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# Post-revegetation carbon dioxide emissions from various peatland cover types in the Sriwijaya Botanical Garden, South Sumatera, Indonesia

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Tropical peatlands are vital carbon reservoirs, yet their degradation and partial revegetation leave uncertainties about post-revegetation carbon dynamics, particularly CO<sub>2</sub> emissions across different vegetation types. This study aimed to assess the emissions from four revegetated peatland cover types in the Sriwijaya Botanical Gardens, South Sumatera. Emission measurements representing soil-atmosphere CO<sub>2</sub> fluxes using soil chambers were conducted weekly from September 18, 2024, to February 12, 2025, in conjunction with observations of groundwater levels, soil temperatures, and air temperatures. Weekly emission rates were extrapolated to estimated annual CO<sub>2</sub> emission expressed in ton ha<sup>-1</sup> year<sup>-1</sup>. Emission data were collected using an infrared gas analyzer on four peatland cover types: *Shorea belangeran* (belangeran) stands planted in 2015 and 2020; *Fagraea fragrans* (tembesu) stands planted in 2015; and a secondary forest dominated by *Melaleuca leucadendron* (gelam). Measurements were conducted in triplicate for each cover type. The results showed that the highest CO<sub>2</sub> emissions were recorded in the Belangeran 2020 stand, closely followed by the Tembesu 2015 stand, with nearly identical values of 36.6 and 36.0 t CO<sub>2</sub> ha<sup>-1</sup> year<sup>-1</sup>, respectively. However, these values were not significantly different from emissions measured in other peatland cover types. The elevated emissions in the Belangeran 2020 stand correlate with higher annual average soil and air temperatures (30.2 °C and 31.1 °C, respectively), resulting from a fire event in 2019. In the Tembesu 2015 stand, elevated emissions are primarily linked to a deeper groundwater level (–52 cm) and potential contributions from root respiration. Environmental variables, such as groundwater level, soil temperature, and air temperature showed significant relationships with CO<sub>2</sub> emissions across all peatland cover types in the Sriwijaya Botanical Gardens, although their relative influences varied among stands. These findings offer additional insights into the biophysical drivers of peatland carbon fluxes and underscore the importance of species selection, canopy structure, and groundwater level dynamics in enhancing revegetation outcomes and supporting peatland management strategies.

## KEYWORDS

groundwater level dynamics, peatland cover types, post-revegetation CO<sub>2</sub> emissions, soil and air temperature, tropical peatland revegetation

## 1 Introduction

Peatland ecosystems are crucial for maintaining the global climate equilibrium; contributing to water balance; providing biodiversity, food, fiber, and wood; and serving as a carbon sink and storage (Page and Baird, 2016; Sasmito et al., 2025). Peatlands constitute merely 3% of the Earth's surface but sequester one-third of the global soil carbon (Dargie et al., 2017). Approximately 11% or 411,025 km<sup>2</sup> of the global peatlands are located in tropical regions, with an estimated carbon storage of 88.6 Gt (Page et al., 2011). Indonesia possesses important tropical peatlands, with an estimated distribution of approximately 134,300 km<sup>2</sup> and a carbon storage capacity of 57.4 Gt (Page et al., 2011; Anda et al., 2021).

Population growth and increasing land demand have intensified the pressure on peatlands (Budiman et al., 2020; Dharmawan et al., 2024; Yuwati et al., 2021). Insufficient understanding and knowledge regarding the sustainable management and utilization of peatlands have resulted in varying levels of degradation (Bakri et al., 2025; Harahap et al., 2023; Lestari et al., 2024). The degradation process often begins with uncontrolled logging or tree felling in peat swamp forests typically followed by land conversion to plantations and the establishment of industrial plantation forests involving extensive canal construction (Miettinen et al., 2017; Cooper et al., 2019). These activities ultimately prompt widespread peatland degradation and an increasing need for peatland restoration in Indonesia. In response, the Indonesia government through the Peatland Restoration Agency (Badan Restorasi Gambut, BRG), has implemented large scale peatland restoration program focussing on rewetting via canal blocking, revegetation with native species, and the revitalization of local livelihoods to ensure long term sustainability (Yuwati et al., 2021; Harrison et al., 2020).

In accordance with the Indonesian government's policy to restore 2 Mha of peatlands from a total of 13.43 Mha (Anda et al., 2021), various initiatives have been implemented in South Sumatera to rehabilitate degraded peatlands. These efforts encompass both conservation and restoration activities, including the establishment of the Sriwijaya Botanical Gardens, which while not an official target of the national peatland restoration program implemented by Peatland Restoration Agency (BRG), support its objectives through site level peatland restoration practices. These botanical gardens, overseen by the Regional Research and Development Agency of South Sumatra Province, were established on 100 ha of peatlands located within the Musi Belida Peat Hydrological Unit (KHG). This area was formerly designated as a production forest; however, it was heavily exploited and subsequently converted into an oil palm plantation (Maryani et al., 2017; Maryani and Novriadhy, 2023).

The Sriwijaya Botanical Gardens serve as a Special Purpose Forest Area (KHDTK: *Kawasan Hutan Dengan Tujuan Khusus*) developed for research, development, education, conservation, and recreation. As the site is located on degraded peatland that was previously land cleared to palm oil plantation development, its establishment represent a site level effort to rehabilitated the ecosystem. The garden is develop using a thematic approach, with the specialized zone, including medicinal, ornamental, and peat gardens (Defriyanti et al., 2018),

the latter specifically designed to support peatland restoration through revegetation, ecological recovery and improved peatland management. As part of this restoration effort, several tree species cultivated in this KHDTK are native peatland species, including Jelutung (*Dyera lowii*), Belangeran (*Shorea belangeran*), Tembesu (*Fagraea fragrans*), and Pulau Rawa (*Alstonia pneumatophora*) (Maryani and Novriadhy, 2023). Research has indicated that these tree species possess strong potential for peatland restoration (Lampela et al., 2017; Smith et al., 2022) and can greatly contribute to carbon sequestration efforts (Budiman et al., 2020; Junaedi et al., 2024).

In addition to the use of different tree species, revegetation activities in the Sriwijaya Botanical Gardens have been implemented with varying levels of intervention, resulting in fire events of differing frequencies experienced. Some planting plots underwent intensive maintenance, whereas others were subjected to minimal intervention. Similarly, the fire history varied; certain plots experienced two fire events in 2014 and 2019, whereas others were affected by a single fire event in 2014. Because tree planting occurred after fires, the trees were of different ages. The variations in tree species, maintenance intensity, and fire history across revegetation plots in the Sriwijaya Botanical Gardens have resulted in distinct environmental conditions in each plot. This variation results in differences in the magnitude of the emissions across each plot. Therefore, the effectiveness of peat revegetation and conservation efforts in this area warrants further investigation, particularly concerning post-revegetation CO<sub>2</sub> emissions. Investigating and analyzing field-level CO<sub>2</sub> emissions from revegetation activities using various tree species and management interventions are essential for evaluating revegetation outcomes and informing adaptive management strategies (Husnain et al., 2014; Mander et al., 2024; Frianto et al., 2024; Yang et al., 2023).

In this study, we aimed to analyze CO<sub>2</sub> emissions across various peatland cover types in the Sriwijaya Botanical Gardens after implementation of revegetation intervention using high-resolution time series data and assess how groundwater table depth, soil temperature, and air temperature influence emission dynamics. Specifically we (i) compared fluxes among different vegetation types, (ii) tracked temporal variation across seasons, and (iii) identified key environmental drivers. The findings of this study are anticipated to advance our understanding of how post-revegetation peatlands cover types modulated carbon dioxide emissions under varying environmental conditions, and provide a theoretical basis for optimizing species selection, canopy development, and hydrological management in tropical peatland revegetation efforts.

