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Strong climate mitigation potential of rewetting oil palm plantations on tropical peatlands

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ABSTRACT

For decades, tropical peatlands in Indonesia have been deforested and converted to other land uses, mainly oil palm plantations which now cover one-fourth of the degraded peatland area. Given that the capacity for peatland ecosystems to store carbon depends largely on hydrology, there is a growing interest in rewetting degraded peatlands to shift them back to a carbon sink. Recent estimates suggest that peatland rewetting may contribute up to 13 % of Indonesia's total mitigation potential from natural climate solutions. In this study, we measured CO_2 and CH_4 fluxes, soil temperature, and water table level (WTL) for drained oil palm plantations, rewetted oil palm plantations, and secondary forests located in the Mempawah and Kubu Raya Regencies of West Kalimantan, Indonesia. We found that peatland rewetting significantly reduced peat CO_2 emissions, though CH_4 uptake was not significantly different in rewetted peatland compared to drained peatland. Rewetting drained peatlands on oil palm plantations reduced heterotrophic respiration by 34 % and total respiration by 20 %. Our results suggest that rewetting drained oil palm plantations will not achieve low CO_2 emissions as observed in secondary forests due to differences in vegetation or land management. However, extrapolating our results to the areas of degraded oil palm plantations in West Kalimantan suggests that successful peatland rewetting could still reduce emissions by 3.9 $MtCO_2\ yr^{-1}$. This result confirms that rewetting oil palm plantations in tropical peatlands is an effective natural climate solution for achieving national emission reduction targets.

1. Introduction

Drained and degraded peatlands are estimated to contribute up to 5 % of all anthropogenic global greenhouse gas (GHG) emissions (Joosten et al., 2016), with peat drainage and peat fire contributing 0.2 GtC yr^{-1} (Friedlingstein et al., 2023). In Indonesia, a vast area of peatlands has been drained and degraded in recent decades, primarily for oil palm and industrial plantation development (Lestari et al., 2024). Peatland drainage for conversion to oil palm plantations encourages aerobic decomposition of peat carbon, resulting in substantial carbon dioxide (CO_2) emissions (Hoyt et al., 2020; Matysek et al., 2018; Murdiyarso et al., 2010). Rewetting drained peatlands via canal blocking has been demonstrated to be an effective strategy to reduce peatland GHG emissions, as raising the water table decreases aerobic de-

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composition (Bianchi et al., 2021; Günther et al., 2020; Humpenöder et al., 2020; Leifeld and Menichetti, 2018; Zou et al., 2022). As such, peatland rewetting and restoration is a promising natural climate solution (NCS) due to the potential for reducing GHG emissions associated with continued peatland drainage and degradation (Leifeld and Menichetti, 2018; Ribeiro et al., 2021). However, Indonesia's 2nd Forest Reference Level (FRL) does not include emission reductions from peatland restoration, making this a potential missed opportunity to claim emission reductions from such efforts.

Peatland rewetting could contribute up to 13 % of Indonesia's emissions reductions from natural climate solutions (Novita et al., 2022). To date, drained peatlands in Indonesia have been rewetted extensively using canal blocking to slow CO_2 emissions from peat decomposition and lower peat fire risks (BRGM, 2021). In the IPCC Wetlands Supplement (Hiraishi et al., 2014), an emission factor of zero has been used for rewetted areas in tropical peatlands based on the assumption that all restored peat will be saturated with the water table maintained continuously near the peat surface. However, this assumption is far from reality, given that the water table in tropical peatlands fluctuate following rainfall variability (Asyhari et al., 2024; Cobb et al., 2017; Deshmukh et al., 2021) and that rewetting does not always raise the water table to the same level present in natural peatlands (Jauhiainen et al., 2008). According to Government Regulation No 57/2016 and Ministry of Environment and Forestry Regulation No 16/2017 on technical guidelines for peat ecosystem functions restoration, a minimum water table level of 40 cm is an indicator of restoration success. Therefore, specifically in this study, we define rewetting as part of the hydrological restoration to assist the recovery of drained/degraded peatlands by developing a series of canal blocking in a smallholder oil palm plantation to raise the water table level to 40 cm below the soil surface. Peatland rewetting maintains high water table levels, which increases anoxic, reduced conditions in the soil. A reduced environment is favorable for CH_4 production (Boonman et al., 2024) and significant decreases in CO_2 emissions (Abdalla et al., 2016; Busman et al., 2023; Nielsen et al., 2023).

While extensive research has been conducted to evaluate the impact of land cover change and drainage on GHG emissions from tropical peatlands (Basuki et al., 2021; Hergoualc'h and Verchot, 2012; Novita et al., 2021a; Novita et al., 2021b), measurements of GHG emissions from rewetted peatlands are scarce. The development of these emission factors is crucial for an accurate accounting of progress toward Indonesia's climate change mitigation goals. Furthermore, the study design and duration of previous efforts to constrain GHG emissions from rewetted tropical peatlands vary widely. These discrepancies create challenges for assessing the net impact of rewetting on tropical peatland GHG emissions (Darusman et al., 2023; Lestari et al., 2022). For example, while a recent meta-analysis suggests peatland rewetting may reduce CO_2 emissions from tropical peatlands by 9.2 ± 5.0 $MgCO_2$ ha^{-1} y^{-1} (Darusman et al., 2023), increased methane (CH_4) emissions following peatland rewetting could offset some of emissions reductions from decreased soil respiration (Azizan et al., 2021; Lestari et al., 2022). Comprehensive assessments are needed to further constrain whether peatland rewetting is effective at reducing GHG emissions in tropical degraded peatlands. Thus, the primary objective of our study was to investigate the impacts of peatland rewetting on CO_2 and CH_4 fluxes, along with soil physicochemical properties and environmental variables that influence GHG emissions in different land uses. The findings of this study help inform decision-making by land managers and policymakers to take appropriate actions for climate change mitigation through peat rewetting and restoration in Indonesia.

2. Methodology

2.1. Site description

We conducted our study in secondary forests and oil palm plantations in Mempawah and Kubu Raya Regencies in West Kalimantan Province, Indonesia (Fig. 1, Table 1). Peatlands in these regencies have faced many anthropogenic disturbances, such as illegal logging, infrastructure development, drainage, and peat fires (Anshari et al., 2010; Anshari et al., 2022). The summary of study site characteristics is shown in Table 1. Mempawah Regency (total area of 279,788 ha) is situated northwest of the city of Pontianak (the capital of the province). The total peatland area in the regency is 67,304 ha (Anda et al., 2021). One of the main economic activities in the regency is agriculture, with main commodities including oil palm plantations, bananas, and pineapple (BPS Kalimantan Barat, 2022). Our study sites were in Anjungan Dalam Village, Anjongan District, where we installed research plots in the community-owned secondary forests and the 10-year smallholder oil palm plantations. Based on our peat survey, the peat in the study sites had a wide range of depth, ranging from 50 to 245 cm in oil palm and 300–420 cm in secondary forests. Peatland rewetting measures in oil palm plantation sites were built by Peatland and Mangrove Restoration Agency (*Badan Restorasi Gambut dan Mangrove*-BRGM) by installing concrete canal blockings in 2018.

Kubu Raya Regency (total area of 698,524 ha) is situated southeast of Pontianak, with a total peatland area of 520,943 ha (Anda et al., 2021). Local communities mainly cultivate food crops, such as rice, maize, sweet potatoes, and cassava (Tampubolon et al., 2020); plant crops, including rubber, oil palm, and coconut; and raise domesticated animals, such as cows, goats, pigs, and chickens (BRG, 2019). In the Regency, peatland burning is often conducted to prepare agricultural land (Putri, 2017), resulting in frequent peat fires. Our study sites were spread over two districts covering two different land covers. In Rasau Jaya Umum Village, Rasau Jaya District, we established our plot monitoring for an oil palm plantation, where the plantation belongs to a company and the age of palm oil is three years. In Permata Village, Terentang District, we installed plots for the secondary forest. Peat depth in the secondary forest site – 660 cm to 780 cm – is twice deeper than in the oil palm sites, which range from 300 cm to 380 cm. Peatland rewetting measures in oil palm plantation sites were conducted by BRGM by installing concrete canal blocking in 2020.

