Below, values are reported as mean ± one standard deviation.

Results and discussion

Methane emissions pathways in tropical canals

Our year-round study revealed that diffusive CH_4 fluxes varied approximately 50-fold over time (Fig. 2A), with individual fluxes varying from 4.3 to 196.8 mg CH_4 m^{-2} d^{-1}. While we observed episodically large (≥ 100 mg CH_4 m^{-2} d^{-1}) emissions from site Blocked-1, on average the two flowing canals had larger diffusive fluxes (51.4 ± 15.3 mg CH_4 m^{-2} d^{-1}) than the three canals with stagnant water (28.4 ± 41.0 mg CH_4 m^{-2} d^{-1}, Kruskal–Wallis $\chi^2 = 58.6$, $p < 0.001$). This pattern is consistent with past observations from ditches in boreal peatlands drained for forestry

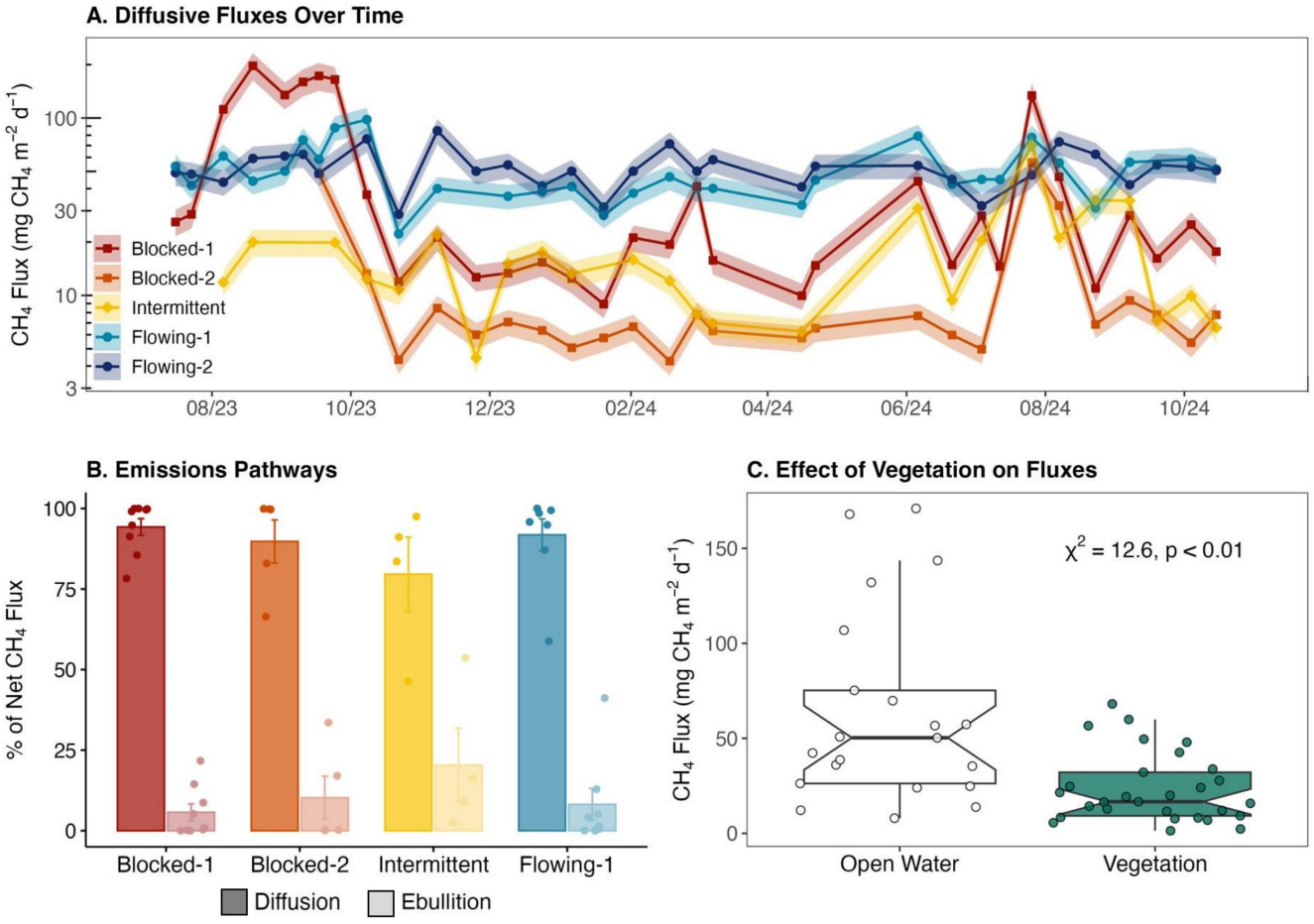

Fig. 2. (**A**) Estimated diffusive CH_4 fluxes over time for stagnant (warm colors, Blocked-1, Blocked-2, and Intermittent) and flowing canals (cool colors, Flowing-1 and Flowing-2). The y-axis is displayed on a $\log_{10}$ scale. The shaded area around each line represents diffusive CH_4 fluxes estimated using ± 1 standard error of the measured gas transfer velocity (k) for stagnant and flowing canals. (**B**) Proportion of net CH_4 emissions via diffusion (darker shade) and ebullition (lighter shade) from all canals instrumented with bubble traps. Bars show the mean ± standard error of monthly contributions from each pathway and points indicate individual monthly contributions. (**C**) Methane fluxes measured using a floating chamber from reaches in canals without vegetation (open water, white) and with aquatic vegetation (green) in April 2024, $n = 7$ canals. Overlain points represent individual flux measurements.