## 2 Materials and methods

### 2.1 Study area description

This study was conducted on peatlands within the Sriwijaya Botanical Gardens located in the Musi-Belida River Peat Hydrological Unit (KHG), Ogan Ilir District, South Sumatra Province (Figure 1). The geographically coordinates are 104°31'23.26"–104°33'9.16"E and

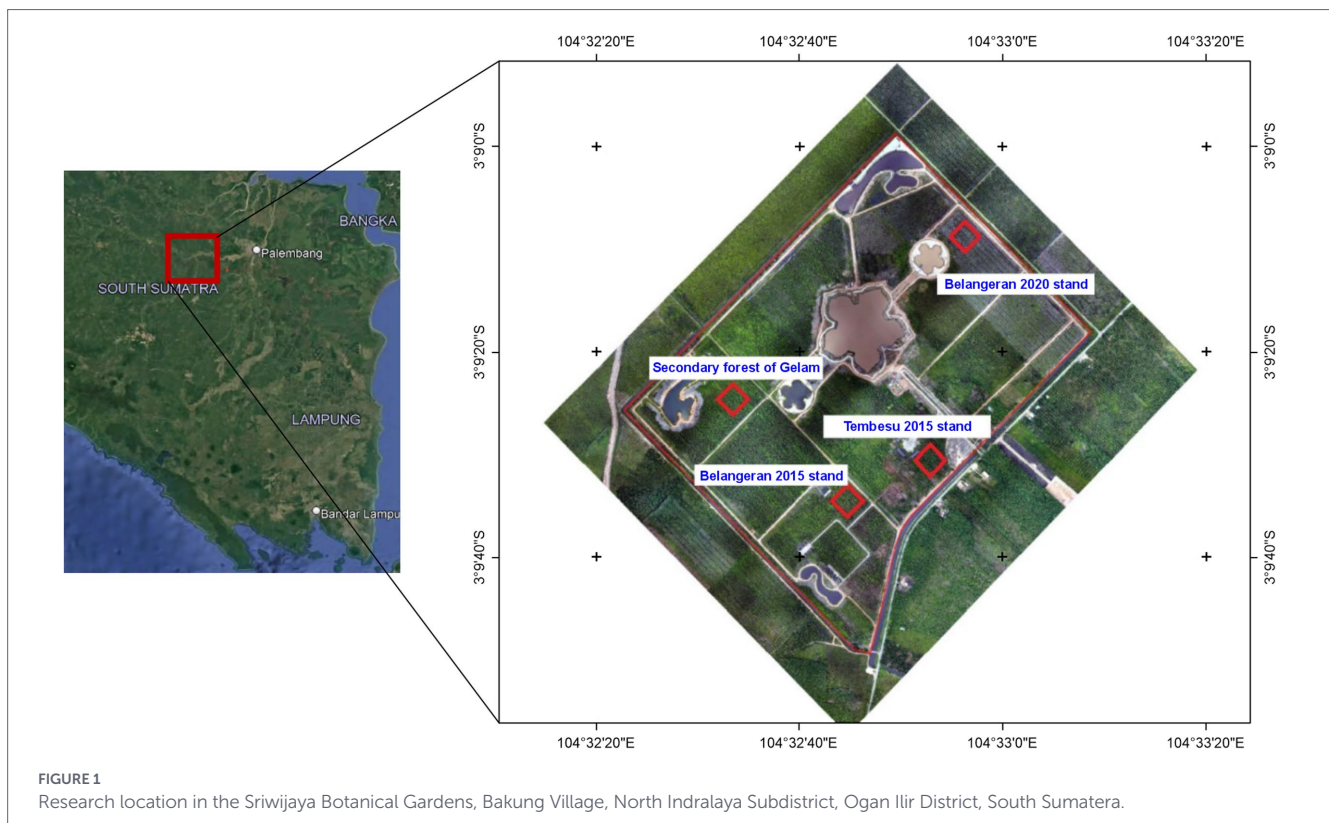


FIGURE 1

Research location in the Sriwijaya Botanical Gardens, Bakung Village, North Indralaya Subdistrict, Ogan Ilir District, South Sumatera.

$3^{\circ}8'58.46''$ – $3^{\circ}9'48.64''$ S. The Sriwijaya Botanical Gardens constitute a Special Purpose Forest Area (KHDTK) established under the Decree of the Minister of Forestry No. 485/Menhut-II/2012. This area is designated for conservation, research, development, environmental education, ecotourism, and environmental services (Defriyanti et al., 2018; Herawati and Maryani, 2018). The botanical gardens cover approximately 100 ha of peatland. The topography is predominantly flat with a slope of less than 1% and an elevation ranging from 17 to 23 m above sea level (Herawati and Maryani, 2018).

The Sriwijaya Botanical Gardens were established in peatlands formerly designated as production forests. The initiative began in 2010, with planting preparations commencing in 2014. Prior to development, the area functioned as a four-year-old oil palm plantation and had experienced considerable drainage (Herawati and Maryani, 2018). Currently, the botanical gardens are revegetated with various tree species, including *Fagraea fragrans* (tembesu), *Shorea belangeran* (belangeran), *Alstonia pneumatophora* (pulai), and *Dyera lowii* (jelutung), all of which exhibit different stand ages. The age differences were primarily attributable to recurrent fires in the area, particularly in 2014 and 2019, which led to replantation efforts in affected plots. The site is characterized by seasonal flooding during the rainy season, with groundwater levels ascending to 40 cm, and highly susceptible to fire during the dry season (Defriyanti et al., 2018).

The most effective revegetation species that thrived and established forest stands following the fires in 2014 and 2019 at the Sriwijaya Botanical Garden were Tembesu and Belangeran; in contrast, areas where revegetation efforts failed tended to develop into secondary forests naturally dominated by Gelam. In further developments, the vegetation in the Sriwijaya Botanical Gardens developed into Belangeran stands planted in 2015 and 2020, Tembesu stands

planted in 2015, and secondary forest of Gelam. Each stand group exhibited varying densities and growth in diameter, height, and volume (Table 1). The most substantial tree dimensions, including diameter at breast height, height, and volume per hectare, were observed in Tembesu 2015 stands, whereas the least were recorded in Belangeran 2020 stands. Soil characteristics, including soil moisture, bulk density, organic material, and C-organic content, varied among the stands (Table 2).

The Sriwijaya Botanical Gardens were established on degraded peatlands with peat depths ranging from 207–454 cm. Upon the commencement of construction, the area experienced extensive drainage, followed by the cultivation of palm oil. The canal network was structured by constructing a conservation reservoir centrally and installing water gates at the southern edge of the area (Figure 2). Water gates in peatland conservation areas regulate water levels and maintain the ecological balance of peat ecosystems. The water gates are kept closed under normal conditions and opened only during flooding events, however, they are not in optimal condition. Consequently, the gates are unable to effectively retain the water level, particularly during prolonged dry season.

## 2.2 Measurement of emissions and environmental factors

Emission measurements were conducted on four types of peatland cover within the Sriwijaya Botanical Gardens: *Shorea belangeran* (belangeran) stands planted in 2015 after the fire in 2014 and planted in 2020 after the fire in 2019; *Fagraea fragrans* (tembesu) stands planted in 2015 after the fire in 2014; and secondary forest dominated by *Melaleuca leucadendra* (gelam), which also emerged after the fire in 2014. Measurements were performed using an infrared gas analyzer (IRGA; LI-830, LI-COR, NE, USA). The measurement chamber was

TABLE 1 Vegetation characterization of various peatland covers in the Sriwijaya Botanical Gardens, South Sumatera.

