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Soil CO_2 flux of rewetted small-scale agricultural peatlands in West Kalimantan, Indonesia

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ABSTRACT

Indonesia hosts one of the largest tropical peatlands and several parts of which have been converted for agriculture, including small-scale systems. These practices have altered soil and ecological function, shifting their role from long-term carbon sinks into sources of carbon emissions. For years Indonesia employs rewetting as strategies for peatland restoration. This is implemented by constructing canal blocks to elevate the groundwater table (GWT), thereby mitigating carbon emissions. Furthermore, this study analyze soil CO_2 fluxes in rewetted small-scale agricultural peatlands, separating peat- and root-derived emissions to support emission factor refinement. The study conducted in four land uses—horticulture (HOR), rubber (RBB), oil palm (OPP), and secondary forest (DSF) in West Kalimantan, Indonesia. Soil CO_2 fluxes were measured using an Infrared Gas Analyzer with closed-chamber and devices to measured environmental factors. The result shows that the highest soil CO_2 flux was recorded in OPP, while the lowest was observed in DSF. Soil CO_2 flux in HOR, RBB, OPP, and DSF were 46.69, 44.46, 64.55, and 21.68 Mg CO_2 ha^{-1} yr^{-1}, respectively. GWT was the feature importance influencing soil CO_2 flux in all sites except DSF, where the soil moisture was the feature importance. These findings indicate that the moisture regime plays a crucial role in regulating soil CO_2 flux. When compared with default emission factors from national (2nd FREL) and global systems (IPCC), these findings revealed varying result. These differences explain the complexity of peatlands and highlight the potential value in refining emission estimates, especially for small-scale agricultural systems.

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1. INTRODUCTION

Tropical peatlands provide multiple ecosystem services, including hydrological and climate regulation, biodiversity conservation, and livelihood support from timber and non-timber forest products (Giesen et al., 2018; Kurnianto et al., 2015; Thornton et al., 2018). Tropical peatlands are characterized by persistent water saturation, anaerobic conditions, low pH, and nutrient-poor environments. These conditions limit organic matter decomposition and promote long-term accumulation of carbon-rich soil (Cobb & Harvey, 2019; Page & Baird, 2016). Tropical peatlands can store up to 20 times more carbon than typical tropical forests (Murdiyarso et al., 2019). Given their substantial ecological importance, maintaining the sustainability of these ecosystems is critical for preserving their carbon storage capacities.

However, land-use changes can compromise these functions, resulting in drought and disruption of the carbon storage function (Baird et al., 2017; Evers et al., 2017). Acknowledging the critical role of tropical peatlands in carbon storage, several studies have assessed their ability to store carbon and estimate it to be over 75 Gt C (Cobb et al., 2020; Dargie et al., 2017; Warren et al., 2017). Indonesia possesses one of the largest tropical peatlands globally, estimated at 13.43 million ha (Anda et al., 2021) and holds the majority of carbon storage reserves, with a final estimate of 28.1 Gt C (Warren et al., 2017). These large reserves highlight the strategic significance of Indonesian peatlands for regional and global climate change mitigation.

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Building on this context, a portion of Indonesia's peatlands, approximately 190,000 hectares (Miettinen et al., 2016), are managed by small-scale farmers who use traditional practices. Most of these practices rely heavily on fire as the primary method for land clearing (Medrilzam et al., 2017). Without strict local control, such burning can spread easily, causing extensive forest and peatland fires that exacerbate ecosystem degradation and release significant amounts of carbon into the atmosphere. Over time, this situation has worsened due to the construction of drainage canals, which lower the water table and disrupt the natural hydrological regime of peatlands (Hooijer et al., 2012). Drainage leads to irreversible peat subsidence through a combination of compaction, consolidation, and oxidation and the aerobic decomposition of organic matter that emits CO_2 into the atmosphere (Evans et al., 2019). Although small-scale plots are individually small, their collective area is extensive and significantly contributes to peatland carbon emissions in Indonesia.

Rewetting is a core component of Indonesia's peatland restoration strategy, aimed at re-establishing saturated conditions to suppress aerobic decomposition and reduce carbon loss (Dohong et al., 2018; Graham et al., 2017). This intervention typically involves the construction of canal blocks and other hydrological infrastructure to maintain GWT in 0.4 m depth (Indonesia's threshold for maximum GWT in cultivated area) and stabilize degraded peat systems. Restoration efforts gained urgency following the catastrophic 2015 fire event, which had widespread socio-economic and regional impacts. In response, the Indonesian government committed to restoring over two million hectares of degraded peatlands (Wardhana, 2016). To support this, the Indonesia Peatland Restoration Agency (BRG) was established in 2016, promoting the "3R" approach: rewetting, revegetation, and revitalization of local livelihoods (Dohong, 2017).

Although rewetting has been widely reported to reduce CO_2 emissions from managed peatlands and improve the carbon balance of previously drained tropical peat forests (Darusman et al., 2022; Lestari et al., 2022; Novita et al., 2024), site-specific evidence remains necessary to refine the EFs. However, long-term rewetting may also alter peat conditions (Negassa et al., 2019), because deeper GWT expand anoxic zones and reduces oxic peat layers (Girkin et al., 2025), thereby suppressing aerobic decomposition and potentially enhancing methanogenesis (Zhong et al., 2020). Recent evidence indicates that rewetting and GWT management can reduce emissions, although their effects on soil CO_2 flux remain specific and depend on interacting hydrological and environmental conditions (Hooijer et al., 2024; Mahardika et al., 2026; Sinclair et al., 2024).