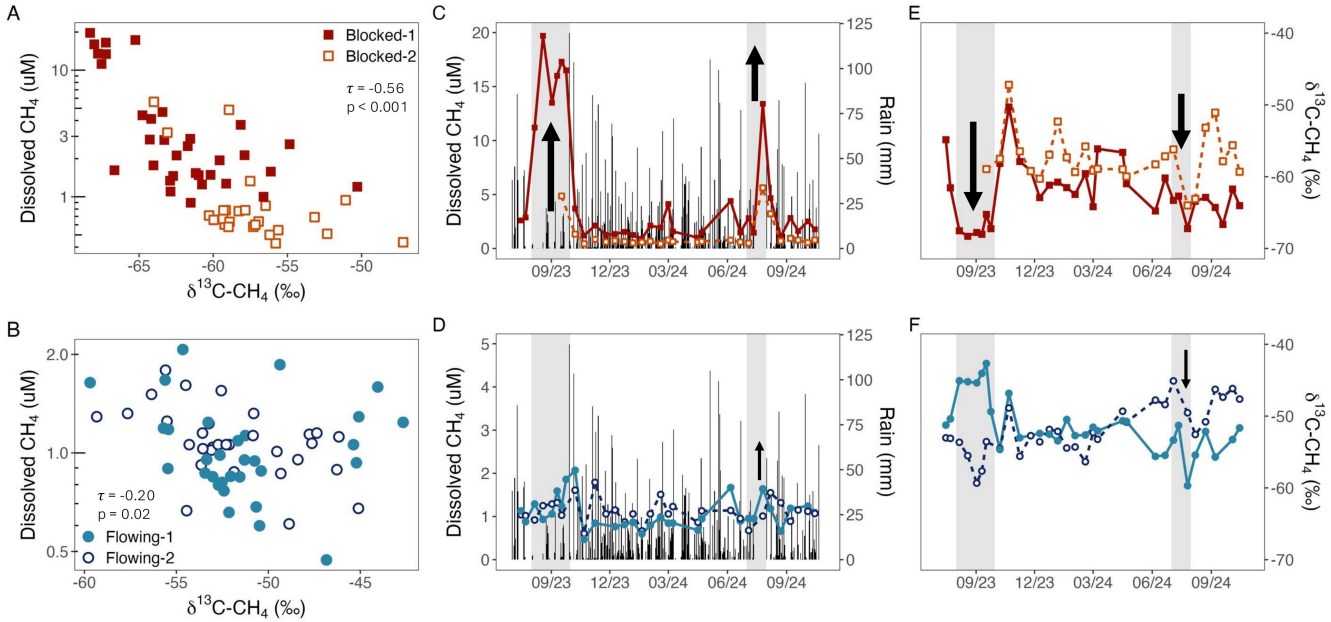

Fig. 3. Dissolved CH_4 concentration and $\delta^{13}C$-CH_4 in blocked (**A**, **C**, and **E**) and flowing (**B**, **D**, and **F**) canals. (A and B) Scatterplots show negative correlation between log_{10}-transformed CH_4 concentration and $\delta^{13}C$-CH_4. Text annotations report results from Kendall's rank correlation tests. Time series of CH_4 concentration and rainfall (C and D) and time series of $\delta^{13}C$-CH_4 (E and F) in blocked and flowing canals. Different color points and lines represent different canals according to legends in panels A and B. Gray boxes show months with low precipitation, including at least one period of ≥ 7 consecutive days without rainfall. Black arrows in panels C to F indicate paired increases in dissolved CH_4 concentration and decreases in $\delta^{13}C$-CH_4 during dry periods.

(Minkkinen and Laine 2006). While stagnant canals are prone to developing anoxic conditions that allow for CH_4 to accumulate in canal waters (Waldron et al. 2019), the gas transfer velocity in the stagnant canals was ~ 5x lower than the flowing canals (Supporting Information Figs. S1 and S2), limiting the degassing of CH_4 from the stagnant canal waters. Our measurements from the blocked canals are from the stagnant upstream side of the blockages; however, it is likely that the CH_4 in these waters is rapidly degassed when canal water levels are high enough to flow over the blockages as observed in waterfalls in natural streams (Rust et al. 2025).

Furthermore, we found that diffusion was the dominant pathway of canal CH_4 emissions. Ebullitive CH_4 fluxes were lower than diffusive CH_4 fluxes in all months in which both measurements occurred. Across individual canals mean ebullitive fluxes were 1.0 ± 2.6 to 4.9 ± 11.9 mg CH_4 m^{-2} d^{-1} (Supporting Information Fig. S3), which on a monthly basis represented between $5.7 \pm 7.8\%$ and $20.4 \pm 22.9\%$ of net CH_4 emissions (Fig. 2B; Supporting Information Table S1). We observed lower ebullitive emissions than previously reported from ditches in temperate and boreal peatlands, but our estimate of the proportion of net CH_4 emissions from ebullition falls within the range of < 1% to > 60% observed in northern peatlands (Hendriks et al. 2024; Minkkinen et al. 1997; Minkkinen and Laine 2006; Vermaat et al. 2011). While aquatic vegetation can also be a conduit for CH_4 emissions due to plant-mediated gas transport (Bodmer et al. 2024; Vroom et al. 2022), we found that fluxes from vegetated canal reaches were lower than those from open water reaches (Kruskal–Wallis $\chi^2 = 12.6$, $p < 0.01$; Fig. 2C). When broken down by vegetation type, CH_4 fluxes from both emergent and floating vegetation were lower than from open water ($\chi^2 = 13.0$, $p < 0.01$; Supporting Information Fig. S4). Methane fluxes may be lower in vegetated canals due to enhanced CH_4 oxidation (Perryman et al. 2024; Struik et al. 2026), suppressed methanogenesis (Jespersen et al. 1998), and/or decreased gas transfer velocity (Kosten et al. 2016). Overall, our results support that diffusion is the primary pathway of CH_4 emissions from canals draining tropical peatlands.