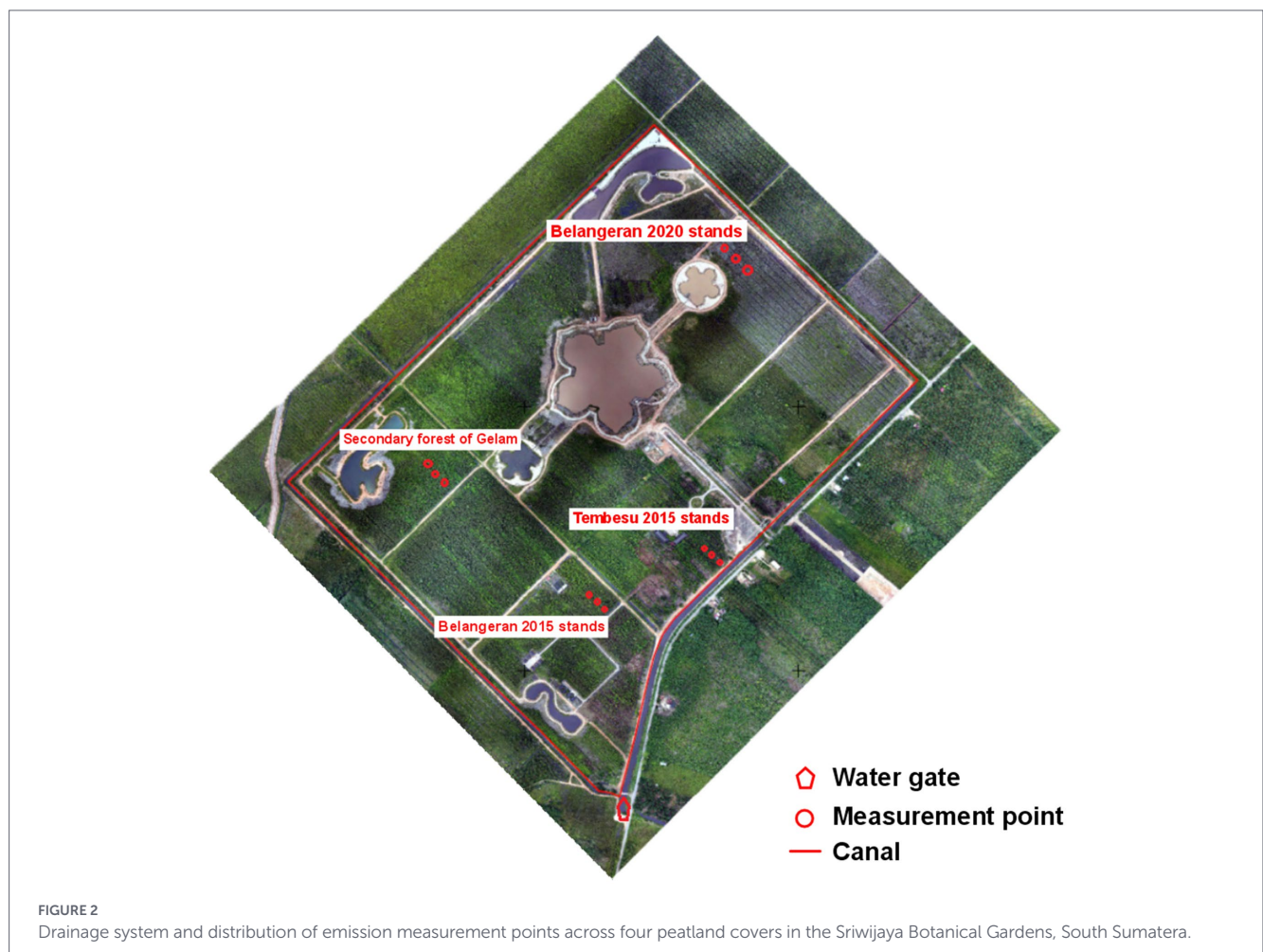
Peatland Cover	Age (year)	Density (N ha <sup>-1</sup> )	Diameter at breast height average (cm)	Height average (m)	Volume (m <sup>3</sup> ha <sup>-1</sup> )
BLGR 2015	10	1,665 ± 283	8.8 ± 0.5	9.4 ± 0.4	82.7 ± 12.3
BLGR 2020	5	1,215 ± 406	4.1 ± 0.6	3.9 ± 0.4	4.9 ± 0.6
SF GLM	10	3,360 ± 829	5.1 ± 1.3	4.8 ± 1.7	31.1 ± 26.7
TBS 2015	10	1,205 ± 304	12.1 ± 0.8	10.6 ± 0.6	114.9 ± 15.6

Remark: BLGR 2015, BLGR 2020, SF GLM, and TBS 2015 refer to the Belangeran 2015 stand, Belangeran 2020 stand, secondary forest of Gelam, and Tembesu 2015 stand, respectively.

TABLE 2 Soil characteristics at a depth of 0–50 cm across various peatland covers in the Sriwijaya Botanical Gardens, South Sumatera.

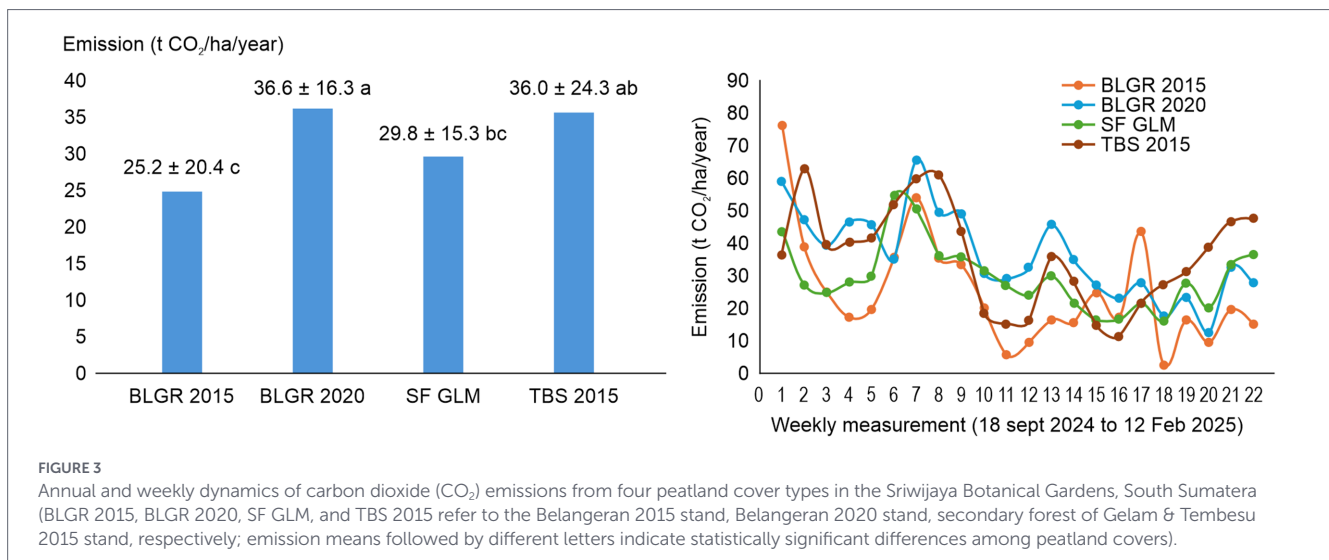
Peatland cover	Moisture content (%)	Bulk density (gr/cc)	Organic material (%)	C-organic (%)
BLGR 2015	91.2 ± 0.4	0.10 ± 0.00	86.4 ± 7.1	45.0 ± 3.7
BLGR 2020	92.2 ± 1.2	0.08 ± 0.01	94.2 ± 3.3	49.0 ± 1.7
SF GLM	88.3 ± 1.9	0.11 ± 0.05	88.2 ± 3.5	45.9 ± 1.8
TBS 2015	84.4 ± 4.3	0.16 ± 0.04	68.8 ± 18.1	35.8 ± 9.4

Remark: BLGR 2015, BLGR 2020, SF GLM, and TBS 2015 refer to the Belangeran 2015 stand, Belangeran 2020 stand, secondary forest of Gelam, and Tembesu 2015 stand, respectively.



constructed using a 25.4 cm diameter polyvinyl chloride (PVC) pipe truncated to a length of 25 cm. Each chamber was embedded in the peat soil to a depth of 5–10 cm, with 15–20 cm remaining above the ground surface for gas sampling and emission assessments.