Expanding measurements across diverse land use and peat conditions will support Indonesia's transition to higher-tier emission estimates. Without accurate CO_2 flux data, particularly from small-scale systems, national peatland carbon accounting will continue to rely on generalized factors, such as those presented in the IPCC Wetlands Supplement 2013 (Hiraishi et al., 2014). The urgency for obtaining such data lies in the fact that smallholder peatlands constitute a substantial yet underrepresented component of Indonesia's peatland carbon assessment. This study focuses on soil CO_2 flux in small-scale systems in West Kalimantan, where several parts of their peatlands are extensively managed by local farmers under low-input conditions, providing a realistic context for improving the accuracy of emission estimates in subnational carbon assessments.

Moreover, only a few studies have investigated CO_2 emissions from smallholder peatlands in Indonesia, including those by Agus et al. (2010), Jamaludin et al. (2020), Khasanah and van Noordwijk (2019), and N_2O and CH_4 emissions by Jovani-Sancho et al. (2023), indicating the need for broader and more detailed measurements. Therefore, this study aimed to quantify soil CO_2 fluxes from small-scale agricultural peatlands to complement the existing datasets and improve EF accuracy. The analysis differentiated between peat and root-derived sources to clarify their relative contributions, providing supplementary information for refining national emission estimates and enhancing the understanding of peatland carbon dynamics.

2. MATERIAL AND METHODS

2.1. Time and Site Description

The study was conducted from January to December 2023, and gas measurements were performed twice per month. The soil analyses were conducted at the Soil and Water Conservation Laboratory of IPB University, Bogor, and the Soil Chemistry and Fertility Laboratory of Tanjungpura University, Pontianak, Indonesia.

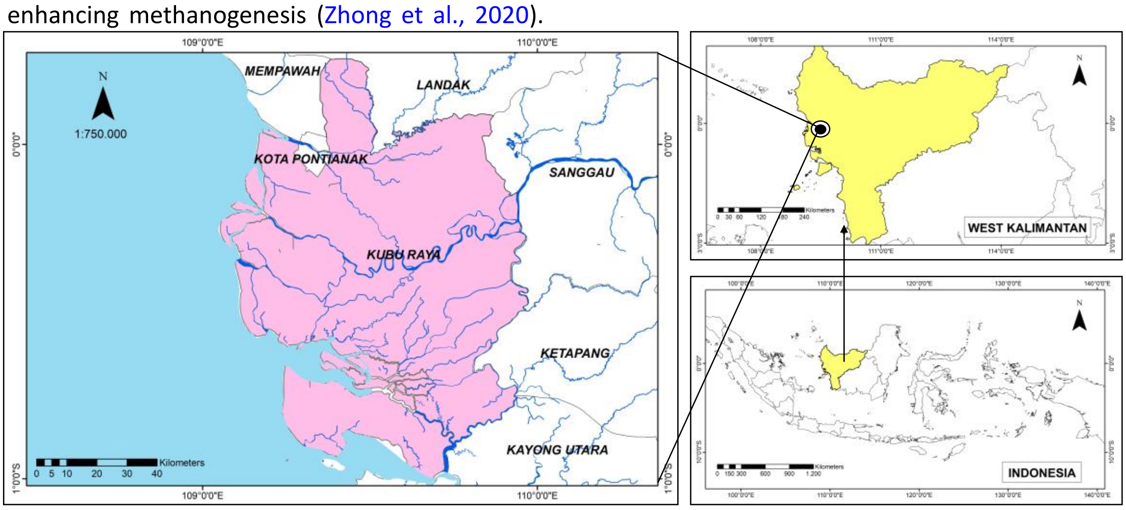

Figure 1. The study sites in Kubu Raya, West Kalimantan, Indonesia

The study site was in Kubu Raya, West Kalimantan, Indonesia divided based on land uses, *i.e*. Horticulture (HOR) at 0°10'36" S, 109°22'34" E, Rubber Plantation (RBB) at 0°10'37"S, 109°22'35"E; Oil Palm Plantation (OPP) at 0°10'35"S, 109°22'38"E; and Secondary Forest (DSF) at 0°5'24"N, 109°25'3"E, (see Fig. 1). All sites are peatland restoration program by the BRG, with rewetting activities conducted through canal blocking construction. HOR, RBB and OPP represent small-scale agricultural practices, whereas DSF represents a rewetted secondary forest.

The HOR, RBB, and OPP sites were situated within former transmigration areas established in the 1950s and were cultivated for approximately 30 to 60 years prior to the study period. The OPP plots, covering about 1 ha, consisted of ~7-year-old oil palm plantations, whereas the RBB plots, approximately 2 ha in size, contained ~15-year-old rubber trees. The HOR, covering approximately 1 ha, was managed using rotational and intercropping systems involving a variety of seasonal crops. These included chili, tomatoes, bitter melon, ginger, and other seasonal crops. The area was in fallow phase at the time of the study. Across all agricultural sites, land management practices remained traditional, relying predominantly on manual labor with minimal mechanization. In contrast, the DSF site has undergone prolonged and intensive drainage for more than two decades. Between 2018 and 2021, the BRG implemented rewetting measures across all sites via the construction of canal blocks.

2.2. Plot Establishment and Soil Measurement

Field instrumentation consisted of an Eijkelkamp peat auger, Kubiēna box with dimensions of 10 cm x 5 cm x 5 cm, and various field tools. The auger facilitated both the disturbed soil sample and piezometer installation holes. Soil sampling with the Kubiēna box occurred at plots 1, 3 and 5 (see Fig. 2), with no repeated sampling conducted within the same plot. The vertical interval for sampling was determined using GWT depth as determined in a preliminary survey. For average GWT depths of 0-50 cm, samples were collected at 20-30 cm depth. In deeper GWT scenarios (>50 cm), the sampling depth was adjusted to half the maximum GWT.