Impact of rainfall on canal CH_4 dynamics over time

To understand what processes shape the temporal variability of diffusive CH_4 emissions, we tracked changes in the concentration and $\delta^{13}C$ of dissolved CH_4 in canal waters. Within a given canal, we observed ~ 15‰ variation in $\delta^{13}C$-CH_4 over time (Supporting Information Table S1), which we suggest reflects a significant role of CH_4 oxidation in canal CH_4 dynamics. Although both microbial CH_4 oxidation and diffusion leave residual CH_4 enriched in ^{13}C, the isotopic fractionation of CH_4 oxidation (~ 1.025; Coleman et al. 1981) has been shown to greatly exceed that of diffusion (~ 1.008; Happell et al. 1995; Knox et al. 1992). For example, diffusion across the water-air interface increases the $\delta^{13}C$ of residual CH_4 by ~ 1–2‰ (Chanton 2005) while oxidation in tropical

canal waters increases δ^{13}C-CH_4 by ~20‰ (Perryman et al. 2024). Furthermore, the concentration and δ^{13}C of CH_4 of peat porewater draining to canals in Southeast Asia is relatively constant throughout the year (Somers et al. 2023; Taillardat et al. 2025), so variation in canal water CH_4 concentration and δ^{13}C are also unlikely to be driven by temporal changes in source δ^{13}C-CH_4.

We observed coincident shifts in the concentration and δ^{13}C of CH_4 in canal waters over time, with δ^{13}C-CH_4 values increasing as dissolved CH_4 concentration decreased (Fig. 3A,B; $p < 0.05$ for Kendall's rank correlations). The paired changes in δ^{13}C-CH_4 and dissolved CH_4 concentration further support that shifts in δ^{13}C-CH_4 are associated with CH_4 oxidation. This correlation has been observed previously in spatial studies of tropical canals (Perryman et al. 2024) and rivers (Sawakuchi et al. 2016), indicating that CH_4 oxidation significantly influences spatial variation in aquatic CH_4 emissions. Here, our results indicate that CH_4 oxidation also influences the temporal variability of tropical canal CH_4 emissions.

Temporal patterns of canal water CH_4 concentration and δ^{13}C-CH_4 during the study period suggest that precipitation has a strong effect on water column CH_4 oxidation. In the blocked canals, we observed two notable peaks in CH_4 concentration (≥ 5 μM) during our measurement campaign, one in August through September 2023 and another in July 2024 (Fig. 3C). All three of these months had low cumulative precipitation (Supporting Information Table S6) and at least one period of ≥7 consecutive days without rainfall. During both intervals, CH_4 concentrations in the blocked canals increased by up to 10-fold and δ^{13}C-CH_4 decreased by > 5‰ (Fig. 3C,E). The paired increase in dissolved CH_4 concentration and decrease in δ^{13}C-CH_4 suggests that decreased CH_4 oxidation led to the episodically large CH_4 emissions observed from blocked canals during these months (Fig. 2A). Due to limited input of oxygenated rainwater, evaporation, and stagnation during low precipitation periods, dissolved oxygen was ~50% lower in blocked canals during dry months than months with typical or above average rainfall (Fig. 4A; dry = 0.23 ± 0.15 mg L^{-1}, normal = 0.44 ± 0.38 mg L^{-1}, wet = 0.50 ± 0.37 mg L^{-1}) which likely limited aerobic CH_4 oxidation in these canals (Perryman et al. 2024).

Conversely, we observed a sharp decrease in dissolved CH_4 concentration (Fig. 3C) and diffusive CH_4 fluxes (Fig. 2A) from blocked canals following large rain events. For example, dissolved CH_4 decreased by 4–10-fold in the blocked canals from the dry periods to weeks immediately following with > 100 mm of cumulative rainfall. Rainwater may dilute the CH_4 concentration in canal waters and diffusive exchange during rainfall events may increase δ^{13}C-CH_4 by ~1–2‰ (Chanton 2005), but these processes alone are unlikely to produce the large (4.4–12.0‰) increase in δ^{13}C-CH_4 we observed alongside drops in CH_4 concentration (Fig. 3C,E). Rainfall provides opportunities for mixing and aeration in blocked canals after prolonged periods of stagnant, hypoxic waters (Liu et al. 2020; Zhu et al. 2018), enabling rapid consumption of CH_4 in the water column by aerobic methanotrophs. Supporting this idea, we observed that in blocked canals dissolved CH_4 decreases and δ^{13}C-CH_4 increases as the cumulative precipitation the week before sampling increases (Fig. 4B,C; $p < 0.01$ for both).

Compared to blocked canals, flowing canals had a more muted response to rainfall. For example, during the 3-week period without rain in July 2024 there was only a ~1.5-fold increase in dissolved CH_4 in flowing canals (Fig. 3D). Unlike in blocked canals, dissolved oxygen did not decrease during dry months in flowing canals (Fig. 4A). Beyond aeration via flow, vegetation in the flowing canals may deliver oxygen to the canal waters via radial oxygen loss from submerged roots (Girkin et al. 2020a; Heilman and Carlton 2001) and promote more consistent rates of CH_4 oxidation over time. The lack of significant correlations between rainfall and dissolved CH_4 concentration or δ^{13}C-CH_4 in flowing canals (Fig. 4B,C) suggests that precipitation has a lesser impact on CH_4 oxidation, and by extension diffusive CH_4 fluxes, in flowing canals than in blocked canals.