Emission measurements were conducted for each peatland cover type. Measurements were conducted in triplicate for each cover type. Emission measurements were conducted for each peatland cover type using three spatial replicates (*n* = 3). Each replicate consisted of a



permanently installed chamber collar representing an independent sampling plot within each cover type. Chamber collars were installed at fixed locations and remained in place throughout the monitoring period. CO<sub>2</sub> fluxes measurements were repeatedly conducted at the same fixed collars on a weekly basis, such that temporal variation was captured through repeated measurements at each replicate plot. Spatial replication was defined by the three independent chamber collars per cover type, whereas temporal replication was represented by repeated weekly measurements at each collar.

The initial measurement points for each peatland cover type were located 20 m from the nearest drainage canal, with successive measurement points spaced 25 m apart (Figure 2). Measurements within each plot were performed in a clockwise direction, alternating the starting point to minimize temporal bias from 07.00 to 12.00. Measurements were performed weekly over a span of 22 weeks from September 18, 2024, to February 12, 2025. Annual CO<sub>2</sub> fluxes were estimated by extrapolating weekly measurements under the assumption that the measured fluxes are representative of prevailing non-inundated conditions during the observation period. Weekly mean fluxes were integrated over time to derive annual estimates. Periods when collars were inundated were excluded from the extrapolation, and the resulting annual values therefore represent estimates of soil-atmosphere CO<sub>2</sub> fluxes under non-inundated conditions. A key limitation of this approach is that the measurement period may not fully represent the full range of seasonal conditions occurring over an entire year and thus introduces uncertainty in the extrapolated annual estimates.

CO<sub>2</sub> emissions were calculated using an equation based on the ideal gas law (Husnain et al., 2014; Marwanto and Agus, 2014) as shown in Equation 1:

$$f_c = \frac{Ph}{RT} \frac{dC}{dt} \quad (1)$$

Where  $f_c$  is the CO<sub>2</sub> efflux ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ), which was converted to  $\text{tons ha}^{-1} \text{year}^{-1}$  by using the molar mass of CO<sub>2</sub> ( $44.01 \text{ g mol}^{-1}$ , area conversion ( $\text{m}^2$  to  $\text{ha}$ ), time conversion ( $\text{s}$  to  $\text{year}$ ), and unit conversion factors ( $\text{g}$  to  $\text{ton}$ );  $P$  is the atmospheric pressure (Pa);  $h$  is the chamber height (cm);  $R$  is the gas constant ( $8,314 \text{ J mol}^{-1} \text{ }^\circ\text{K}^{-1}$ );  $T$  ( $^\circ\text{K}$ ), and  $dC/dt$  is the change in CO<sub>2</sub> concentration.

Simultaneously with the emission measurements, groundwater level depth was assessed using a piezometer, whereas air, soil, and in-chamber temperatures were recorded using a solid stem mercury water thermometer, Indonesia. The piezometer was constructed using a 7.62 cm diameter PVC pipe with a total length of 2.75 m. It was installed vertically in the peat soil, with approximately 50 cm protruding above the ground surface. The submerged portion of the pipe was perforated with holes spaced 10 cm apart on all sides to facilitate groundwater ingress and precisely reflect the water-table level.

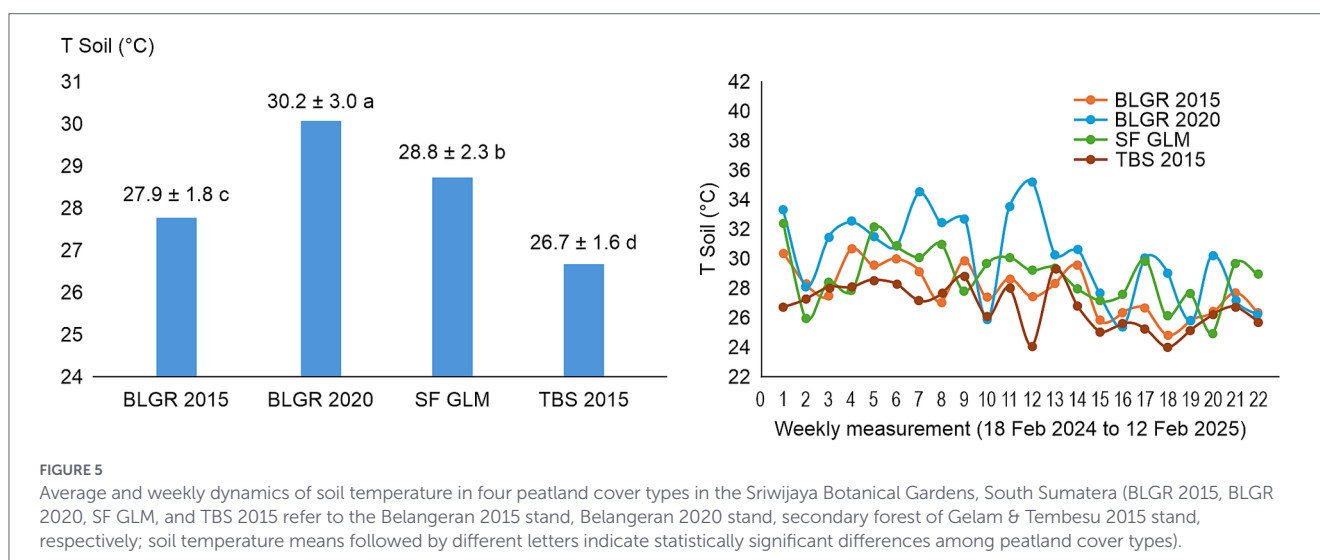
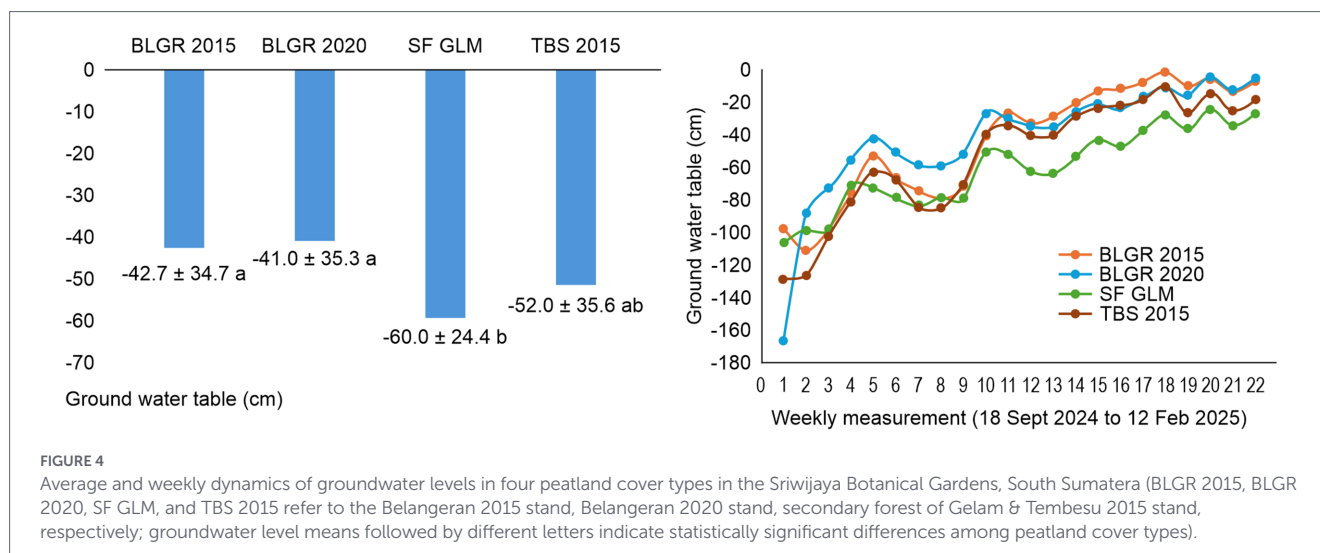
Data on CO<sub>2</sub> emissions, along with associated environmental variables, groundwater depth, soil temperature, and air temperature, were analyzed and tabulated according to peatland cover type. All statistical analysis was conducted in RStudio version 2025.05.1 + 513 Posit Software. Variations in CO<sub>2</sub> emissions and environmental parameters across various peatland cover types were analyzed using linear-mixed effects models-based Anova (LMMs) with peatland cover type treated as a fixed effect and collar identity nested within stand included as a random effect to account for repeated measurements. This model structure appropriately reflects the nesting of observations within collars and avoids pseudo-replication arising from temporal autocorrelation.