2.2. GHG fluxes and environmental variables measurements

GHG flux measurements were conducted in three sites for each regency: secondary forest (SF), drained oil palm plantation (D-OP), and rewetted oil palm plantation (R-OP). The measurements were carried out fortnightly for one year, from January to December 2022 in Mempawah and from April 2022 to March 2023 in Kubu Raya. For each site, the measurements were taken from five pairs of trenched and non-trenched plots going from 50 m to > 200 m away from the canal (Fig. 2). There was no surface aboveground vegetation in any of the measurement plots. We separated soil respiration associated with root activities (autotrophic respiration) from peat decomposition (heterotrophic respiration) to assess the impact of peat rewetting on soil organic carbon cycling. Control and trenched plots were employed to measure total soil respiration and heterotrophic respiration, respectively. The trenching method was used to separate autotrophic and heterotrophic CO_2 fluxes (Hergoualc'h et al., 2017; Ishikura et al., 2019), in which a trench of 1 × 1 m^2 in size using a chainsaw and around 80 cm in depth. The inner side of the trenches is covered with porous fiber plastic to facilitate water flow and, subsequently, backfill the trenches. Regular monitoring was conducted to prevent new vegetation from growing inside the trenched plots. The first measurement was conducted at least 1 month after trenching to avoid the effect of decomposition from cut

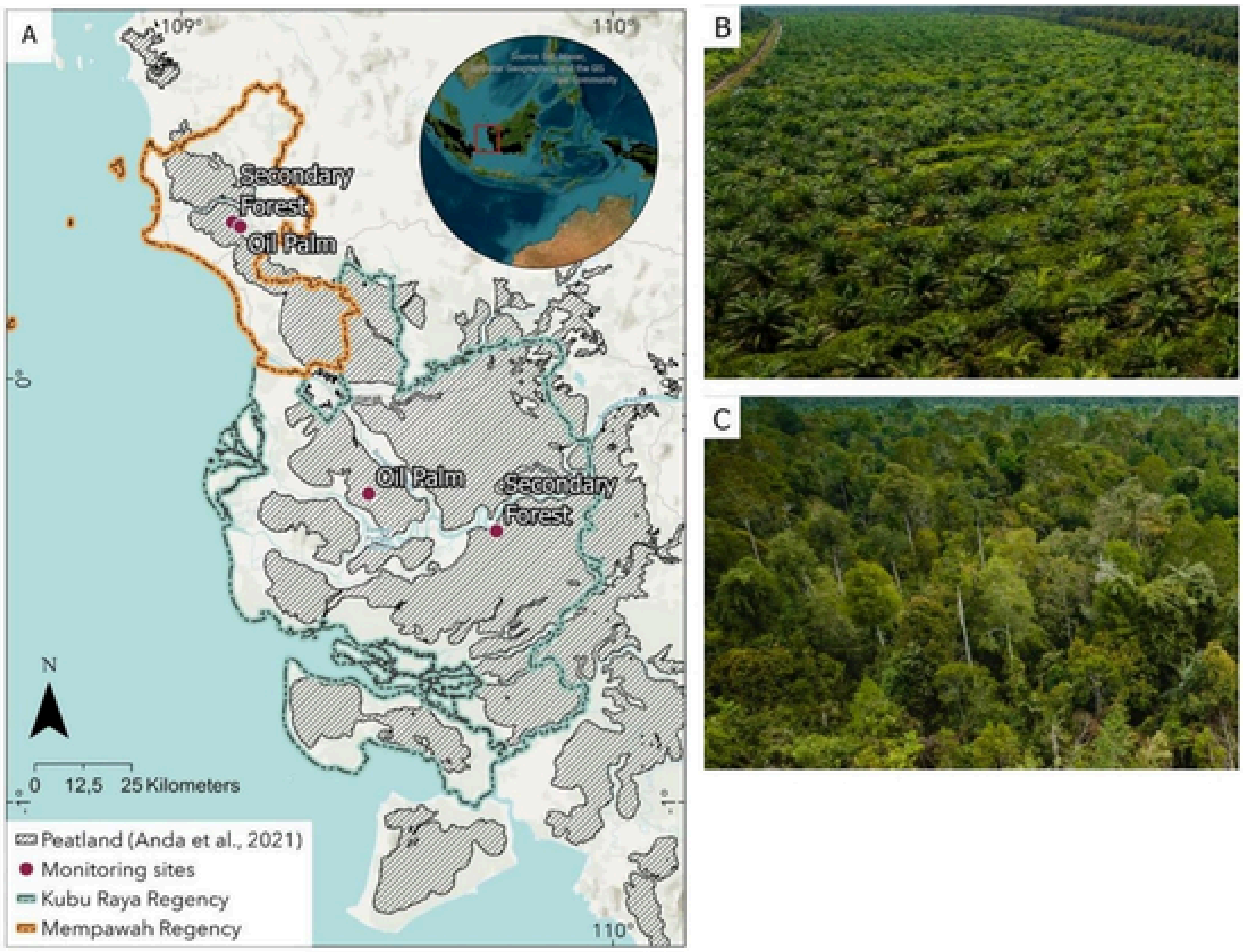

Fig. 1. Study areas located in (a) two districts of Mempawah and Kubu Raya; (b) Kubu Raya site - oil palm plantation (c) Mempawah site - secondary forest.

roots. For CH_4 fluxes, only the values from non-trench plots were considered.

The CO_2 and CH_4 fluxes from the peat surface were measured using LICOR LI-7810 portable GHG analyzer. The measurements were conducted following a closed chamber technique using LICOR 8200-01S Smart chamber equipped with a Stevens HydraProbe consisting of soil moisture, temperature, and electrical conductivity probe. Prior to the first measurement, about 5 cm of the collar was inserted into the ground until it was sealed to the ground surface. To avoid bias from diurnal variation of GHG fluxes, all measurements were conducted within a specific time window (08:00–12:00 LT). Hence, the CO_2 and CH_4 fluxes measured at each site took place on different days. For each plot, the GHG flux measurements were taken for 2 min with 3 replicates.

Upon data collection from the field, SoilFluxPro software was used to calculate GHG fluxes. Here, the linear fit was selected by specifying a dead band of 10 s and a stop time of 120 s. The flux measurements were quality-filtered to include only fluxes with sufficient linear fit. Fluxes were rejected if they had a coefficient of determination lower than 0.9 and 0.7 for CO_2 and CH_4 fluxes, respectively. For the statistical analysis, the average value from the three replicates was used to represent the flux from each plot.

The flux measurements in ppm s^{-1} were converted to $MgCO_2$ ha^{-1} yr^{-1} and $kgCH_4$ ha^{-1} yr^{-1} for CO_2 and CH_4 respectively, using the ideal gas law:

$$P\,V = n\,R\,T \tag{1}$$

where: P = atmospheric pressure (Pa); V = volume of headspace (m^3); n = number of moles (mol); R = universal gas constant (8.3145 J mol^{-1} K^{-1}); and T = temperature (K), with conversion factor, 1 mol of CO_2 = 44.01 g and 1 mol CH_4 = 16.02 g. The quantity of CH_4 is expressed as CO_2e by multiplying the amount of CH_4 fluxes with 27 as Global Warming Potential (GWP) over a 100-year period (IPCC, 2023).