Impact of land use and drainage history on canal CH_4 emissions

Our measurements of CH_4 emissions from canals draining tropical peatlands under smallholder agriculture indicate that average diffusive emissions are 38.3 ± 34.5 mg CH_4 m^{-2} d^{-1} and ebullitive emissions are 3.0 ± 8.0 mg CH_4 m^{-2} d^{-1}. Our estimate is on the lower end of previous estimates of diffusive CH_4 emissions from canals in Southeast Asia, which range from 13.1 ± 12.3 to 1073 ± 1744 mg CH_4 m^{-2} d^{-1} (Supporting Information Table S4 and references therein). Comparing our study sites to those from past efforts, we note two key differences. Firstly, we sampled canals draining peat soils under smallholder agriculture, while past work focused on emissions from canals in timber and oil palm plantations (Jauhiainen and Silvennoinen 2012; Kasak et al. 2025; Manning et al. 2019) or deforested but uncultivated land (Jauhiainen and Silvennoinen 2012; Kent 2019). Secondly, the peat soils in our focal area were drained in the 1970s (Anshari et al. 2022), compared to past efforts that quantify emissions from canals on peatlands drained in the 1990s-2010s. Both current land use and the length of time peat soils have been drained can influence CH_4 production in tropical peatlands (Cooper et al. 2019; Girkin et al. 2020b). As the major source of CH_4 in canal waters is the adjacent drained peat soils (Somers et al. 2023), peatland land use and drainage history may also impact canal CH_4 emissions.

To assess the impact of land use history, we synthesized CH_4 emissions estimates from canals across Southeast Asia (Supporting Information Table S4). When all land uses are considered together, we find an apparent decrease in canal CH_4 emissions over time following drainage (Fig. 5; Kendall's

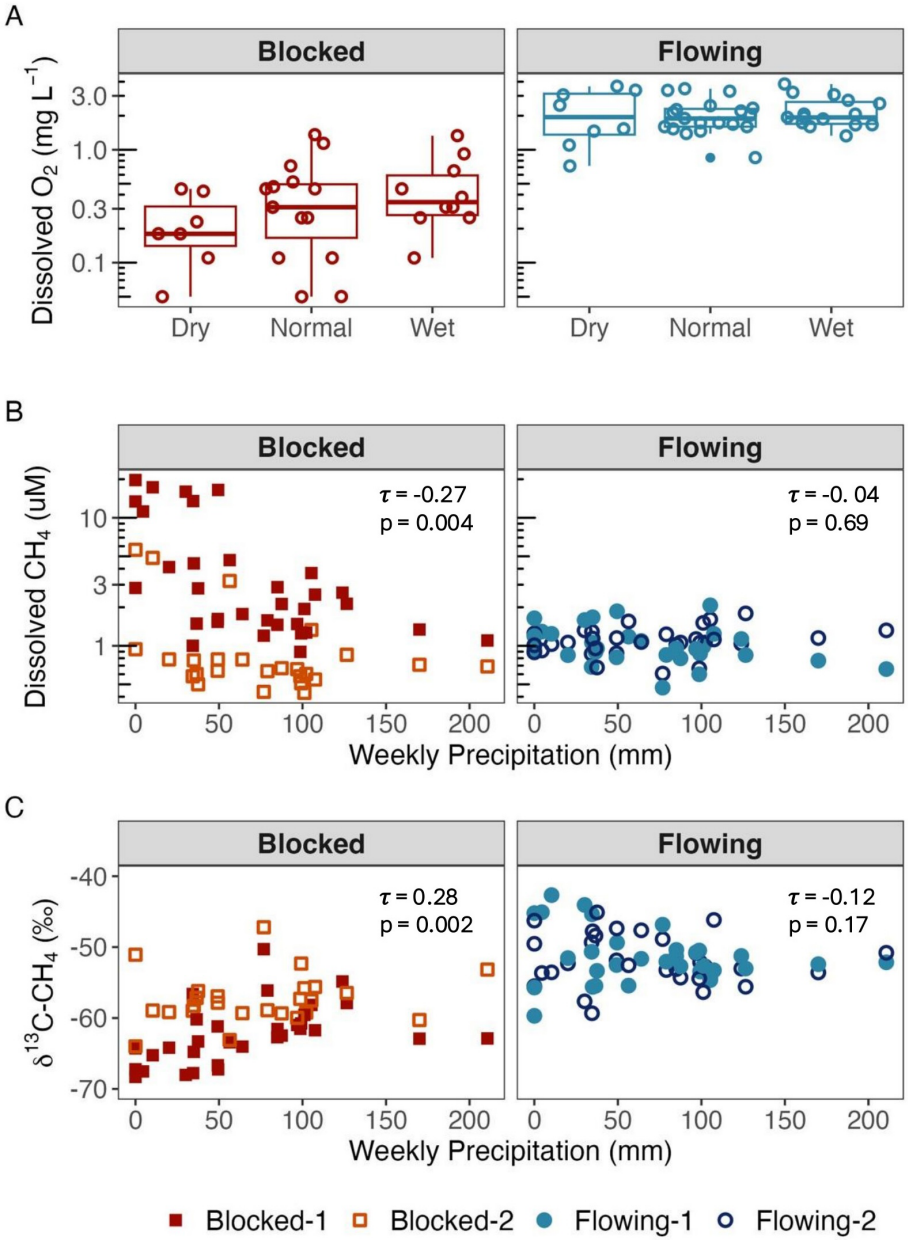

Fig. 4. (**A**) Dissolved oxygen concentration (mg L^{-1}) measured at the surface (0–5 cm depth) in blocked (Blocked-1 and Blocked-2) and flowing (Flowing-1 and Flowing-2) canals during dry months, months with average cumulative precipitation (200–350 mm), and wet months with above average cumulative precipitation. Overlain points represent individual flux measurements. (**B** and **C**) Scatterplots of cumulative precipitation the 7 days prior to sample collection vs. (B) dissolved CH_4 concentration and (C) $\delta^{13}C$-CH_4 in blocked and flowing canals. Each point is an individual measurement. Annotations in B and C report results from Kendall's rank correlation tests. Note the y-axis is displayed on a $\log_{10}$ scale in panels A and B.