Several biophysical and chemical parameters were measured in the field and laboratory. Peat thickness and GWT were measured directly in the field using an Eijkelkamp peat corer and basic field tools, such as measuring tapes and stakes. The peat decomposition levels were assessed in the field using the Von Post method. Bulk density was determined using the gravimetric method, involving soil sampling with a Kubiēna box, drying in a Memmert UNB 400 oven at 105°C, and weighing with an analytical balance. The total porosity was also derived gravimetrically by using a pycnometer filled with 95% alcohol. The soil samples for chemical analysis were transported to the laboratory on the same day as collection for immediate preparation. Sample preparation included the determination of the initial moisture content, followed by air-drying for carbon and nitrogen analyses. In contrast, soil pH was measured directly on fresh samples without air-drying. Soil pH was measured using a SenseLine Plus FP70 (Prosense, Oosterhout, NL). The organic carbon (C-organic) content was quantified using the Loss on Ignition (LOI) method, employing an LOI furnace and an analytical balance. The total nitrogen (N-total) was analyzed using the Kjeldahl method.

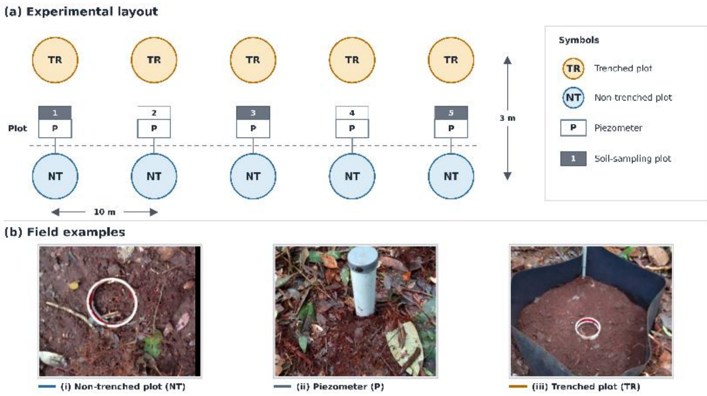

Figure 2. Layout of experimental plots and field instrumentation

2.3. Soil CO_2 Flux and Environmental Factors

Soil CO_2 flux measurements were conducted between 08:00 and 11:00 in the HOR, RBB, and OPP, whereas measurements in the DSF were performed between 10:00 and 11:00 because of limited site accessibility. Each plot was measured for two minutes with one additional replicate, and the most representative measurement was retained for analysis, whereas the others were excluded. Soil CO_2 flux was measured using an Environmental Gas CO_2 Monitoring 5 (EGM-5, PP System, MA, USA) infrared gas analyzer using the closed chamber method. The custom-designed stainless steel soil respiration chamber (SRC-2) had a height of 15 cm and a diameter of 10 cm. A soil temperature probe (STP-2) monitored the soil temperature (Ts) and soil moisture (RHs) concurrently in a soil surface layer of ~ 5 cm. Average air temperature (Ta) and air moisture (RHa) were measured using a Barometer Logger MHB-382SD (Lutron, TPE, TW). Soil CO_2 flux calculations employed the closed-chamber equation derived from the Ideal Gas Law (Madsen et al., 2009) detailed in Equation 1.

Soil CO_2 flux was differentiated based on its sources: heterotrophic respiration, autotrophic respiration and total respiration. Total respiration was measured in the non-trenched plot (NT), whereas heterotrophic respiration was measured in the trenched plot (TR) (Fig. 2). Autotrophic respiration was calculated by subtracting fluxes in the NT and TR plots. The trenching treatment (TR plots) was conducted by cutting plant roots at a depth of 60–70 cm using knives and saws. Trenches measuring 50 cm × 50 cm were constructed around the designated area, and plastic fiber sheets were installed along the trenches. Moreover, this study used ΔCO_2 data with R^2 ranging from 95% to 100%, where ΔCO_2 represents the temporal change in flux concentration derived from the linear regression analysis of scatter plots. The data analysis used flux values where NT > TR; otherwise, these values were excluded.

$$F = \Delta CO_2 \frac{P\,Ar\,(h/100)}{[(Tc + Ti)\,R]} \qquad [1]$$

Where F represents soil CO_2 flux (µg ΔCO_2 m^{-2}), ΔCO_2 denotes the change in CO_2 concentration (ppm s^{-1} or µmol s^{-1}), P is the pressure at the time of measurement (Pa), *Ar* is the atomic mass of CO_2 (44.01), *h* indicates the chamber height (15 cm), *Ti* is the standard temperature (273.15 K), *Tc* is the average soil temperature (°C), and *R* is the universal gas constant (J mol^{-1} K^{-1}). To calculate the annual average CO_2 emission, the soil CO_2 flux (*sF*) is converted into megagrams of CO_2 per hectare per year (Mg CO_2 ha^{-1} yr^{-1}) by multiply to area (in ha) and time period (in year).