Significance difference of variables between peatland cover were tested by Least Significance Difference at  $p < 0.05$ . To examine the relationships between CO<sub>2</sub> emissions and environmental variables, linear mixed-effects regression models were applied, allowing both fixed effects of environmental predictors and random effects associated with repeated observations to be accounted for.

## 3 Results

### 3.1 Carbon dioxide emissions

The average annual CO<sub>2</sub> emissions in the Sriwijaya Botanical Gardens reached  $31.9 \pm 19.9 \text{ t CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$ , representing soil-atmosphere CO<sub>2</sub> fluxes. This value is obtained from the average emissions of four peatland cover types found in the area during the six-month periods of 18 September, 2024, to 12 February, 2025, ranging from  $25.2 \pm 20.4 \text{ t CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$  in the Belangeran stand 2015 to  $36.6 \pm 16.3 \text{ t CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$  in the Belangeran stand 2020. No significant differences were



observed in the magnitude of emissions among peatland cover types, and mean values are presented with its standard deviation (Figure 3, left).

The temporal dynamics of CO<sub>2</sub> emissions across the peatland cover types in the Sriwijaya Botanical Gardens exhibited high initial fluctuations, followed by a consistent decrease from the onset to the end of the weekly measurement period (Figure 3, right). Emission measurements commenced during the dry season in September 2024 and continued throughout the rainy season in February 2025.

## 3.2 Environmental factors

### 3.2.1 Groundwater level

Across all peatland cover types in the Sriwijaya Botanical Gardens, mean groundwater tables fell below the peat surface (negative values). However, statistically significant differences were observed among the different peatland cover types ( $p$ -value < 0.01). The deepest groundwater level was detected in the secondary forest of Gelam at  $-60.0 \pm 24.4$  cm. This was followed by the Tembesu 2015 stand at  $-52.0 \pm 35.5$  cm, with values expressed as means and standard deviations (Figure 4, left).

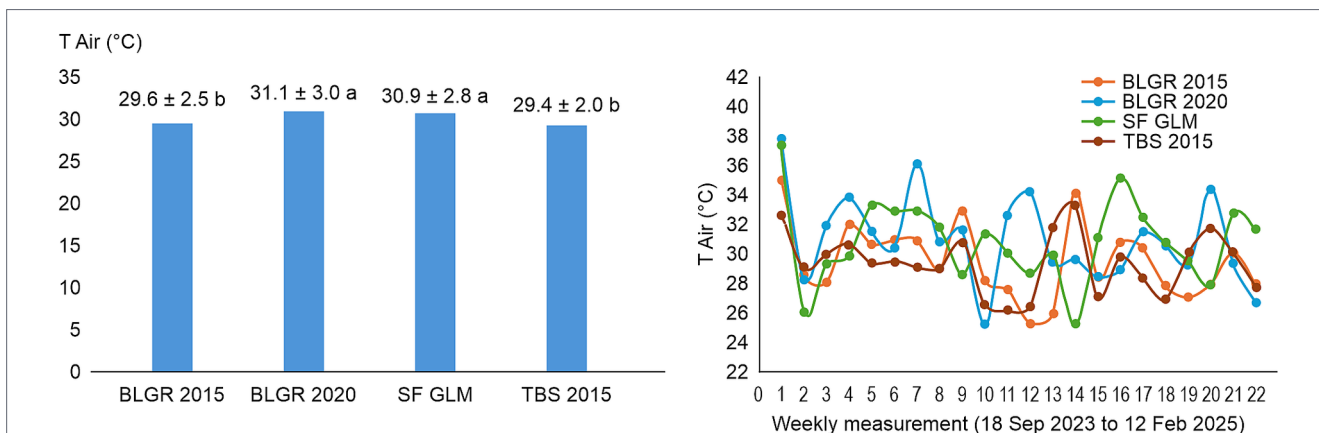
Weekly groundwater level measurements showed that across all peatland cover types, groundwater levels increased significantly over

22 weeks of observation period (Figure 4, right). Groundwater tables became progressively shallower over time in all plots. The greatest fluctuation in groundwater depth was observed in the Belangeran 2020 stand, ranging from  $-166$  cm in the first week to  $-5.5$  cm in the last week.

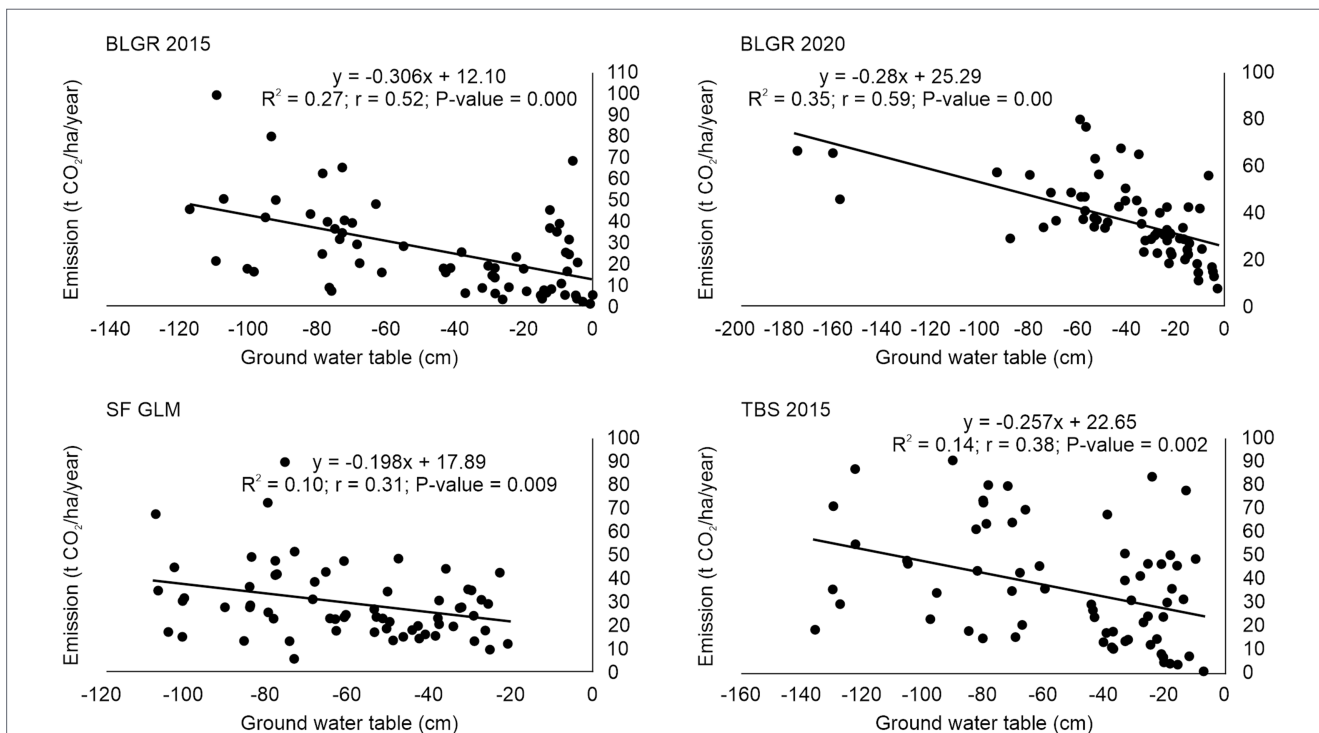
### 3.2.2 Soil temperature

Soil temperature differed significantly among the four peatland cover types in the Sriwijaya Botanical Gardens ( $p$ -value < 0.01). The highest soil temperature was found in the Belangeran 2020 stand with a mean and standard deviation of  $30.2 \pm 3.0$  °C. Conversely, the lowest soil temperature was observed in the Tembesu 2015 stand at  $26.7 \pm 1.6$  (Figure 5, left).