$\tau = -0.59$, $p = 0.004$). Reports of CH_4 emissions from more recently constructed canals are largely from timber and oil palm plantations, which could confound the apparent changes in canal CH_4 emissions with time since drainage. However, when the impact of time since drainage on canal CH_4 emissions is assessed for plantations alone, a similar negative correlation is observed (Kendall's $\tau = -0.56$, $p = 0.06$), suggesting that time since drainage impacts canal CH_4 emissions independent of land use. Drained and cultivated peat soils become increasingly degraded over time from enhanced decomposition (Könönen et al. 2016), as shown by a 35% reduction in labile organic matter between young and mature oil palm plantations (Cooper et al. 2019). Methanogens also become less abundant in peat soils after drainage (Bandla

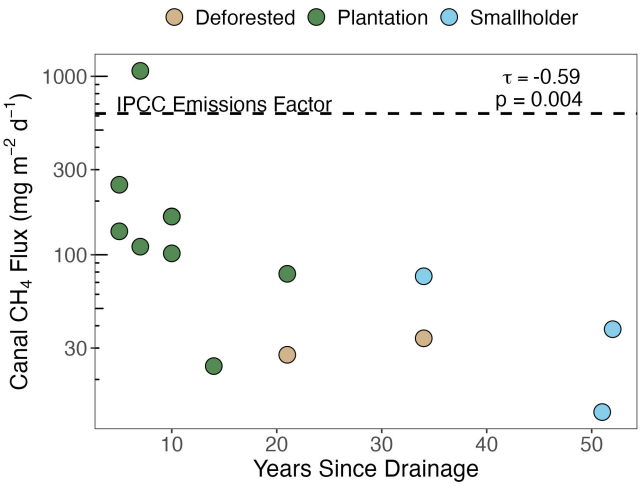

Fig. 5. Methane emissions (expressed per unit of canal water surface area) across canals draining peat soils in Indonesia and Malaysia vs. the approximate amount of time (in years) between canal construction to drain peat soils and canal CH_4 flux measurements. Flux values on the y-axis are displayed on a $\log_{10}$-scale. The text annotation reports the result of a Kendall's rank correlation test. The dashed black line shows the value listed as the emissions factor for canals in tropical peatlands in the IPCC 2013 Wetlands Supplement. Data from Jauhiainen and Silvennoinen (2012), Kasak et al. (2025), Kent (2019), Manning et al. (2019), Perryman et al. (2024), and this study.

et al. 2023; Midot et al. 2025). Combined, these factors limit peat CH_4 production, and therefore potential canal CH_4 emissions, over time following drainage.

We did not find a correlation between canal water CH_4 concentration and time since drainage (Supporting Information Fig. S5). However, there is little overlap in studies characterizing canal CH_4 emissions and dissolved CH_4, limiting our ability to infer if the apparent decrease in CH_4 emissions over time following drainage is due to CH_4 supply or other factors. If CH_4 concentrations do not vary with time since drainage, other factors like unmaintained canals infilling with debris and aquatic vegetation may decrease flow and degassing (Supporting Information Fig. S1), reducing CH_4 emissions over time.

As emissions from canals can offset reductions in peat soil CH_4 emissions after drainage (Deshmukh et al. 2020; Wong et al. 2025), constraining canal emissions is critical to developing robust landscape-level estimates of CH_4 emissions from drained tropical peatlands. Our synthesis showed that reported CH_4 emissions from canals draining tropical peatlands with diverse land use histories are lower than the IPCC Emissions Factor from the 2013 Wetlands Supplement (Fig. 5; Hiraishi et al. 2013). The emissions factor is derived from a single study focused primarily on canals in a ~ 5-year-old pulp wood plantation sampled only during notably dry and wet months of the year (Jauhiainen and Silvennoinen 2012). Following a similar sampling schedule, we would estimate that canal CH_4 emissions are ~ 40% higher than we observed via our year-round monitoring (Supporting Information Table S7). Taken together, our new measurements and data synthesis demonstrate that further refinements of the CH_4 emissions factor for canals draining tropical peatlands should consider temporal variation alongside land use for accurate inclusion of canals in the global CH_4 budget.

Author Contributions

The study was conceived by Clarice R. Perryman, Jennifer C. Bowen, and Alison M. Hoyt. The study was designed and led by Clarice R. Perryman. Field and laboratory data collection was conducted by Clarice R. Perryman, Jennifer C. Bowen, Desi Silviani Putri Aulian Barry, Erin Dayanti, Yulita Andriyani, and Ruby L. Gates. Nisa Novita and Gusti Z. Anshari provided access to field sites, laboratory space, and analytical instrumentation. Funding for this work was acquired by Clarice R. Perryman and Alison M. Hoyt. Clarice R. Perryman led the data analysis and visualization and wrote the original draft of the manuscript. All authors contributed to reviewing and editing the manuscript.