2.4. Data Analyses

The soil CO_2 flux data were derived from the total flux of NT (non-trenched) plots, as these plots represent natural soil respiration conditions without root-cutting treatment. Statistical analyses were performed using Python (v3.12) in a Google Colab environment using the Pandas, Scikit-learn, and Matplotlib libraries. Principal Component Analysis (PCA) was conducted to examine the integrated relationships between soil CO_2 flux and soil properties. All CO_2 flux measurement data were retained to preserve natural variability, whereas soil properties measured at the plot level were aligned using mean-based interpolation to construct a unified analytical matrix. All variables were standardized prior to analysis to remove scale effects, and the first two principal components (PC1 and PC2) were extracted to represent the variance structure. PCA results were visualized using biplots to identify key soil gradients and assess land-use separation.

Furthermore, the effects of environmental factors on soil CO_2 flux were evaluated using a Random Forest regression framework to capture non-linear relationships and complex interactions among predictors. Each model comprised 500 bootstrap decision trees. Predictive performance was assessed primarily through grouped cross-validation using R^2, MAE, and RMSE, while OOB statistics were retained as supplementary diagnostics. Predictor relevance was quantified using cross-fitted permutation importance, and Accumulated Local Effects (ALE) plots characterized the direction and nonlinearity of associations within data-supported ranges. All analyses were interpreted as descriptive or predictive rather than causal.

3. RESULTS

3.1. Peat Properties

Peat profile analysis showed that the surface layers at HOR, RBB, and DSF were dominated by sapric peat with some hemic material, indicating advanced decomposition, whereas OPP was characterized by fibric peat, reflecting lower decomposition (Table 1). Higher peat decomposition was associated with increased bulk density, as observed at HOR and RBB under intensive smallholder management and at DSF due to long-term drainage despite its forest status. In contrast, OPP maintained a relatively low bulk density, likely due to the loss of more mature peat layers and the exposure of less decomposed material at the surface.

Table 1. Soil Properties in Study Sites

Variable	Unit	HOR	RBB	OPP	DSF
Peat Depth	cm	142.20 ± 2.64	236.20 ± 18.67	197.80 ± 28.48	628.0 ± 10.77
Bulk Density	g cm^{-3}	0.13 ± 0.01	0.148 ± 0.01	0.087 ± 0.01	0.146 ± 0.02
Total Porosity	%	85.28 ± 0.46	86.59 ± 0.16	91.94 ± 0.42	90.18 ± 1.17
Peat Decomposition	-	hemic-sapric	hemic-sapric	fibric	hemic-sapric
pH (H_2O)	-	4.36 ± 0.20	3.84 ± 0.07	4.18 ± 0.04	3.98 ± 0.15
C-Organic	%	43.78 ± 9.15	47.63 ± 4.72	50.50 ± 1.65	42.22 ± 8.11
N-Total	%	1.66 ± 0.06	1.34 ± 0.29	1.80 ± 0.05	1.43 ± 0.13
C/N	-	26.36	35.54	28.06	29.52

Remarks: Peat decomposition represents the decomposition level at the 50 cm surface layer. OPP = Oil Palm Plantation; RBB = Rubber Plantation; DSF = Secondary Forest; HOR = Horticulture.

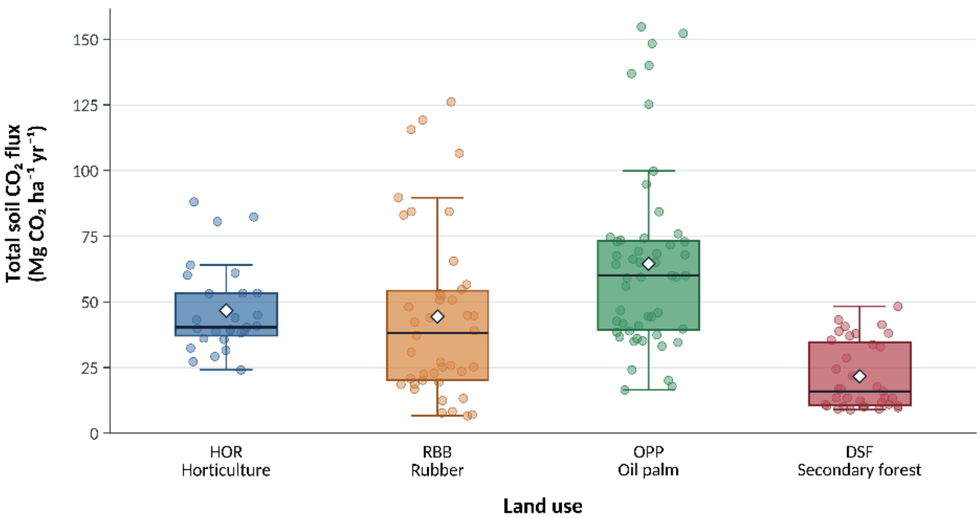

Figure 3. Distribution of soil CO_2 fluxes (total respiration) across study sites.