We also measured environmental variables for each plot during GHG fluxes measurement, including the water table level (WTL), soil temperature, soil moisture, atmospheric pressure, and air temperature. The WTL (cm) refers to the depth of groundwater from the ground surface. The WTL was measured by conducting manual readings from a piezometer made of perforated polyvinyl chloride (PVC) tube inserted vertically into the peat between trenched and non-trenched plots. For continuous WTL measurement, we supplemented the manual measurement using a Keller DCX-22 automatic logger (Keller, Switzerland) in the middle of each transect, which provides hourly data. Soil temperature (°C) was measured at 10 cm depth using a TM-947SD Thermometer (Lutron, Taiwan). Concurrently, the volumetric soil moisture (%) was measured at 10 cm depth using HH2 Moisture Meter (Delta-T Devices, UK). Air pressure (Pa) and air temperature (°C) were monitored using MHB-382SD Humidity, Barometer, and Temperature Data Recorder (Lutron, Taiwan).

Table 1
Characteristics of the study sites.

	Secondary forest		Oil palm	
	Site 1	Site 2	Site 1	Site 2
Location	Anjungan Dalam Village, Mempawah Regency, West Kalimantan	Permata Village, Kubu Raya Regency, West Kalimantan	Anjungan Dalam Village, Mempawah Regency, West Kalimantan	Rasau Jaya Village, Kubu Raya Regency, West Kalimantan
Coordinate	109,11845683; -0,37029372	109,73030281; -0,35994559	109,13641459; 0,35976705	109,4342; -0,27148611
Elevation (masl)	17	22	25	19
Average annual rainfall from 2012 to 2022 (mm)	2760	3080	2760	3080
Surface peat classification	Sapric	Hemic	Sapric	Hemic
Peat depth (cm)	346.3 ± 22.8	711.3 ± 17.5	122.0 ± 33.4	349.2 ± 11.9
Aboveground carbon stocks (ton C/ha)	116.4 ± 13.4	N/A	47.3 ± 12.8	N/A
Total organic carbon (%)	52.0 ± 1.2	50.1 ± 0.6	52.1 ± 2.4	51.9 ± 0.6
Total nitrogen (%)	1.3 ± 0.5	1.5 ± 0.1	1.5 ± 0.1	1.4 ± 0.1
Peat age (year BP)	6810 ± 19 (Depth ~320 cm)	5940 ± 18 (Depth ~680 cm)	4460 ± 17 (Depth ~230 cm)	3130 ± 17 (Depth ~320 cm)

For aboveground carbon stocks, we identified the composition, structure, and the amount of carbon stored within the forest ecosystems using the procedures described in Kauffman et al. (2016) and (Novita, 2016). We placed six circular plots with a fixed radius of 10 m (covering approximately 0.0314 ha) at intervals of 50 m along a 250-meter-long transect. The allometric equation from (Manuri et al., 2014) was applied to estimate aboveground biomass. The root biomass was computed using the formula provided by Mokany et al. (2006). The carbon content (C) was computed from the biomass by multiplying it by a factor of 0.47 (Kauffman and Donato, 2012; Mudiyarso et al., 2009).

To quantify belowground carbon stocks, we collected soil samples up to mineral layer. We classified the depth of each peatland site according to the Indonesian standard for peat thickness (SNI 7925:2019). The standard consists of shallow (0–100 cm), moderate (100–200 cm), deep (200–300 cm), very deep (300–500 cm), extremely very deep (500–700 cm), and extraordinarily very deep (>700 cm) peatlands. We analyzed subsections of all cores for bulk density (BD) and total organic carbon (TOC) at 50 cm resolution for thickness between 0 and 200 cm, at 100 cm resolution for thickness between 200 and 500 cm, and at 200 cm resolution for thickness >500 cm. The numbers of BD and TOC samples are dependent upon peat depths of the corresponding cores. In order to determine peat age analysis, we selected samples for radiocarbon dating from the cores' surface, middle, and bottom sections, down to the mineral substratum. Dry weight samples (2–6 g) of bulk peat were sent to Waikato Radiocarbon Dating Laboratory, New Zealand, to determine the radiocarbon isotope (^{14}C) composition by accelerator mass spectrometry. The laboratory pretreated the samples using standard protocols prior to radiocarbon analysis. Basal peat ages were determined from ^{14}C isotopic compositions as previously described (Ruwaimana et al., 2020).

Measurement of soil physicochemical properties for site description was also determined for each plot. The peat bulk density was measured using the gravimetric method upon taking peat samples in the field at 10 cm depth using a soil ring concomitantly with the measurement of

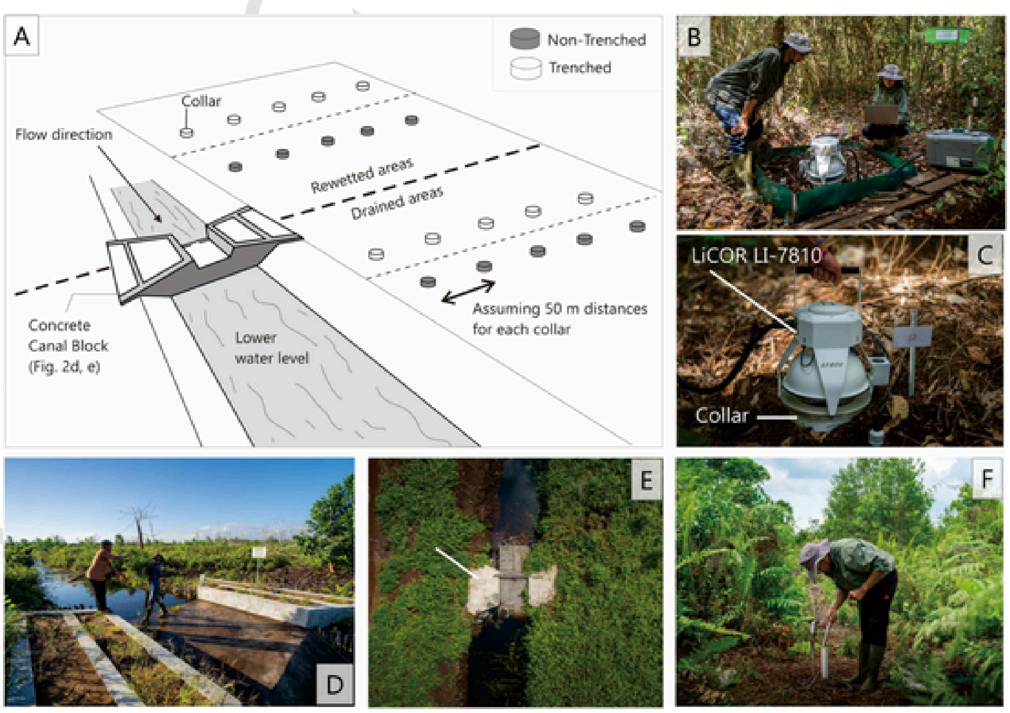

Fig. 2. Plot design for GHG fluxes measurements at the oil palm plantations, (a) schematic illustration of plot design for GHG fluxes measurements in rewetted and drained areas; (b) trenched plot for heterotrophic respiration monitoring; (c) non-trenched plot for total respiration monitoring; (d) typical concrete canal blocking structure in the study site; (e) top view of canal blocking structure; (f) water table monitoring.

GHG fluxes. Soil pH and Eh (redox potential) at 10 cm depth were measured using a portable pH meter (HANNA Instruments Hi 99,121, USA). Cation exchange capacity was determined by an ammonium acetate solution. Calcium concentrations of surface peat soils were determined with 25 % HCl extraction. Phosphorus content was determined with a standard P-Bray approach. Total carbon (%) and total nitrogen (%) were measured with Yanaco JM 1000 CN Corder, using hippuric acid ($C_9H_9NO_3$) as a standard. Before the laboratory analysis, peat samples with some woody remains were oven-dried at 70 °C. The results for the soil physicochemical properties are presented in Table 1 and Supplementary Table 1.