Acknowledgments

The research was supported by the NSF Earth Sciences Postdoctoral Research Fellowship (Award ID 2305578, Clarice R. Perryman), the Precourt Institute for Energy (Clarice R. Perryman, Desi Silviani Putri Aulian Barry, Yulita Andriyani, Erin Dayanti, Jennifer C. Bowen, Ruby L. Gates, Alison M. Hoyt), and the Stanford Woods Institute for the Environment (Alison M. Hoyt, Ruby L. Gates). Alison M. Hoyt was also supported in part by National Science Foundation Award 2406964. This research was conducted under permit #37/SIP/IV/FR/1/2024 from the Indonesian National Research and Innovation Agency (BRIN). We thank Anggit Djoko Wibowo for his contributions to fieldwork and Rob Jackson and Colin Finnegan (Stanford University) for access to and assistance with the Picarro CRDS used to analyze samples.

Conflicts of Interest

None declared.

Data Availability Statement

Data and metadata are available in the Zenodo repository at: https://doi.org/10.5281/zenodo.15678483.

References

Anshari, G. Z., E. Gusmayanti, M. Afifudin, M. Ruwaimana, L. Hendricks, and D. G. Gavin. 2022. "Carbon Loss From a Deforested and Drained Tropical Peatland Over Four Years as Assessed From Peat Stratigraphy." *Catena* 208: 105719. https://doi.org/10.1016/j.catena.2021.105719.

Bandla, A., S. Mukhopadhyay, S. Mishra, A. S. Sudarshan, and S. Swarup. 2023. "Genome-Resolved Carbon Processing Potential of Tropical Peat Microbiomes From an Oil Palm Plantation." *Scientific Data* 10, no. 1: 373. https://doi.org/10.1038/s41597-023-02267-z.

Bodmer, P., R. J. E. Vroom, T. Stepina, P. A. Del Giorgio, and S. Kosten. 2024. "Methane Dynamics in Vegetated Habitats in Inland Waters: Quantification, Regulation, and Global Significance." *Frontiers in Water* 5: 1332968. https://doi.org/10.3389/frwa.2023.1332968.

Cawley, K., K. Goodman, S. Weintraub, and S. Parker. 2020. "*Neon User Guide to Dissolved Gases in Surface Water*." (DP1.20097.001) neonDissGas package. [Dataset].

Chanton, J. P. 2005. "The Effect of Gas Transport on the Isotope Signature of Methane in Wetlands." *Organic Geochemistry* 36, no. 5: 753–768. https://doi.org/10.1016/j.orggeochem.2004.10.007.

Coleman, D. D., J. B. Risatti, and M. Schoell. 1981. "Fractionation of Carbon and Hydrogen Isotopes by Methane-Oxidizing Bacteria." *Geochimica et Cosmochimica Acta* 45, no. 7: 1033–1037. https://doi.org/10.1016/0016-7037(81)90129-0.

Cooper, H. V., S. Evers, P. Aplin, N. Crout, M. P. B. Dahalan, and S. Sjogersten. 2020. "Greenhouse Gas Emissions Resulting From Conversion of Peat Swamp Forest to Oil Palm Plantation." *Nature Communications* 11, no. 1: 407. https://doi.org/10.1038/s41467-020-14298-w.

Cooper, H. V., C. H. Vane, S. Evers, P. Aplin, N. T. Girkin, and S. Sjögersten. 2019. "From Peat Swamp Forest to Oil Palm Plantations: The Stability of Tropical Peatland Carbon." *Geoderma* 342: 109–117. https://doi.org/10.1016/j.geoderma.2019.02.021.

Dadap, N. C., A. M. Hoyt, A. R. Cobb, et al. 2021. "Drainage Canals in Southeast Asian Peatlands Increase Carbon Emissions." *AGU Advances* 2, no. 1: e2020AV000321. https://doi.org/10.1029/2020AV000321.

Deshmukh, C. S., D. Julius, C. D. Evans, et al. 2020. "Impact of Forest Plantation on Methane Emissions From Tropical Peatland." *Global Change Biology* 26, no. 4: 2477–2495. https://doi.org/10.1111/gcb.15019.

Drösler, M., L. V. Verchot, A. Freibauer, et al. 2014. "Drained Inland Organic Soils." In *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*, edited by T. Hiraishi, T. Krug, K. Tanabe, N. Srivastava, J. Baasansuren, M. Fukuda, and T. G. Troxler, 2.1–2.79. Geneva, Switzerland: IPCC.

Gan, D., Z. Zhang, H. Li, et al. 2024. "Ditch Emissions Partially Offset Global Reductions in Methane Emissions From Peatland Drainage." *Communications Earth & Environment* 5, no. 1: 640. https://doi.org/10.1038/s43247-024-01818-5.

Girkin, N. T., S. Dhandapani, S. Evers, N. Ostle, B. L. Turner, and S. Sjögersten. 2020*b*. "Interactions Between Labile Carbon, Temperature and Land Use Regulate Carbon Dioxide and Methane Production in Tropical Peat." *Biogeochemistry* 147, no. 1: 87–97. https://doi.org/10.1007/s10533-019-00632-y.

Girkin, N. T., C. H. Vane, B. L. Turner, N. J. Ostle, and S. Sjögersten. 2020*a*. "Root Oxygen Mitigates Methane Fluxes in Tropical Peatlands." *Environmental Research Letters* 15, no. 6: 064013. https://doi.org/10.1088/1748-9326/ab8495.

Greifswald Mire Centre. 2022. "*Global Peatland Map 2.0*." [Map]. https://wesrmapportal.unep.org/portal/apps/experiencebuilder/experience/?id=33b49f8757c441faae975671c2425241&page=Page.