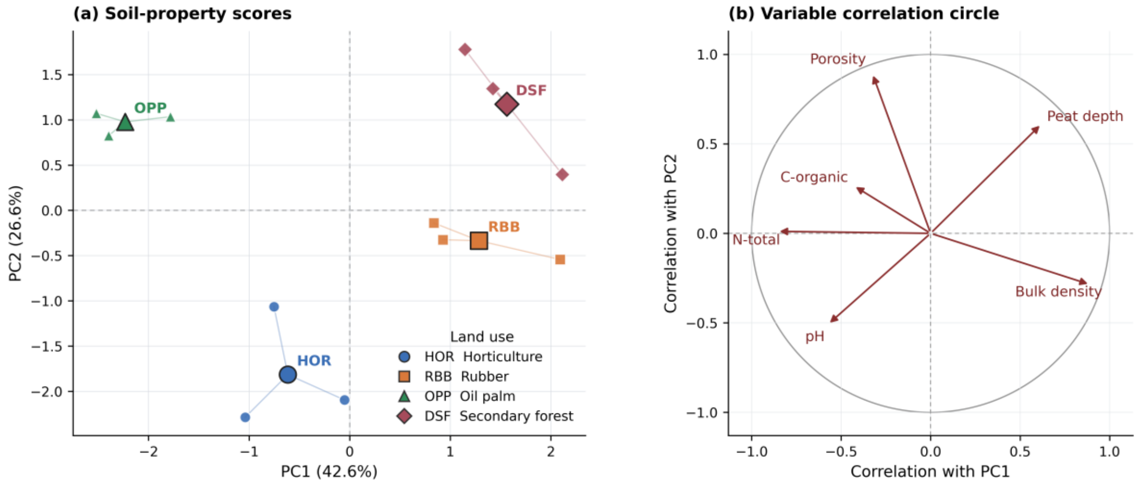

Figure 4. . PCA of peat properties across study sites. (a) Scores for soil-property replicates per land use; large symbols denote land-use centroids and spokes show within-group dispersion. (b) Correlations of soil variables with PC1 and PC2.

This pattern is consistent with the understanding that peat structural changes result from oxidation, compaction, shrinkage, and long-term subsidence (Hooijer et al., 2012; Sinclair et al., 2020). The soil chemical properties (Table 1) further reflected minimal external inputs and limited soil management across all sites, with consistently low pH based on the Indonesian Soil Research Institute fertility thresholds (Eviati et al., 2023) and higher total nitrogen and C-organic ratios. These results confirmed that soil fertility remained poor, likely due to the absence or limited use of fertilizer and soil amendments.

The PCA results (Fig. 4) indicated that the first two principal components explained 69.2% of the total variance, with PC1 accounting for 42.6% and PC2 accounting for 26.6%. PC1 represents the dominant gradient separating land use according to the degree of disturbance and management intensity, where bulk density shows the strongest positive loading, while CO_2 flux (*F_CO_2*), soil organic carbon, total nitrogen, and pH exhibited strong negative loadings. This pattern suggests that increased peat compaction and structural degradation in managed land use (HOR, RBB, and OPP) are closely associated with shifts in soil chemical properties and elevated CO_2 fluxes. In contrast, PC2 reflected a gradient of intrinsic peat physical characteristics, primarily driven by porosity and peat depth, both of which showed high positive loadings. This gradient clearly distinguishes DSF from cultivated land use, with DSF characterized by deeper, more porous, and relatively less degraded peat. The proximity of the *F_CO_2* vector to pH and organic carbon further indicates that variations in CO_2 flux are mainly governed by changes in organic matter quality and soil chemical conditions induced by land-use conversion rather than by peat depth alone.

3.2. Soil CO_2 Flux and Environmental Factors

The results showed that soil CO_2 fluxes varied across the sites, as presented in Table 2. Furthermore, the CO_2 flux data were highly variable across land use types, as shown in boxplots (Fig. 3). However, the mean values were used to represent average emissions and allow comparison with values reported in previous studies. In the HOR, heterotrophic respiration contributed the largest portion of the total flux, indicating that the microbial decomposition of soil organic matter dominated the CO_2 release. Conversely, in OPP, autotrophic respiration formed a substantial share of the total flux, highlighting the influence of root activity and plant physiological processes in these systems. RBB and DSF maintained a relatively small contribution between autotrophic and heterotrophic components. These findings emphasize that peat soil CO_2 flux may not only be determined by land-use type but also by vegetation structure and peat condition. These patterns suggest that land use type influences not only the magnitude but also the source contribution of soil CO_2 fluxes.

The environmental factors influencing the soil CO_2 flux were comprehensively monitored, as presented in Table 3. Random Forest regression analysis (Fig. 5 & 6) revealed that soil CO_2 flux was consistently dominated by subsurface variables, with GWT identified as the primary feature importance in most locations, except for DSF, where RHs exerted the strongest influence. Based on the ALE plots (Fig. 7), no common critical threshold pattern was observed for GWT, as its relationship with soil CO_2 flux differed among locations; conversely, HOR and RBB exhibited the most variable and least predictable pattern. Regarding model performance, the DSF and OPP sites demonstrated the highest predictive accuracy, with OOB R^2 values of 0.46 and 0.25, respectively, in contrast to the RBB site, which showed the lowest accuracy (OOB R^2 = 0.14) and highest mean absolute error (OOB MAE = 29.0). Globally, these results confirm that GWT and RHs serve as significantly influential environmental drivers compared to atmospheric variables (Ta and RHa), which maintain consistently low relative importance across all sitess.