2.3. Statistical analysis

The field data were analyzed and visualized using R Statistical Software version 4.2.0. Prior to analysis, we removed data outliers using an objective procedure (i.e. graphical approach) to avoid anomalous measurements. We used mixed-effects models to assess differences in GHG fluxes, environmental variables, and soil physicochemical properties between sites (Fig. 3). For each response variable, treatment was defined as the fixed effect, while the location of the site with respect to the regency, month of measurement, and plot distance from the canal were included as a random effect using the "lmer" function of the "lme4" package. The level of significance for all analyses was set to be 0.05. We used one-way analysis of variance (ANOVA) to assess the significance of fixed effects and their interactions. The simple linear regression analysis was applied to analyze the effects of locally measured environmental variables on GHG fluxes. Here, the variables used include WTL, air temperature, soil moisture, and soil temperature. As part of our QA/QC analysis, we excluded extreme values of CO_2 flux outside the range of 0 to 200 t CO_2 ha^{-1} yr^{-1} and CH_4 flux outside the range of −500 to 2000 kg CO_2e ha^{-1} yr^{-1}. These values were considered outliers based on data distribution. Consequently, we excluded 81 CO_2 data points (6 %) and 97 CH_4 data points (7 %) from a total of 1410 data points collected during the measurement period. Further, we created the binning by setting the output to be 15 groups for the filtered data in an orderly manner. This was done to understand more distinct relationship as data was varied as the numbers increases with response to environmental variables and fluxes. An autocorrelation analysis on the key variables of fluxes and environmental variables was performed. Firstly, the autocorrelation function (ACF) derived from the statsmodels Python library was used to analyze the temporal dependencies in the dataset (Statsmodels Developers, 2024). We also visualized the ACF to identify significant spikes outside the confidence interval, which indicates autocorrelation. In addition, the Durbin-Watson test was conducted to specifically test for autocorrelation in the residuals of our regression models. The Durbin-Watson statistic ranges from 0 to 4, with a value around 2 indicating no autocorrelation, values <2 indicating positive autocorrelation, and values >2 indicating negative autocorrelation. The Cochrane Orcutt method was used to transform the data to address any autocorrelation problems in our model.

2.4. Upscaling the impacts of peatland rewetting to provincial level

In order to evaluate the impacts of peatland rewetting at a larger scale, we estimated the maximum potential for reduced emission from peatland rewetting on oil palm plantations in West Kalimantan following two steps. First, the emissions avoided with peatland rewetting were calculated as the difference in annual GHG emissions (CO_2 from heterotrophic respiration, only) determined for the rewetted versus drained oil palm plantations ($MgCO_2e$ ha^{-1} y^{-1}). Second, the emissions avoided with rewetting oil palm ($MgCO_2e$ ha^{-1} y^{-1}) were multiplied by the area of drained oil palm plantations in West Kalimantan. This calculation assumes that the canal blocking structures installed during peatland rewetting projects were constructed successfully resulting in water table levels comparable to those measured in our study. The area of oil palm plantations was derived from the Indonesian oil palm concessions map provided by Global Forest Watch (https://data.globalforestwatch.org/). The data were then clipped with Indonesian peatland extent (Anda et al., 2021) to calculate the oil palm extent within peatland in West Kalimantan. Because our field measurements took place on plots located along a transect going from 50 m to > 200 m away from a canal, we assume our measurements reflect the spatial heterogeneity of environmental conditions within oil palms. The administration boundary was publicly available data from the Indonesian Geospatial Information Agency (https://tanahair.indonesia.go.id/).

3. Results

Peat soils in the oil palm plantation and secondary forest of our study areas are Histosols, with acidic reaction and decomposition degrees of sapric and hemic (Table 1). In our study sites, the basal dates of these Histosols range from 3130 to 6810 years BP with peat depths be-

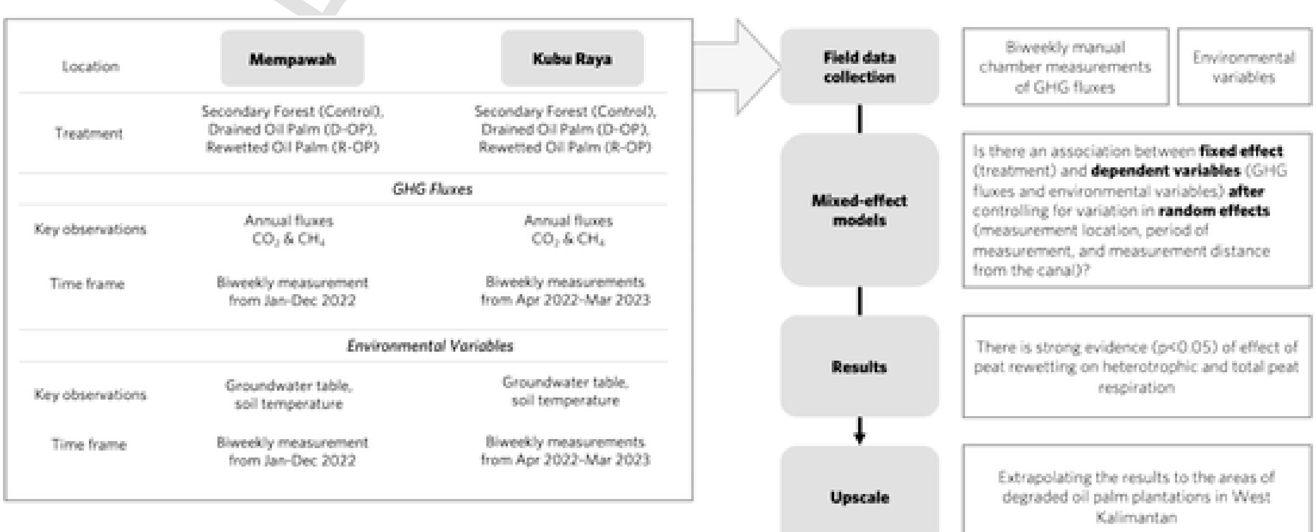

Fig. 3. Flowchart of data processing and result analysis from our study.

tween 1.2 and 7.1 m below the ground surface (Table 1). Based on our field measurements, the mean aboveground carbon stock of secondary forests and oil palm plantations were 116 ± 13 Mg C ha^{-1} and 47 ± 13 Mg C ha^{-1}, respectively. The average of total organic carbon among sites is relatively similar, ranging from 50.1 to 52.1 %. Soil nitrogen was not significantly different among sites and land uses. Redox potentials (Eh) suggest a moderately reduced environment at the soil surface (323–346 mV; Supplementary Table 1).

Land use significantly affected water table level (WTL), soil temperature, and soil moisture. WTL fluctuations closely followed rainfall dynamics in both secondary forests and oil palm plantations, with the deepest WTL occurring during the dry season (<100 mm/month) (Fig. 4). The peatland WTL was deepest in drained oil palm (D-OP), with average annual WTL significantly higher in D-OP compared to the secondary forest (SF) with ($p < 0.01$) (Table 2, Supplementary Table 2, Fig. 4). The rewetted oil palm plantation (R-OP) had an average WTL that was similar to the secondary forest (40.1 ± 2.3 cm versus 40.7 ± 2.5 cm, respectively; Table 2). Soil temperature was significantly higher in the D-OP and R-OP plantation sites compared to the SF site ($p < 0.01$) (Table 2, Supplementary Table 2, Fig. 4). The highest soil moisture is observed in the R-OP, followed by the secondary forest and the drained oil palm (Table 2, Fig. 4).

Rewetting through canal blocking in oil palm plantations of R-OP reduced both heterotrophic and total respiration compared with drained condition of D-OP ($p < 0.01$), but there was no significant difference in CH_4 uptake ($p > 0.01$; Table 3, Supplementary Table 3, Fig. 5). Our data clearly showed rewetting drained peatlands in oil palm (R-OP) plantations significantly reduced heterotrophic respiration by 34 % and total respiration by 20 % compared to D-OP. Despite a similar WTL, heterotrophic and total respiration in R-OP were 10 % and 30 % larger than SF, respectively (Table 3). Our data clearly showed the D-OP had 69 % larger total and 62 % larger heterotrophic soil respiration than SF ($p < 0.01$) (Table 3, Supplementary Table 2). Overall, heterotrophic emissions contributed 88 %, 84 %, and 68 % of the total respiration in the SF, D-OP, and R-OP, respectively.