Günther, A., A. Barthelmes, V. Huth, et al. 2020. "Prompt Rewetting of Drained Peatlands Reduces Climate Warming Despite Methane Emissions." *Nature Communications* 11, no. 1: 1644. https://doi.org/10.1038/s41467-020-15499-z.

Happell, J. D., J. P. Chanton, and W. J. Showers. 1995. "Methane Transfer Across the Water–Air Interface in Stagnant Wooded Swamps of Florida: Evaluation of Mass-Transfer Coefficients and Isotropic Fractionation." *Limnology and Oceanography* 40, no. 2: 290–298. https://doi.org/10.4319/lo.1995.40.2.0290.

Heilman, M. A., and R. G. Carlton. 2001. "Methane Oxidation Associated With Submersed Vascular Macrophytes and Its Impact on Plant Diffusive Methane Flux." *Biogeochemistry* 52: 207–224. https://doi.org/10.1023/A:1006427712846.

Hendriks, L., S. Weideveld, C. Fritz, et al. 2024. "Drainage Ditches Are Year-Round Greenhouse Gas Hotlines in Temperate Peat Landscapes." *Freshwater Biology* 69, no. 1: 143–156. https://doi.org/10.1111/fwb.14200.

Hergoualc'h, K., and L. V. Verchot. 2014. "Greenhouse Gas Emission Factors for Land Use and Land-Use Change in Southeast Asian Peatlands." *Mitigation and Adaptation Strategies for Global Change* 19, no. 6: 789–807. https://doi.org/10.1007/s11027-013-9511-x.

Hiraishi, T., T. Krug, K. Tanabe, eds., et al. 2013. *Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands: Methodological Guidance on Lands With Wet and Drained Soils, and Constructed Wetlands for Wastewater Treatment*. Hayama, Japan: IPCC, Intergovernmental Panel on Climate Change. https://www.ipcc.ch/site/assets/uploads/2018/03/Wetlands_Supplement_Entire_Report.pdf.

Jackson, R. B., M. Saunois, A. Martinez, et al. 2024. "Human Activities Now Fuel Two-Thirds of Global Methane Emissions." *Environmental Research Letters* 19, no. 10: 101002. https://doi.org/10.1088/1748-9326/ad6463.

Jauhiainen, J., and H. Silvennoinen. 2012. "Diffusion GHG Fluxes at Tropical Peatland Drainage Canal Water Surfaces." *Suoseura* 63, no. 3–4: 93–105. https://www.suoseura.fi/Alkuperainen/suo/pdf/Suo63_Jauhiainen.pdf.

Jespersen, D. N., B. K. Sorrell, and H. Brix. 1998. "Growth and Root Oxygen Release by Typha Latifolia and Its Effects on Sediment Methanogenesis." *Aquatic Botany* 61, no. 3: 165–180. https://doi.org/10.1016/S0304-3770(98)00071-0.

Kasak, K., I. Dronova, K. Soosaar, et al. 2025. "Greenhouse Gas Emissions From Ditches in Oil Palm Plantations on Tropical Peatlands in Malaysia." *Scientific Reports* 15, no. 1: 37126. https://doi.org/10.1038/s41598-025-21094-3.

Kent, M. S. 2019. *Greenhouse Gas Emissions From Channels Draining Intact and Degraded Tropical Peat Swamp Forest*. The Open University.

Knox, M., P. D. Quay, and D. Wilbur. 1992. "Kinetic Isotopic Fractionation During Air–Water Gas Transfer of O_2, N_2,

CH_4, and H_2." *Journal of Geophysical Research: Oceans* 97, no. C12: 20335–20343. https://doi.org/10.1029/92JC00949.

Könönen, M., J. Jauhiainen, R. Laiho, et al. 2016. "Land Use Increases the Recalcitrance of Tropical Peat." *Wetlands Ecology and Management* 24, no. 6: 717–731. https://doi.org/10.1007/s11273-016-9498-7.

Kosten, S., M. Piñeiro, E. De Goede, J. De Klein, L. P. M. Lamers, and K. Ettwig. 2016. "Fate of Methane in Aquatic Systems Dominated by Free-Floating Plants." *Water Research* 104: 200–207. https://doi.org/10.1016/j.watres.2016.07.054.

Liu, M., Y. Zhang, K. Shi, et al. 2020. "Effects of Rainfall on Thermal Stratification and Dissolved Oxygen in a Deep Drinking Water Reservoir." *Hydrological Processes* 34, no. 15: 3387–3399. https://doi.org/10.1002/hyp.13826.

Manning, F. C., L. K. Kho, T. C. Hill, T. Cornulier, and Y. A. Teh. 2019. "Carbon Emissions from Oil Palm Plantations on Peat Soil." *Frontiers in Forests and Global Change* 2: 37. https://doi.org/10.3389/ffgc.2019.00037.

Midot, F., K. M. Goh, K. J. Liew, et al. 2025. "Temporal Dynamics of Soil Microbial C and N Cycles With GHG Fluxes in the Transition From Tropical Peatland Forest to Oil Palm Plantation." *Applied and Environmental Microbiology* 91, no. 1: e01986-24. https://doi.org/10.1128/aem.01986-24.

Minkkinen, K., and J. Laine. 2006. "Vegetation Heterogeneity and Ditches Create Spatial Variability in Methane Fluxes From Peatlands Drained for Forestry." *Plant and Soil* 285, no. 1–2: 289–304. https://doi.org/10.1007/s11104-006-9016-4.