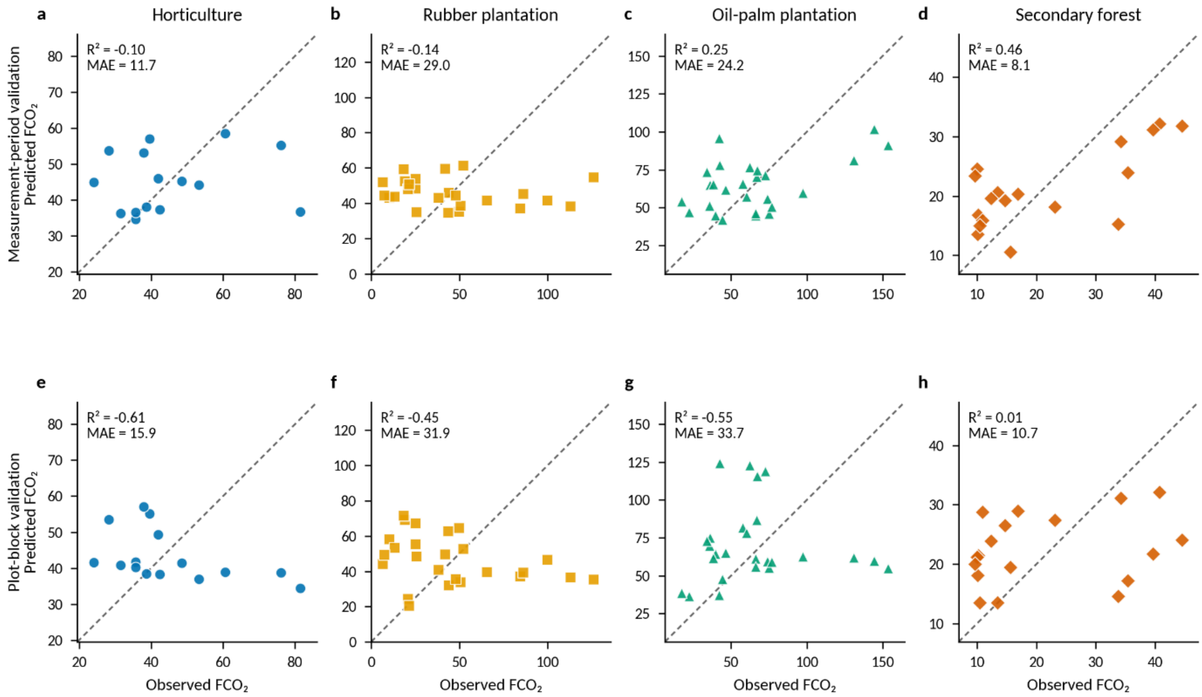

Figure 5. Observed and Random Forest-predicted soil CO_2 (Mg CO_2 ha^{-1} yr^{-1}) flux under measurement-period validation (a–d) and plot-block validation (e–h).

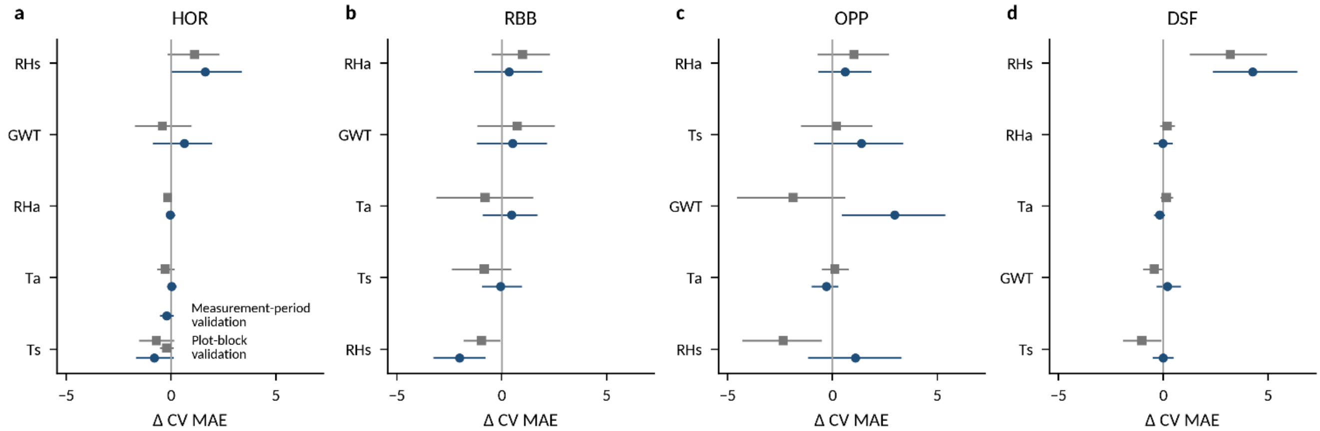

Figure 6. Permutation importance of environmental predictors in the Random Forest models, expressed as the change in cross-validated MAE (Δ CV MAE) after 200 random permutations. Circles represent measurement-period validation and squares represent plot-block validation, while bars indicate the 5th–95th percentile range. Positive values indicate greater predictive relevance. Results were interpreted only for models with positive R^2.

4. DISCUSSION

These results directly indicate that, even under smallholder management, land-use intensity substantially shapes the magnitude of peat- and root-derived CO_2 emissions (see Table 2). In OPP, the particularly high fluxes are attributed to the dominance of root (autotrophic) respiration and the presence of fibric peat, which together enhance CO_2 release through both biological and physical pathways. The proportion of autotrophic respiration in the OPP was higher than that in Sarawak (34%) (Ishikura et al., 2018) and Riau (47.6%) (Jamili et al., 2021), further indicating that the combined effects of peat decomposition level, land management practices, and plantation age (Dariah et al., 2014; Matysek et al., 2018) jointly regulate site-specific emission magnitudes. Although the total fluxes in the OPP were lower than those recorded in Jambi (Khasanah & van Noordwijk, 2019), they were still higher than those in similar systems in Kubu Raya (Jamaludin et al., 2020). The higher heterotrophic respiration in the HOR, exceeding the 62% proportion reported for small-scale peatlands in Aceh (Agus et al., 2010), confirms that horticultural peatlands, although limited in size, can contribute disproportionately to the total emissions, particularly under persistent drainage and soil exposure.