While not the goal of this study, our statistical analysis indicates that seasonality and landscape position also contribute to the variability we observed in GHG fluxes (Supplementary Table 4). Standard deviations (SDs) in random effects provide insights into the variability within the data that is not explained by the fixed effects. This indicates how much the environmental variables and GHG fluxes vary due to the random factors and the residual unexplained variability. During the dry months (Jan - Mar 2022), the CO_2 fluxes tended to be larger, while in the wet months (Apr - Dec 2022), the CO_2 fluxes tended to be smaller (Fig. 5). There were strong linear relationships between GHG fluxes and both WTL and soil temperature (Fig. 6). For example, CO_2 fluxes increased with the depth of the WTL below the ground surface and the soil temperature measured at a 10 cm depth. On the other hand, the CH_4 fluxes were negatively correlated to the WTL, with no apparent relationship to soil temperature. Drained oil palm plantations cover an area of 378,308 ha and 1,455,840 ha in West Kalimantan and Indonesia, respectively. Applying the emission factors from our study for heterotrophic respiration (10.3 tCO_2 ha^{-1} yr^{-1}), rewetting degraded peatlands on oil palm plantations in West Kalimantan contributes to emissions reduction of 3.9 $MtCO_2$ ha^{-1} yr^{-1}.

4. Discussion

4.1. Rewetting oil palm plantations reduces GHG fluxes

Our results demonstrate that rewetting peatlands on oil palm plantations through canal-blocking projects substantially lowers CO_2 emissions due to higher water table levels and soil moisture following restoration. For example, we reported that a ~10 cm increase in annual water table level after canal blocking reduced total peat soil respiration by 20 % and heterotrophic respiration by over 34 % in oil palm plantations (compared to the drained oil palm site; Tables 2–3). These results are comparable with those of Lestari et al. (2022), who observed a 36 % decrease in CO_2 emissions from oil palm after rewetting, as well as observations from northern and temperate peatlands where rewetting significantly reduced CO_2 emissions (Richardson et al., 2023; Wilson et al., 2022). The relationships observed between total and heterotrophic respiration and water table depth (Fig. 6) support the dominant role of water table level in controlling peat respiration (Carlson et al., 2015; Couwenberg et al., 2011). Our observation of higher surface soil moisture following rewetting may further contribute to the reduced rates of surface peat decomposition (Ishikura et al., 2018a,b; van Lent et al., 2019).

Our findings suggest that raising the water table depth to 40 cm below the ground surface maintains the water table below observed thresholds for significant CH_4 emissions (Couwenberg and Hooijer, 2013; Jovani-Sancho et al., 2023). The lack of CH_4 emission observed following rewetting is consistent with previous studies that found net CH_4 uptake in rewetted tropical peatlands with water table levels still ~40 cm below the peat surface (Darusman et al., 2023; Jauhiainen et al., 2008). As the majority of CH_4 oxidation has been shown to occur in the top ~10 cm of the soil profile (Lang et al., 2020), raising the water table to 40 cm should have negligible impact on CH_4 uptake. It follows that our results confirm this hypothesis and provides additional evidence that raising the water table to 40 cm in rewetted oil palm plantations preserves CH_4 uptake. Furthermore, recent metagenomic analyses of oil palm microbiomes failed to detect genes for CH_4 production (Bandla et al., 2023), suggesting that conversion of tropical peat swamp forests to oil palm plantations may impart lasting changes to peatland microbiota and CH_4 emissions that persist after canal blockage. Alternatively, the lack of CH_4 emissions observed from the peatland soil surface could be due to the escape of CH_4 from the ecosystem through other avenues that were not captured in this study. For example, we did not quantify CH_4 emissions from trees nor drainage canals, which have been shown to contribute significantly to CH_4 emissions from forested tropical peatlands (Pangala et al., 2013; Sjögersten et al., 2020; Somers et al., 2023) and oil palm plantations (Manning et al., 2019). As such, net ecosystem CH_4 emissions from these sites may be higher than what is reflected in our measurements of peat surface CH_4 fluxes.

Our field evidence indicates that raising the WTL by 9.4 cm during rewetting reduces heterotrophic emissions by 10.3 ton CO_2 $ha^{-1}yr^{-1}$. When rounding the WTL increase to 10 cm, the reduction in heterotrophic emissions is estimated to be 11.0 ton CO_2 $ha^{-1}yr^{-1}$. This estimate aligns closely with studies by Hooijer et al. (2010) and Carlson et al. (2015), which report CO_2 emission reductions of 9.10 and 9.20 ton CO_2 ha^{-1} yr^{-1}, respectively, for every 10 cm increase in WTL below the soil surface. Evans et al. (2021) reported a reduction of 3 ton CO_2 $ha^{-1}yr^{-1}$ for the same water table increase in temperate peatlands, suggesting there may be different controls driving emissions reductions in tropical versus temperate peatlands. As such, our results add to the growing body of literature that suggests the climate mitigation potential of rewetting tropical peatlands in Southeast Asia is ~3 times greater per area than for temperate peatlands.

4.2. Rewetting oil palm does not fully restore GHG emissions

Our results demonstrate that rewetting peatlands on oil palm plantations is insufficient to return GHG emissions to the reference levels observed in secondary swamp forests. Total and heterotrophic respiration rates from the rewetted oil palm plantations were still higher by 9.9 and 2.3 Mg CO_2e ha^{-1} yr^{-1}, respectively (Table 3), despite similar WTL between the two land use types (Table 2). These differences in CO_2 emissions between the rewetted oil palm and secondary forests were likely due to higher overall soil temperatures in the oil palm plantations (Table 2). Numerous studies have demonstrated that even a modest in-