The groundwater level and soil temperatures exhibited a temporal pattern characterized by high fluctuations during the early weeks (dry season) and gradual stabilization as the rainy season progressed (Figure 5, right). Based on weekly measurements, the soil temperature in the Belangeran 2020 stand displayed higher fluctuations among the different peatland cover types; however, it tended to stabilize toward the end of the observation period (similar to the other peatland cover types). In contrast, the soil



**FIGURE 6** Average and weekly dynamics of air temperature in four peatland cover types in the Sriwijaya Botanical Gardens, South Sumatera (BLGR 2015, BLGR 2020, SF GLM, and TBS 2015 refer to the Belangeran 2015 stand, Belangeran 2020 stand, secondary forest of Gelam & Tembesu 2015 stand, respectively; air temperature means followed by different letters indicate statistically significant differences among peatland cover types).



**FIGURE 7** Regression analysis between groundwater levels and carbon dioxide (CO<sub>2</sub>) emissions across four peatland cover types in the Sriwijaya Botanical Gardens, South Sumatera (BLGR 2015, BLGR 2020, SF GLM, and TBS 2015 refer to the Belangeran 2015 stand, Belangeran 2020 stand, secondary forest of Gelam & Tembesu 2015 stand, respectively).

temperatures in the Belangeran 2015 stand remained relatively stable throughout the measurement period.

### 3.2.3 Air temperature

Similar to the soil temperature, the air temperature also showed significant differences in each peatland cover type, as indicated by different letters following the mean temperature values (Figure 6, left). The highest temperature was observed in the Belangeran 2020 stand (31.1 ± 3.0 °C), while the lowest was detected in the Tembesu 2015 stand (29.4 ± 2.0 °C). Weekly measurements showed that air temperatures remained relatively stable throughout the observation period, although they fluctuated slightly more in the Belangeran

2020 stand. However, all peatland cover types demonstrated air temperature stabilization over time, corresponding to rising groundwater levels. This indicated that increased soil moisture and canopy development during the rainy season contributed to the moderation of air temperature extremes across various peatland cover types (Figure 6, right).

### 3.3 Relationship between carbon dioxide emissions and environmental factors

The relationships between CO<sub>2</sub> emissions and environmental factors, including groundwater level, soil, and air temperature, were analyzed using linear-mixed effects regression models with collar

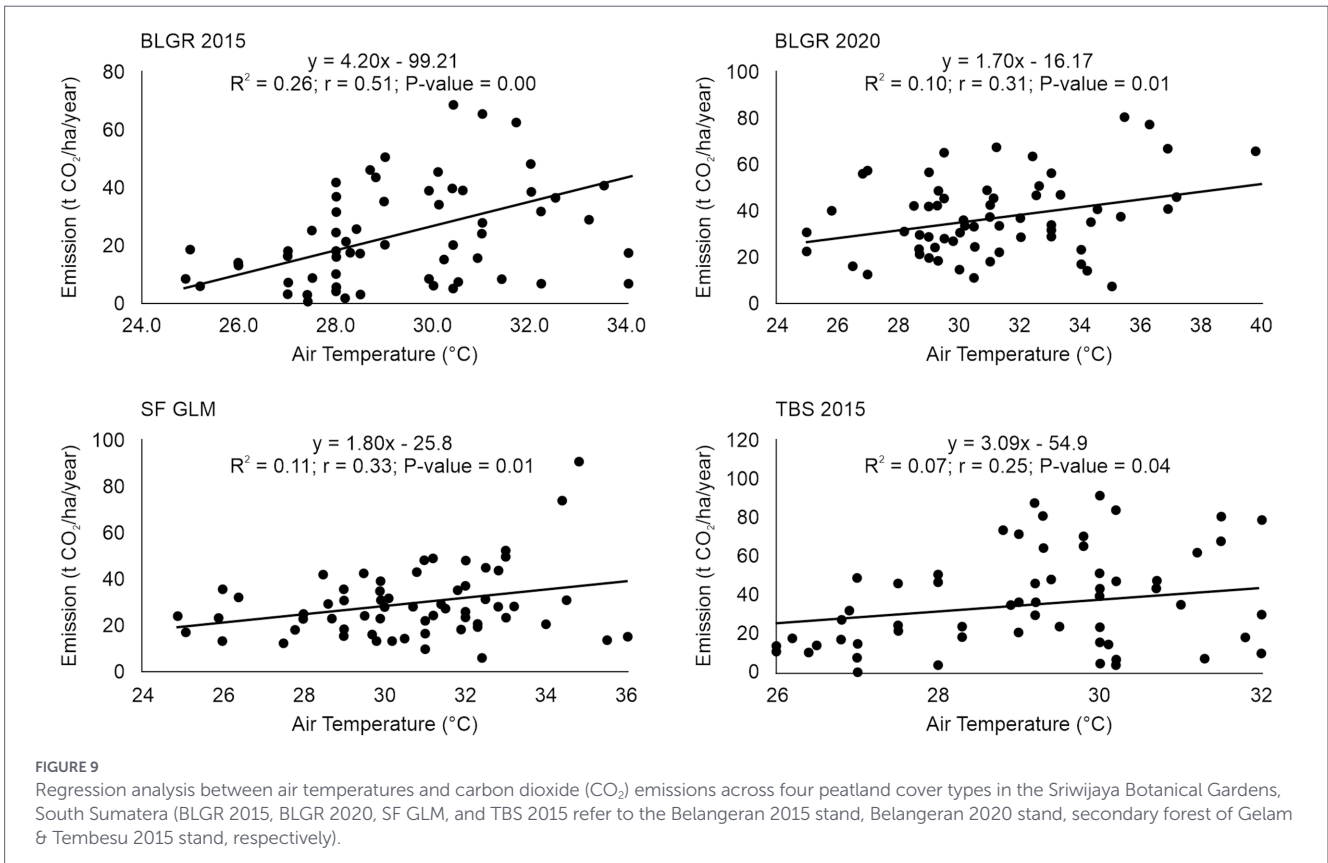
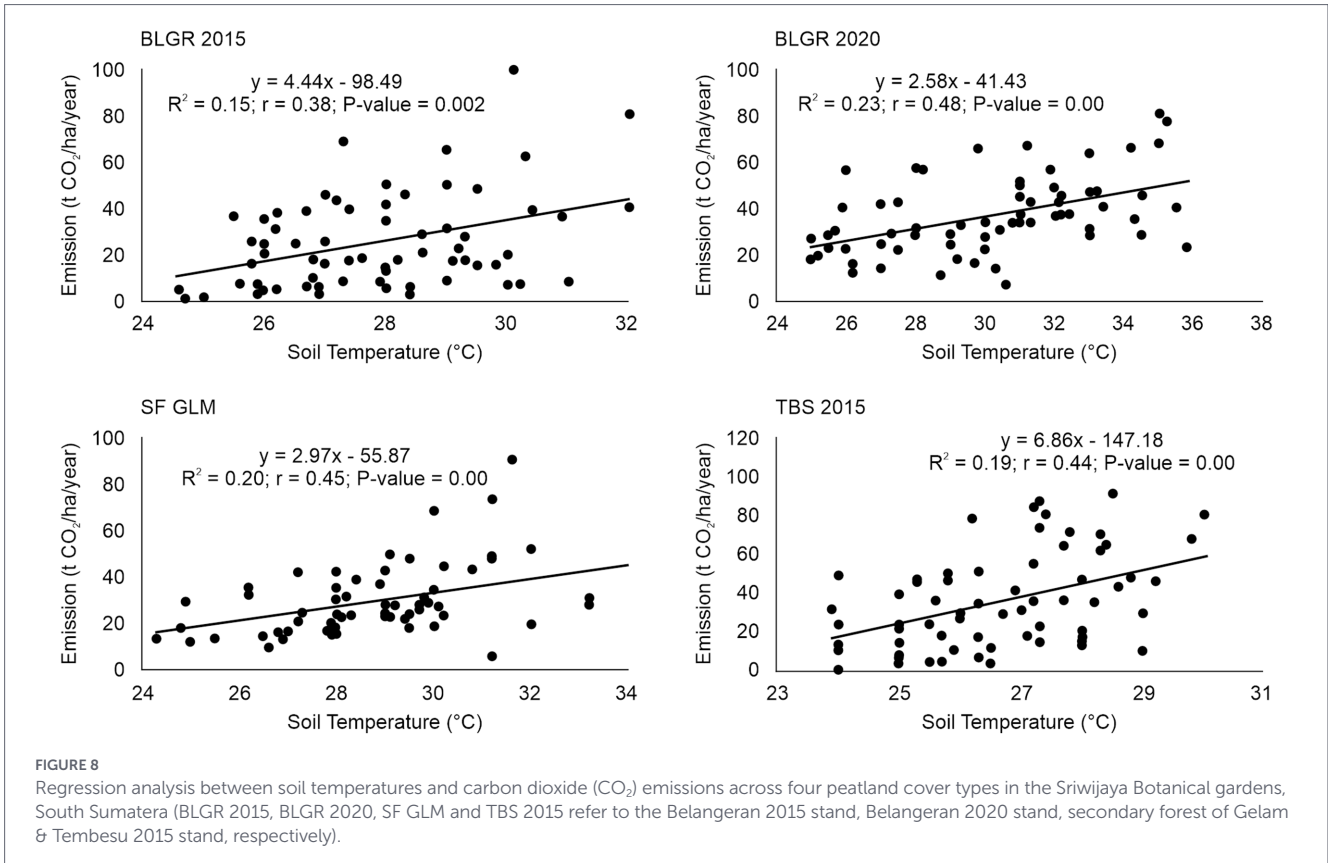