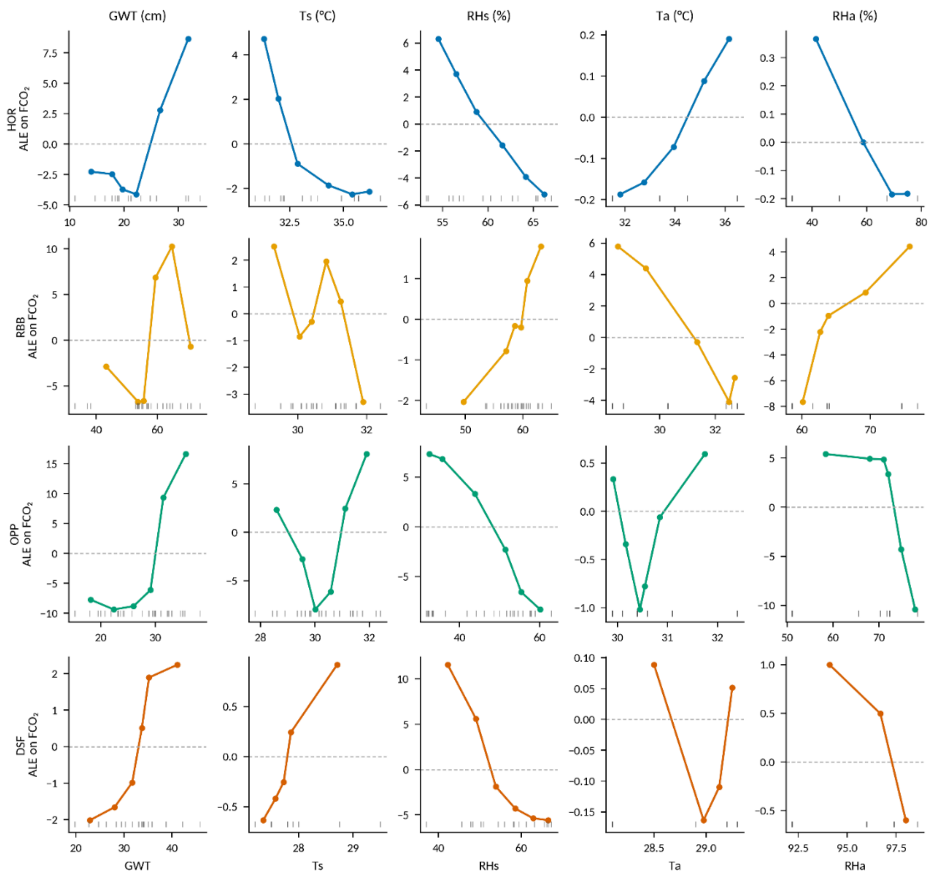

Figure 7. Exploratory ALE of environmental factors on site-specific Random Forest predictions. Curves are centred at zero; rug marks show observed predictor distributions. Curves from models with non-positive grouped R^2 should not be interpreted as transferable ecological response functions or management thresholds.

Table 2. Soil CO_2 Flux and Its Components Across Study Sites

Land use/site	Total Respiration	(%)	Heterotrophic Respiration	(%)	Autotrophic Respiration	(%)
	(Mg CO_2 ha^{-1} yr^{-1})					
Horticulture	46.69 ± 16.40	(100)	35.38 ± 13.95	(75.78)	11.31 ± 10.81	(24.22)
Rubber	44.46 ± 31.95	(100)	23.06 ± 22.69	(51.87)	21.95 ± 21.95	(48.13)
Oil Palm	64.55 ± 34.13	(100)	29.37 ± 13.12	(45.50)	35.17 ± 25.31	(54.49)
Secondary Forest	21.68 ± 12.21	(100)	11.33 ± 6.71	(52.26)	10.35 ± 8.63	(47.74)

Table 3. Measured environmental factors

Site	GWT (cm)	*Ts* (°C)	*RHs* (%)	*Ta* (°C)	*RHa* (%)
Horticulture	22.07 ± 6.69	33.73 ± 1.90	59.59 ± 4.49	33.98 ± 1.65	59.99 ± 18.03
Rubber	59.19 ± 10.04	30.67 ± 0.80	58.88 ± 3.65	31.04 ± 1.83	66.81 ± 6.86
Oil Palm	27.33 ± 5.88	30.30 ± 1.17	44.93 ± 12.09	30.73 ± 0.82	69.46 ± 7.79
Secondary Forest	32.20 ± 6.44	27.78 ± 0.55	55.37 ± 8.40	28.89 ± 0.45	96.20 ± 2.36

Remarks: GWT = Groundwater Table; *Ta* = Air Temperature; *Ts* = Soil Temperature; *RHa* = Air Humidity; *RHs* = Soil Humidity; n = 27 for HOR, 42 for RBB; 51 for OPP and 35 for DSF.

Table 4. Comparisons with National FREL and IPCC Default Emission Factors

This Study	2nd FREL	IPCC Default Value
Land Use (value in Mg CO_2 ha^{-1} yr^{-1})		
Horticulture (46.69)	Mixed Dry Agriculture (54.66)	Cropland and fallow, drained (51.38)
Oil Palm (64.55)	Pure Dry Agriculture (45.42)	Plantations, drained, oil palm (40.37)
Rubber (44.46)	Pure Dry Agriculture (45.42)	Plantations, drained, oil palm (40.37)
Secondary Forest (21.68)	Secondary Swamp Forest (32.42)	Forest Land and cleared, drained (19.45)

Remarks: the emission factors used in Indonesia's 2nd FREL (Tier 2, Budiharto et al. (2022)) and IPCC (Tier 1, Hiraishi et al. (2014)).