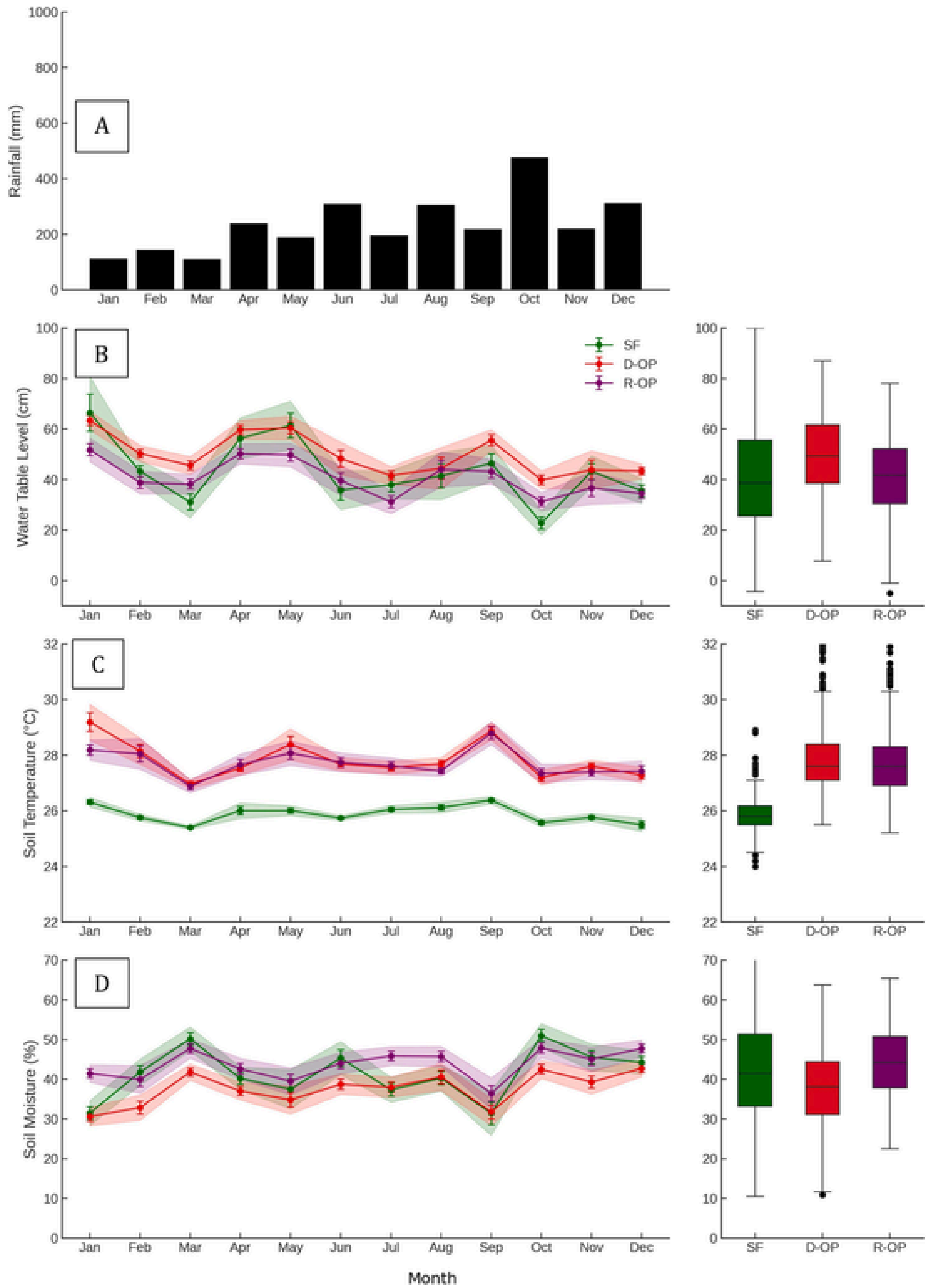

Fig. 4. Summary of monthly measurement of environmental variables during 2022–2023, namely (a) water table and rainfall; (b) soil temperature; (c) soil moisture. The shaded area represents the standard deviation while the vertical line represents the Standard Error Mean (SEM).

Table 2
Summary of environmental variables, namely water table, soil moisture and soil temperature across our study sites (average ± standard error). The values with different superscript letters in a column are significantly different ($p < 0.05$).

No	Site	Water table (cm)	Soil moisture (%)	Soil temperature (°C)
1	Secondary forest (SF)	40.7 ± 2.5^a	39.5 ± 1.7^a	25.9 ± 0.1^a
2	Drained oil palm (D-OP)	49.5 ± 2.1^b	36.0 ± 1.2^b	28.1 ± 0.2^b
3	Rewetted oil palm (R-OP)	40.1 ± 2.3^a	42.6 ± 1.3^c	28.0 ± 0.2^b

Table 3
Summary of GHG fluxes across our study sites (average ± standard error). The values with different superscript letters in a column are significantly different ($p < 0.05$).

No	Site	Total peat respiration (Mg CO_2 ha^{-1} yr^{-1})	Heterotrophic respiration (Mg CO_2 ha^{-1} yr^{-1})	Methane flux (kg CO_2e ha^{-1} yr^{-1})
1	Secondary forest (SF)	23.1 ± 1.7^a	20.3 ± 1.8^a	-12.8 ± 5.9^a
2	Drained oil palm (D-OP)	39.1 ± 3.1^b	32.9 ± 3.0^b	-10.5 ± 7.2^a
3	Rewetted oil palm (R-OP)	33.0 ± 2.3^c	22.6 ± 1.5^c	-7.7 ± 8.1^a

crease in temperature can significantly enhance microbial activity in peatlands, leading to higher CO_2 emissions or increased soil carbon decomposition rates (Davidson and Janssens (2006); Busman et al., 2023; Ishikura et al., 2018a,b; Hirano et al., 2013; Girkin et al., 2019; Lafleur et al., 2005; Updegraff et al., 2001). In addition, a recent study showed that GHG emissions from oil palm plantations can vary at different stages of the plantation cycle due to changes in temperature (Cooper et al., 2020). Consistent with these findings, we found that CO_2 emissions increased over an increase in soil temperature from 25 to 30 °C (Fig. 6).

Conversion of peat forests to oil palm alters canopy structure and changes the microclimate of soils and aerobic zones that support peat respiration (Hardwick et al., 2015; Meijide et al., 2018). For example, increased sunlight exposure to soils in deforested areas or on newly developed plantations can increase soil temperatures and lead to higher CO_2 emissions from the peat surface (Cooper et al., 2019; Hoyt et al., 2019; Jauhiainen et al., 2014; Melling et al., 2005). Higher soil temperatures have generally been observed in cultivated and degraded peatlands compared to intact peat swamp forests (Ludang et al., 2007; Ishikura et al., 2018a,b). In some cases, differences in CO_2 emissions between these land use types have been attributed to differences in soil temperature alone (Murdiyarso et al., 2019). It follows that changes in vegetation cover and management during land use change may have lasting effects on GHG emissions that cannot be mitigated with rewetting projects alone. However, the different relationships observed between soil temperature and GHG emissions in our study (Fig. 6) and past studies (Cooper et al., 2019; Furukawa et al., 2005; Hoyt et al., 2019; Jauhiainen et al., 2014; Melling et al., 2005) suggest that emissions from tropical peatlands may vary across different land cover types, microclimates, and organic matter characteristics as well.

Changes to the peat's physical and chemical properties following degradation and oil palm cultivation could also contribute to the different CO_2 emissions observed between the rewetted oil palm and secondary forests. For example, the conversion of peatland forest to oil palm lowers the quality of soil organic matter within peatland soils due to the changes in aboveground vegetation and litterfall, lower aboveground carbon stocks (Table 1), and the enhanced decomposition of peat following drainage (Cooper et al., 2019; Swails et al., 2018).

Previous studies suggest that the stability of soil organic carbon (SOC) increases in restored, cultivated peatlands due to high water table regimes, which slow down peat decomposition (Grover & Baldock, 2013; Hirano et al., 2024; . Xu et al. (2019) found that wetland restoration in temperate regions leads to increased SOC through carbon sequestration over time. In the Selangor peat forest, Malaysia, SOC values are 43 % during the dry season and 47 % during the wet season (Adeolu et al., 2018). Over the long term, SOC in rewetted peatlands may either increase or become more stable. Moreover, although we did not detect significant differences in the C/N ratio of peat between our study sites (Table 1), inputs of nutrient-rich litter to soils on oil palm plantations could have led to higher heterotrophic emissions compared to the secondary forests. Fertilizer application on oil palm plantations could further contribute to a faster decomposition rate and a higher CO_2 emission (Azizan et al., 2021).

4.3. Seasonal variability of GHG fluxes and their relationship to environmental variables

Our year-long monitoring of GHG emissions alongside WTL and soil temperature demonstrates that seasonality and site-level differences can be sources of variability in peatland GHG emissions. We found that GHG fluxes throughout the year closely followed patterns in rainfall, where higher rainfall led to higher water table levels and lower CO_2 emissions (Figs. 4–5). This strong dependence of CO_2 emissions on seasonal rainfall has been observed previously in natural peat forests and acacia plantations (Deshmukh et al., 2021). We also observed a larger variation in heterotrophic respiration measured across plots within the drained oil palm plantation compared to the rewetted oil palm, consistent with past findings in other restored wetlands (McNicol et al., 2017). Important factors like water table and peat bulk density can vary with the distance from drainage canals (Sinclair et al., 2020; Sutikno et al., 2020). Dissolved CO_2 and CH_4 in peat porewater have also been shown to vary with distance from drainage canals (Somers et al., 2023), reflecting differences in microbial activity at a depth that influences peat surface GHG emissions. We captured much of the variation in GHG emissions associated with position on the landscape by measuring fluxes on plots located between 50 to >200 m from a drainage canal (Fig. 2). Thus, our results suggest that studies quantifying the GHG emissions avoided with peatland rewetting projects need to account for the heterogeneity of emissions across space and time (e.g., Lestari et al., 2022).