Minkkinen, K., J. Laine, H. Nykänen, and P. J. Martikainen. 1997. "Importance of Drainage Ditches in Emissions of Methane From Mires Drained for Forestry." *Canadian Journal of Forest Research* 27: 949–952. https://doi.org/10.1139/x97-016.

Peacock, M., J. Audet, D. Bastviken, et al. 2021. "Global Importance of Methane Emissions From Drainage Ditches and Canals." *Environmental Research Letters* 16, no. 4: 044010. https://doi.org/10.1088/1748-9326/abeb36.

Pedersen, T. L. 2020. "*Patchwork: The Composer of Plots*." (Version R package version 1.1.1) [Computer software]. https://CRAN.R-project.org/package=patchwork.

Perryman, C. R. 2025. *Methane Emissions From Canals Draining Peatlands in Southeast Asia: Field Measurements and Data Synthesis*. Zenodo. https://doi.org/10.5281/zenodo.15678483.

Perryman, C. R., J. C. Bowen, J. Shahan, et al. 2024. "Fate of Methane in Canals Draining Tropical Peatlands." *Nature Communications* 15, no. 1: 9766. https://doi.org/10.1038/s41467-024-54063-x.

Rust, R. L., A. Frizzell, and J. D. Kessler. 2025. "Waterfalls Enhance Regional Methane Emissions by Enabling Dissolved Methane to Bypass Microbial Oxidation." *Communications Earth & Environment* 6, no. 1: 140. https://doi.org/10.1038/s43247-025-02060-3.

Saunois, M., A. Martinez, B. Poulter, et al. 2025. "Global Methane Budget 2000-2020." *Earth System Science Data* 17: 1873–1958. https://doi.org/10.5194/essd-17-1873-2025.

Sawakuchi, H. O., D. Bastviken, A. O. Sawakuchi, et al. 2016. "Oxidative Mitigation of Aquatic Methane Emissions in Large Amazonian Rivers." *Global Change Biology* 22, no. 3: 1075–1085. https://doi.org/10.1111/gcb.13169.

Somers, L. D., A. Hoyt, A. R. Cobb, et al. 2023. "Processes Controlling Methane Emissions From a Tropical Peatland Drainage Canal." *Journal of Geophysical Research: Biogeosciences* 128, no. 3: e2022JG007194. https://doi.org/10.1029/2022JG007194.

Struik, Q., R. E. Groenbos, J. R. Paranaíba, et al. 2026. "Macrophyte-Associated Methane Oxidation as a Key Process Diminishing Methane Emissions From Agricultural Drainage Ditches." *Aquatic Botany* 205: 104007. https://doi.org/10.1016/j.aquabot.2026.104007.

Taillardat, P., J. Moore, S. Sasmito, et al. 2025. "Methane and Carbon Dioxide Production and Emission Pathways in the Belowground and Draining Water Bodies of a Tropical Peatland Plantation Forest." *Geophysical Research Letters* 52, no. 4: e2024GL112903. https://doi.org/10.1029/2024GL112903.

Vermaat, J. E., F. Hellmann, A. T. C. Dias, B. Hoorens, R. S. P. Van Logtestijn, and R. Aerts. 2011. "Greenhouse Gas Fluxes From Dutch Peatland Water Bodies: Importance of the Surrounding Landscape." *Wetlands* 31, no. 3: 493–498. https://doi.org/10.1007/s13157-011-0170-y.

Vroom, R. J. E., M. Van Den Berg, S. R. Pangala, O. E. Van Der Scheer, and B. K. Sorrell. 2022. "Physiological Processes Affecting Methane Transport by Wetland Vegetation—A Review." *Aquatic Botany* 182: 103547. https://doi.org/10.1016/j.aquabot.2022.103547.

Waldron, S., L. Vihermaa, S. Evers, M. H. Garnett, J. Newton, and A. C. G. Henderson. 2019. "C Mobilisation in Disturbed Tropical Peat Swamps: Old DOC Can Fuel the Fluvial Efflux of Old Carbon Dioxide, But Site Recovery Can Occur." *Scientific Reports* 9, no. 1: 11429. https://doi.org/10.1038/s41598-019-46534-9.

Wickham, H. 2016. *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag.

Wickham, H., R. Francois, L. Henry, and K. Muller. 2021. "*dplyr: A Grammar of Data Manipulation*." (Version R package version 1.0.5.) [Computer software]. https://CRAN.R-project.org/package=dplyr.

Wik, M., P. M. Crill, R. K. Varner, and D. Bastviken. 2013. "Multiyear Measurements of Ebullitive Methane Flux From Three Subarctic Lakes: Methane Ebullition From Subarctic Lakes." *Journal of Geophysical Research:*

Biogeosciences 118, no. 3: 1307–1321. https://doi.org/10.1002/jgrg.20103.

Wong, G. X., R. Hirata, T. Hirano, et al. 2025. "Impact of Land Conversion on Environmental Conditions and Methane Emissions From a Tropical Peatland." *Science of the Total Environment* 962: 178466. https://doi.org/10.1016/j.scitotenv.2025.178466.

Zhao, J. 2019. "FluxCalR: A R Package for Calculating CO_2 and CH_4 Fluxes From Static Chambers." *The Journal of Open Source Software* 4, no. 43: 1751. https://doi.org/10.21105/joss.01751.

Zhu, L., B. Qin, J. Zhou, B. Van Dam, and W. Shi. 2018. "Effects of Turbulence on Carbon Emission in Shallow Lakes." *Journal of Environmental Sciences* 69: 166–172. https://doi.org/10.1016/j.jes.2017.10.005.

Supporting Information

Additional Supporting Information may be found in the online version of this article.

Submitted 20 August 2025
Revised 27 February 2026
Accepted 04 June 2026