TABLE 3 Results of multiple regression analysis using mixed effect model on carbon dioxide (CO<sub>2</sub>) emissions in relation to environmental factors across various peatland cover types in the Sriwijaya Botanical Gardens, South Sumatera.

Peatland cover	Predictor	Coefficients	P-value	P-value (model)	R <sup>2</sup>
BLGR 2015	Intercept	-27.87	0.428 <sup>ns</sup>	1.69 × 10 <sup>-8</sup>	52%
	GWL	-0.292	0.00003***		
	T <sub>Soil</sub>	-2.248	0.1443 <sup>ns</sup>		
	T <sub>Air</sub>	3.488	0.0002***		
BLGR 2020	Intercept	3.669	0.833 <sup>ns</sup>	2.73 × 10 <sup>-9</sup>	52%
	GWL	-0.257	0.00000***		
	T <sub>Soil</sub>	2.497	0.0015***		
	T <sub>Air</sub>	-1.704	0.0034**		
SF GLM	Intercept	-52.82	0.0197*	2.7 × 10 <sup>-4</sup>	35%
	GWL	-0.136	0.052 <sup>ns</sup>		
	T <sub>Soil</sub>	1.988	0.0275*		
	T <sub>Air</sub>	0.554	0.416		
TBS 2015	Intercept	-81.40	0.089 <sup>ns</sup>	2.1 × 10 <sup>-4</sup>	53%
	GWL	-0.165	0.024*		
	T <sub>Soil</sub>	3.37	0.059		
	T <sub>Air</sub>	0.64	0.60		

Remark: BLGR 2015, BLGR 2020, SF GLM, and TBS 2015 refer to the Belangeran 2015 stand, Belangeran 2020 stand, secondary forest of Gelam, and Tembesu 2015 stand, respectively. Levels of significance: \*\*\* $p < 0.001$ , \*\* $p < 0.01$ , \* $p < 0.05$ , <sup>ns</sup> = not significant.

identity treated as a random effect. Reported effects therefore reflect differences among cover types while accounting for repeated measurements at the same collars over time. Separate mixed-effects regression models were fitted to examine the effect of each environmental factor individually (Figures 7–9), whereas a multiple mixed-effects regression models was performed to evaluate the combined effect of all three environmental factors within a single model (Table 3). In all models, collar identity (nested within stand) was included as a random effect to account for repeated measurements.

The linear mixed-effects model showed that CO<sub>2</sub> emissions from peatland cover types could be moderately to strongly explained by a combination of environmental factors, including groundwater level, soil temperature, and air temperature, with conditional coefficients of determination (R<sup>2</sup>) ranging from 0.35 to 0.53 (Table 3). Groundwater levels consistently exhibited a strong negative effect on emissions, especially in the Belangeran 2015 and 2020 stands. In contrast, soil temperature had a more significant positive effect on the Belangeran 2020 and secondary forest of Gelam stands, furthermore, air temperature more influential in Belangeran 2015 and 2020 stands.

Linear mixed-effects model analysis showed a negative relationship between groundwater level and CO<sub>2</sub> emissions in all peatland cover types (Figure 7). The conditional coefficient of determination value was relatively low (ranging from 0.28 in the secondary forest of Gelam to 0.52 in the Tembesu 2015 stand), thereby indicating that the groundwater level explained only approximately 28–52% of the variability in CO<sub>2</sub> emissions. However, the relationship remained highly statistically significant ( $p$ -value < 0.01). The coefficient of correlation (ranging from 0.53 to 0.72) further suggested that the groundwater level consistently affected CO<sub>2</sub> emissions across peatland cover types.

In contrast to groundwater level, soil temperatures exhibited a significant positive linear relationship with CO<sub>2</sub> emissions across all peatland cover types, with  $p$ -value < 0.01 and a coefficient of correlation ranging from 0.52 to 0.69 (Figure 8). The conditional coefficient of determination was relatively low, ranging from 0.27 in the Belangeran 2015 stand to 0.48 in the Tembesu 2015 stand. However, the highly significant difference indicated that soil temperature consistently influenced the magnitude of CO<sub>2</sub> emissions. Similar to soil temperature, air temperature also demonstrated a strong correlation with CO<sub>2</sub> emissions across all peatland cover types, with a  $p$ -value < 0.01 and coefficient of correlation ranging from 0.46 to 0.66 (Figure 9). However, the coefficients of determination for all these relationships were relatively low.

## 4 Discussion

### 4.1 Carbon dioxide emissions

The estimated annual CO<sub>2</sub> emissions from the four representative peatland covers in the Sriwijaya Botanical Gardens were 31.9 ± 19.9 t CO<sub>2</sub> ha<sup>-1</sup> year<sup>-1</sup> (Figure 3). The emissions are relatively low compared with the national average peat emissions of 48.22 t CO<sub>2</sub> ha<sup>-1</sup> year<sup>-1</sup>, as reported by multiple studies on various peatland applications in Sumatera and Kalimantan, encompassing forests, shrublands, burned areas, agriculture, and plantations (Novita et al., 2021). For comparison, CO<sub>2</sub> emissions from a 15-year-old oil palm plantation were 46 ± 30 t CO<sub>2</sub> ha<sup>-1</sup> year<sup>-1</sup> (Marwanto and Agus, 2014), whereas those from an 8-year-old rubber plantation were 32.93 ± 10.39 t CO<sub>2</sub> ha<sup>-1</sup> year<sup>-1</sup> (Wakhid et al., 2017). The observed emissions in this study

are also lower than the IPCC Tier 1 default emission factors for peatlands plantation, which are  $73.3 \text{ t CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$  for short rotation systems and  $55 \text{ t CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$  for long rotation systems (IPCC, 2013). Although the emissions in this revegetated peatland under hydrological recovery remain higher than those reported for undrained peatlands in Muara Siran, East Kalimantan, amounting to  $11.02 \pm 0.49 \text{ t CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$  (Asyhari et al., 2024), it nonetheless indicates that peat management and revegetation efforts in the Botanical Gardens have likely contributed to a reduction in emissions relative to more degraded or intensively drained peatland systems. Given that deep groundwater levels were still observed during the monitoring period, the study area is more appropriately characterized as a recovering or rehabilitated peatland, rather than a fully restored system, and the observed emission levels should be interpreted within this transitional recovery context.