There are four potential limitations to the approach used in our study which can be explored for future studies. First, we only measured emissions during daytime, which can underestimate daily fluxes because peat respiration (Hoyt et al., 2019) and CH_4 emissions (Deshmukh et al., 2020) from tropical peatlands have diel variation related to changes in temperature and water table parameters. Second, our estimates of heterotrophic respiration do not account for photosynthetic uptake of CO_2, which is needed to constrain how canal blocking impacts oil palm plantation net ecosystem exchanges of carbon (e.g., Kiew et al., 2020). Third, differences in peat characteristics like bulk density, redox potential, and nutrient content (phosphorus, calcium) between sites with the same land cover (Supplementary Table 1) could cause variability in GHG emissions. Nevertheless, the year-long duration of our study and large spatial coverage (varying distances from canals and between two regencies) allowed us to capture the largest range of physical conditions to date. Capturing the GHG emissions across these conditions was needed to demonstrate that peatland rewetting via canal blocking successfully reduces GHG emissions compared to degraded peatlands on the same land use. Lastly, due to limited resources, we do not include N_2O emissions in this study, which mainly originates from nitrification and denitrification processes or water treatment. Decreased N_2O emissions after rewetting has been reported by Lestari et al. (2022) in various land cover types of peatlands in Riau, Indonesia. In addition, Liu et al. (2020) reported that rewetting European peatlands reduced N_2O emissions. Hence, future studies should

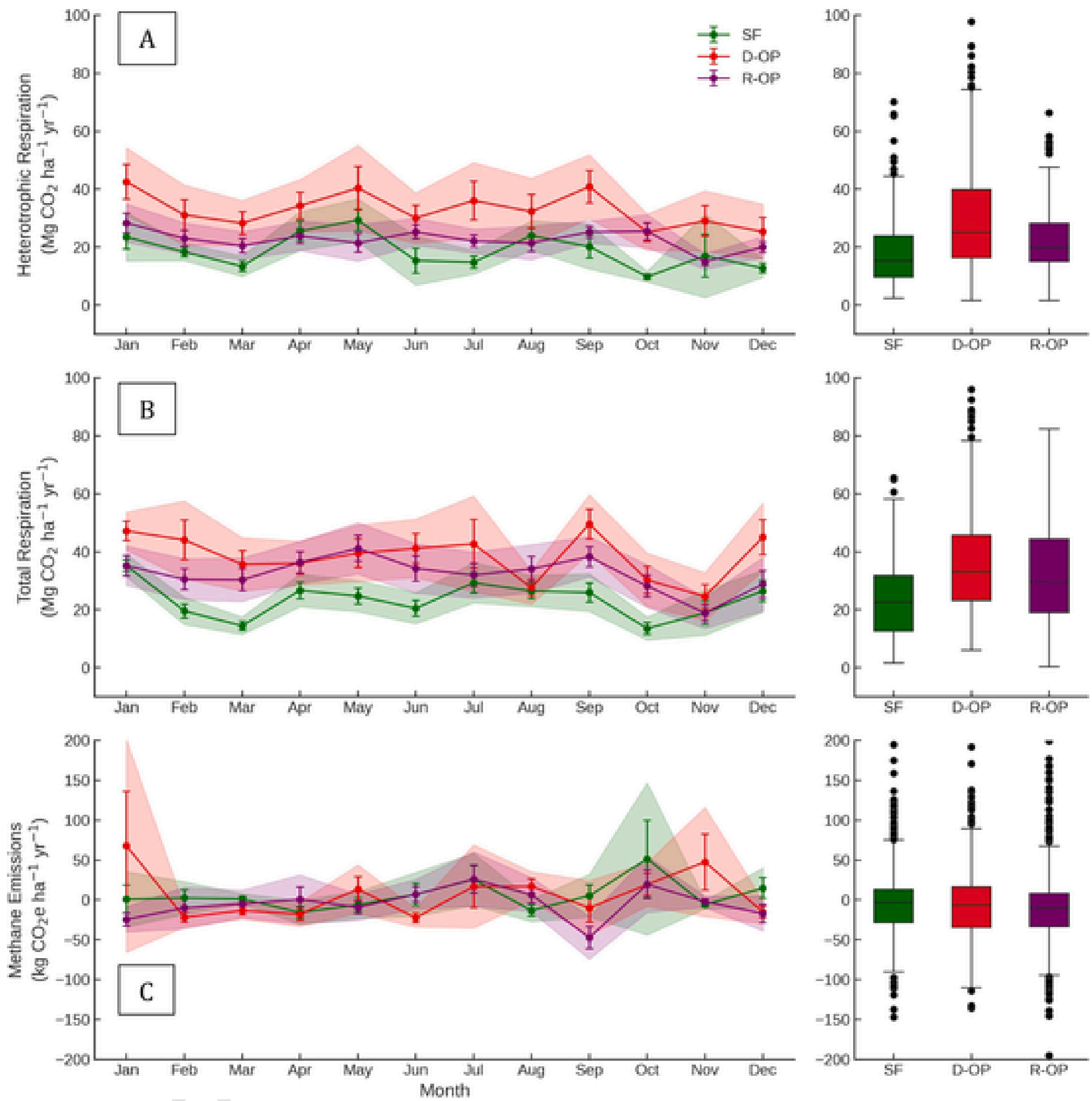

Fig. 5. Summary of monthly measurement of GHG fluxes during 2022–2023: (a) heterotrophic respiration; (b) total respiration; and (c) methane fluxes. The shaded area represents the standard deviation, while the vertical line represents the Standard Error Mean (SEM).

monitor the extent that rewetting reduces N_2O emissions in Indonesian peatlands.

4.4. Climate mitigation opportunity from rewetting oil palm plantation and policy implication

The Government of Indonesia has committed to restoring degraded peatlands by maintaining higher water table levels in as much as 1.7 million hectares of plantation forests and oil palm plantations to achieve Indonesia's Forestry and Other Land Use Net Sink by 2030 (MoEF, 2022). Specifically in West Kalimantan, the government has set the target to maintain 272,691 ha of water management in oil palm plantations, which is about 72 % of the current degraded oil palm in West Kalimantan (MoEF, 2022). Assuming that oil palm plantations would be rewetted gradually until 2030, we estimate that the average emission reduction is 10.3 $MgCO_2$ ha^{-1} yr^{-1} or 3.9 $MtCO_2$ yr^{-1} in West Kalimantan through 2030. Thus, our results provide the first evidence supporting expectations that rewetting in oil palm plantations to water levels that maintain crop production on cultivated peatlands (~40 cm) reduces GHG emissions from Indonesia and is a promising natural climate solution.