Furthermore, the total CO_2 fluxes were higher than those reported for ginger cultivation in Kubu Raya, West Kalimantan (Jamaludin et al., 2020). The RBB site exhibited moderately lower emissions than small-scale rubber agroforestry systems in Jambi (Khasanah & van Noordwijk, 2019) but was closely aligned with those observed in West Kalimantan (Jamaludin et al., 2020).

In contrast, the DSF site showed the lowest soil CO_2 flux among all land uses, comparable to rewetted peat forests in Central Kalimantan (Darusman et al., 2022) but much lower than that of secondary forests in Ketapang, West Kalimantan (Basuki et al., 2021), and remnant forests (Khasanah & van Noordwijk, 2019). These results highlight that even after previous drainage, certain secondary forest sites can retain relatively low emission rates owing to moisture retention, denser vegetation cover, and minimal disturbance history, supporting the effectiveness of rewetting in reducing CO_2 emissions.

Despite the previous drainage, the relatively low fluxes in the DSF suggest that rewetting and vegetation recovery successfully suppressed aerobic decomposition through improved soil moisture retention and canopy cover. The consistently lower emissions in DSF compared with other land uses in this study supports the view that rewetting is an effective mitigation strategy for reducing peat-derived CO_2 while promoting ecological recovery. Similar findings from Mempawah, West Kalimantan (Novita et al., 2024), reported that rewetting reduced heterotrophic and total respiration in palm oil plantations by 34% and 20%, respectively, whereas another study reported reductions of up to 39% in rubber and 36% in oil palm systems (Lestari et al., 2022). However, peat-derived CO_2 emissions remained above 80% post-rewetting, indicating that organic matter mineralization continued even after hydrological restoration. These findings collectively emphasize that rewetting lowers, but does not eliminate, carbon emissions, because its effectiveness depends strongly on local peat properties and moisture dynamics (Grand-Clement et al., 2015; Mahardika, Tarigan, et al., 2024).

The Random Forest regression results demonstrate that hydrological variables dominate the control of soil CO_2 flux across land use types, with GWT consistently identified as the most influential feature at HOR, OPP, and RBB, confirming that moisture-related factors are the primary drivers of the fluxes. An exception was observed at the DSF site, where RHs exerted feature dominance (Fig. 5 & 6). Previous studies have reported a strong relationship between GWT and RHs (Taufik et al., 2019; Widiarso et al., 2020), which emerged as the dominant factor influencing soil CO_2 flux in this study. Partial Dependence Plots revealed clear threshold responses, where the CO_2 flux increased sharply once the GWT declined beyond ~25 cm at the HOR and ~30 cm at the OPP, indicating the enhanced aerobic decomposition of peat organic matter under deeper drainage conditions (Carlson et al., 2015; Husen et al., 2014; Mahardika, Anshari, et al., 2024). At the DSF site, RHs emerged as the dominant control on CO_2 flux, consistent with evidence that peat respiration peaks at intermediate moisture levels and declines under both excessively dry and near-saturated conditions (Comeau et al., 2021). In contrast, RBB exhibited highly variable and less predictable emission patterns, as reflected by low model performance (OOB R^2 = 0.216), suggesting greater heterogeneity in management and micro-hydrological conditions. Soil moisture and temperature showed higher relative importance than atmospheric variables (*T*a and *RH*a), which consistently played a minor role, differing from studies that emphasized temperature as a primary control (Marwanto & Agus, 2014; Sjögersten et al., 2018).

When evaluated against reference emission factors, CO_2 fluxes in HOR, RBB, and DSF were lower than or close to both IPCC Tier-1 and Indonesia's 2nd FREL defaults, whereas OPP exceeded both (Table 4). These comparisons demonstrate that generalized default EFs often fail to represent accurately small-scale systems because they overlook local differences in management intensity, cultivation cycles, and hydrological regulation. In smallholder peatlands, minimal fertilizer use, short cultivation periods, and irregular water control create emission patterns distinct from large-scale, intensively drained plantations that underpin most Tier-1 and Tier-2 estimates. The variability observed across sites reinforces the need for EFs that account for site-specific environmental and hydrological conditions. As shown by Murdiyarso et al. (2024), CO_2 emissions from undrained and rewetted peatlands differ substantially depending on GWT, peat degradation, and site condition—where CH_4 emissions decline rapidly after rewetting, but heterotrophic CO_2 fluxes may take decades to stabilize. Similarly, He and Roulet (2023) refined the IPCC EF of northern peatlands by incorporating seasonal variability and hydrological stratification, reducing uncertainty nearly threefold. These insights align with the findings of this study, which emphasize that the GWT and soil moisture regime act as the dominant environmental control of CO_2 fluxes.

Nevertheless, the observation period may not capture seasonal or interannual variations in CO_2 flux, whereas unmeasured differences in microtopography and site-level management could have introduced spatial variability that was not fully reflected in the regression analysis. Future research should prioritize long-term and continuous measurements across a wider range of smallholder peatland uses to improve emission factor precision and to better evaluate the long-term impacts of rewetting and low-input agricultural practices on peat carbon dynamics.

5. CONCLUSION

Among the observed sites, oil palm plantations showed the highest total soil CO_2 fluxes, while secondary forests tended to have the lowest emissions. These results suggest that land use influences the magnitude and sources of soil CO_2 fluxes in small-scale peatland systems, with environmental regulation predominantly controlled by several factors. Furthermore, this study provides additional information that may support future refinement of Indonesia's emission factors toward higher-tier approaches. Further research covering a wider range of peat conditions, management practices, and seasonal variations is needed to enhance the understanding of CO_2 flux dynamics in small-scale tropical agricultural peatlands.

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Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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