Maintaining water levels at 40 cm below the ground surface with peatland rewetting projects in concession areas following Government Regulation No. 57 of 2016 may have indirect benefits and costs as well. For example, this water table management regulation considers the livelihoods of communities dependent on crop cultivation, but it does not take into account potential challenges faced during the rainy season. Higher overall water levels make oil palm plantations more prone to floods during the wet season, which can have lasting effects on the agricultural crop yields at the end of the year. It is also expected that

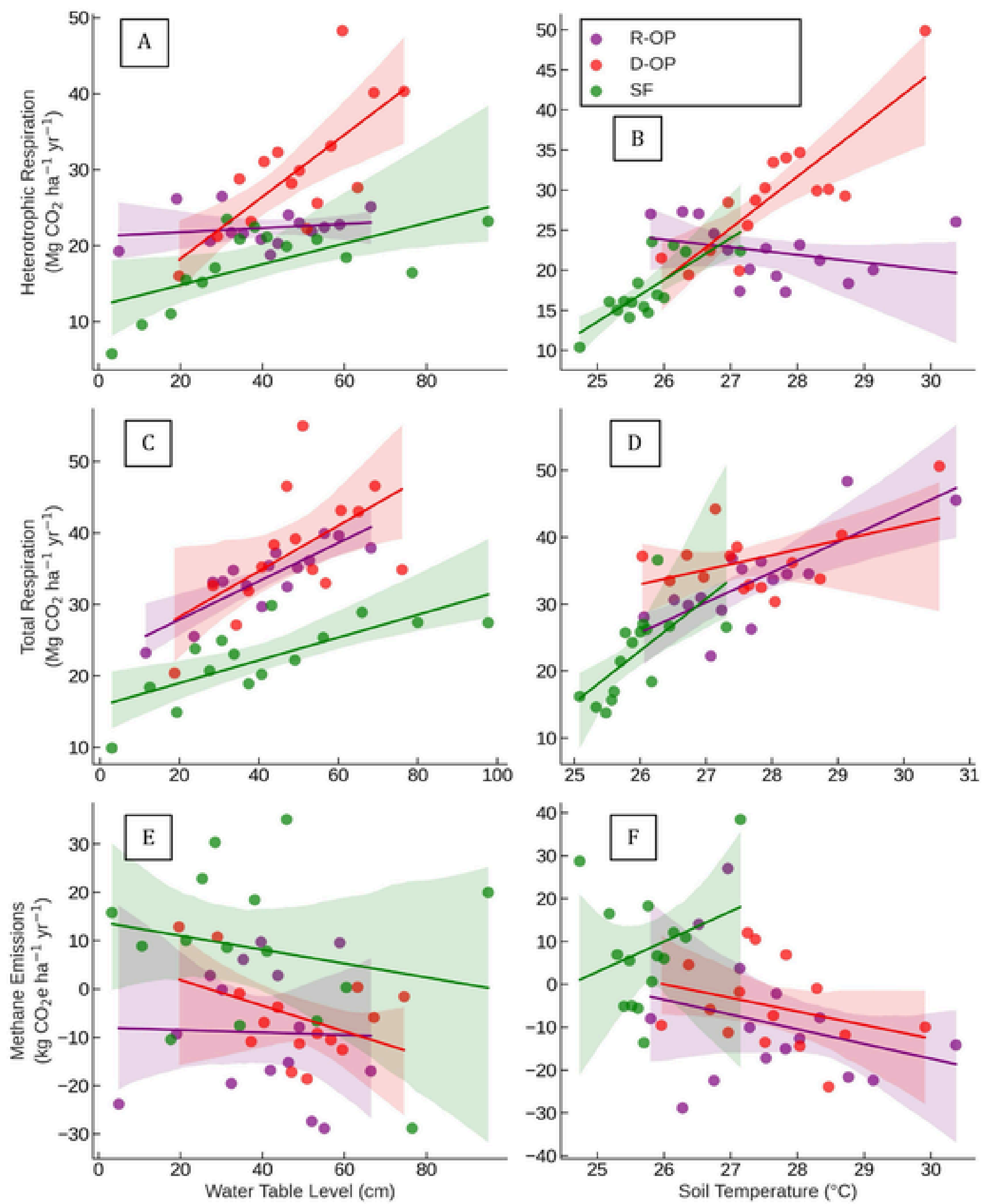

Fig. 6. Water table and soil temperature relationship with CO_2 and CH_4 fluxes. Segmented binning was applied with a bin size of 15 (the final value comes from the average of each bin) where: a) Relationship between water table level (cm) and heterotrophic respiration (Mg CO2 ha^{-1} yr^{-1}) in rewetted oil palm, drained oil palm and secondary forest; b) Relationship between soil temperature (°C) and heterotrophic respiration (Mg CO2 ha^{-1} yr^{-1}); c) Relationship between water table level (cm) and total respiration (Mg CO2 ha^{-1} yr^{-1}); d) relationship between soil temperature (°C) and total respiration (Mg CO2 ha^{-1} yr^{-1}); e) Relationship between water table level (cm) and Methane emissions (kg CH_4 ha^{-1} yr^{-1}); d) relationship between soil temperature (°C) and methane emissions (kg CH_4 ha^{-1} yr^{-1});

peatland rewetting may reduce peat fire risks, which is another important source of emissions in the tropics (Silviana et al., 2021; Taufik et al., 2023; Turetsky et al., 2015). Yet, some studies suggest that maintaining water table depths at 30–40 cm below the ground surface does not sufficiently reduce peat vulnerability to fires (Putra et al., 2018; Wösten et al., 2008). Thus, while our results show that significant reductions in CO_2 emissions are possible while maintaining the water table at a depth recommended for concession areas, more long-term and spatially resolved studies are needed to quantify the climate mitigation benefits of rewetting projects alongside the social costs.

Taken together, our study offers new country-level emission factors for degraded and rewetted oil palm plantations. Our estimates of peat surface CO_2 emissions from drained peatlands on oil palm plantations (32.9 ± 3.0 $MgCO_2$ ha^{-1} yr^{-1}) were comparable with the currently used emission factors for oil palm grown on drained tropical peatlands (average of 40.4 $MgCO_2$ ha^{-1} yr^{-1}, range of 20.5–62.4 $MgCO_2$ ha^{-1} yr^{-1}) (Hiraishi et al., 2014). The default IPCC emission factor for rewetted tropical peatlands has been set to zero due to the lack of available data and assumptions that rewetted peatlands are fully saturated year-round after the hydrological intervention. Our result shows that successful rewetting in smallholder oil palm plantation areas, reduces carbon emissions by about one-third, but not all the way, challenging current assumptions by the IPCC for rewetted tropical peatlands.

5. Conclusion

Currently, there is a limited capacity and lack of evidence to measure and monitor GHG emissions in rewetted peatlands in Indonesia. Our study has demonstrated that peatland rewetting through canal blocking in oil palm plantations is a promising option for emissions reduction. Even though improved water management by raising the water table in oil palm plantations brings positive action to curb carbon emissions, protecting the remaining forest remains the best option for climate mitigation Establishing accurate national GHG inventories of peat restoration is crucial to evaluate the impacts of rewetting on various peatland cover types and land uses, including oil palm plantations. Robust estimation of GHG emissions can also support the implementation of carbon market regulation by providing appropriate baselines and measuring emission reduction performance.

CRediT authorship contribution statement

Nisa Novita: Writing – original draft, Validation, Supervision, Project administration, Methodology, Data curation, Conceptualization. **Adibtya Asyhari:** Writing – original draft, Software, Formal analysis, Data curation. **Rasis P. Ritonga:** Writing – review & editing, Visualization, Software, Formal analysis. **Adi Gangga:** Writing – review & editing, Project administration. **Gusti Z. Anshari:** Writing – review & editing, Supervision, Conceptualization. **Joni Jupesta:** Writing – review & editing. **Jennifer C. Bowen:** Writing – review & editing. **Nurul Silva Lestari:** Writing – original draft. **J. Boone Kauffman:** Writing – review & editing. **Alison M. Hoyt:** Writing – review & editing. **Clarice R. Perryman:** Writing – review & editing. **Israr Albar:** Writing – review & editing. **Chandra Agung Septiadi Putra:** Investigation. **Wahyu Catur Adiugroho:** Writing – original draft. **Bondan Winarno:** Writing – review & editing. **Miguel Castro:** Writing – original draft. **Samantha Yeo:** Writing – review & editing. **Tryan Budiarna:** Formal analysis, Data curation. **Eko Yuono:** Formal analysis, Data curation. **Velyn C. Sianipar:** Formal analysis, Data curation.

Uncited references

Novita, 2016

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Nisa Novita reports financial support was provided by Bezos Earth Fund and The Jeremy and Hannelore Grantham Environmental Trust. Nisa Novita reports a relationship with Yayasan Konservasi Alam Nusantara that includes: funding grants. No conflict of interest. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.175829.

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