The extrapolated annual  $\text{CO}_2$  fluxes should be interpreted as first-order estimates, given that the measurement period may not fully represent the complete range of seasonal hydrological conditions occurring over an entire year. In tropical peatlands, seasonal inundation can alter dominant  $\text{CO}_2$  transport pathways, shifting from soil-atmosphere exchange under non inundated conditions to surface-mediated fluxes during inundation. As periods of inundation were excluded from the present analysis, the reported annual estimates primarily reflect non-inundated conditions and may either underestimate or overestimate true annual emissions.

The Sriwijaya Botanical Gardens have been equipped with water management infrastructure, including a central conservation reservoir and a series of water gates along the southern perimeter of the area. The installation of water gates is intended to sustain groundwater at a depth of approximately 40 cm below the surface and preserve the natural ecological balance of the peat ecosystem. While the performance of this system cannot be considered fully optimal, it has demonstrated a measureable capacity to retain the groundwater level. Average groundwater levels in this study area ranged from  $-41.0 \pm 35.3$  to  $-60.0 \pm 24.4$  cm indicating a moderate groundwater level compared with more degraded peatland. These levels are higher than those reported by (Wakhid et al., 2017), who recorded an average of  $-69$  cm with a range from  $-3$  to  $-171$  cm, suggesting that water management interventions in the Sriwijaya Botanical Garden contributed to reducing extreme groundwater table drawdown. The primary objectives of water management systems in peatland areas are to maintain the groundwater table, regulate water flow, prevent peat degradation, support ecosystem rehabilitation, and mitigate fire risk (Wakhid et al., 2017; Dohong et al., 2018).

Based on the differences in peatland cover types,  $\text{CO}_2$  emissions in the Sriwijaya Botanical Gardens showed variations in annual average values, however, these differences were not statistically significant (Figure 3). The highest emissions were recorded in the Belangeran 2020 stand, closely followed by the Tembesu 2015 stand, with values of  $36.6$  and  $36.0 \text{ t CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$ , respectively. The lowest emissions were recorded in the Belangeran 2015 stand at  $25.2 \pm 20.4 \text{ t CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$ . However, the  $\text{CO}_2$  emissions from all peatland cover types in this area were substantially lower than those recorded in degraded peatlands, which amounted to  $45.1 \text{ t CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$  because of inadequate water management resulting in a reduced groundwater level of  $-65 \pm 17$  cm (Deshmukh et al., 2023). This indicates that the water management system at the Sriwijaya Botanical Gardens may contribute to reducing emissions compared with more disturbed, unmanaged peatland conditions.

In contrast to other peatland cover types in the Sriwijaya Botanical Gardens, the elevated emissions in the Belangeran 2020 stand are associated with increased annual averages of soil and air temperatures at  $30.2$  and  $31.1$  °C, respectively. This stand was replanted in 2020 following its impact from peat fires in 2019 (Maryani and Novriadhy, 2023), which likely contributed to its elevated values. The occurrence of fires resulted in the loss of peatland canopy cover, rendering the area relatively exposed (Siahaan et al., 2020), whereas the emergence of young plant canopies failed to restore it, resulting in increased solar radiation penetration to the ground surface and elevated soil and air temperatures. Peat combustion during fires eliminates surface organic layers, exposing deeper and more decomposable peat (Astiani et al., 2018; Siahaan et al., 2025).

Meanwhile, the high annual emissions in the Tembesu 2015 stand, despite possessing a relatively dense canopy cover and reduced soil and air temperatures (Figures 5 and 6), may be attributed to a deeper groundwater level of  $-52$  cm (Figure 4). The proximity of the stand to the main drainage channel leads to a more expedited decline in groundwater level. Reducing the groundwater level in peatlands increases  $\text{CO}_2$  emissions by exposing additional peat to the atmosphere, thereby intensifying aerobic microbial activity and accelerating the decomposition of organic matter. Under saturated (anaerobic) conditions, decomposition is slower (Pärn et al., 2025; Ritzema et al., 2014) and emissions are lower. However, when the water table drops, oxygen penetrates deeper, thereby stimulating microbial respiration and carbon release (Miettinen et al., 2017; Marwanto et al., 2019).

In addition to being driven by low groundwater levels, the high  $\text{CO}_2$  emissions recorded in the Tembesu 2015 stand plausibly be associated with enhanced root-related respiration, as inferred from its larger diameter at breast height and higher stand volume (Table 1). Previous studies have shown that root respiration tends to increase in denser and mature stands (Pacaldo and Aydin, 2023). For example, root based respiration has been reported to contribute approximately 19 and 29% to total soil respiration ( $R_s$ ) in 6 and 15 year old palm plantation, respectively (Dariah et al., 2014). Furthermore (Batubara et al., 2019) reported that  $\text{CO}_2$  emission measured with deep collars (excluding root based respiration) were 29% lower than those measured using shallow collars in a 25 year oil palm plantation. Although no direct partitioning between autotrophic (root derived) and heterotrophic respiration was performed in this study, the structural characteristics of the Tembesu stand, namely its larger tree diameter and higher stand volume, likely supports a more intensive root system that may be contribute to higher soil  $\text{CO}_2$  fluxes. In peatlands, root respiration, particularly from rapidly developing or densely rooted vegetation is widely recognized as an important component of total soil respiration, alongside microbial peat decomposition ( $R_h$ ). Consequently, the interplay between reduced groundwater level and potentially intensified root activity in the Tembesu 2015 stand likely accounts for the elevated emission levels.

Compared with the Belangeran 2020 stand, the Belangeran 2015 stand (an older stand) demonstrated the lowest  $\text{CO}_2$  emissions, recorded at  $25.2 \text{ t CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$  (Figure 3). This reduced emission rate correlates with a shallower groundwater level of  $-42.7$  cm (Figure 4) and slightly cooler soil and air temperatures, cumulatively leading to reduced peat decomposition ( $R_h$ ). The prevalence of more mature vegetation in the 2015 stand likely enhances microclimatic conditions, such as increased shade and humidity, which aid in maintaining cooler soil conditions and inhibiting microbial activity, thereby limiting  $\text{CO}_2$  emission. Conversely, despite having the deepest groundwater level ( $-60.0$  cm),  $\text{CO}_2$  emissions in the secondary forest of Gelam remained moderate, surpassing those in the Belangeran 2015

stand but falling short of those in the Belangeran 2020 and Tembesu 2015 stands. This may be attributed to the relatively small stand diameter and reduced stand volume, leading to lower root respiration (Table 1). A further explanation is the relatively low soil temperature observed in this stand, potentially linked to high aboveground litter accumulation, providing insulation and reducing heat penetration into the soil. Additionally, this area did not experience fire in 2019, which aided in the preservation of its forest structure and surface organic layer, thereby further moderating temperature and emissions.

## 4.2 Dynamics and effects of groundwater levels

The average groundwater levels in the Sriwijaya Botanical Garden differed significantly between peatland cover types (Figure 4). The averages ranged from  $-41.0 \pm 35.3$  cm in the Belangeran 2020 stand to  $-60 \pm 24.4$  cm in the secondary forest of Gelam. The difference in the groundwater table depth is associated with the proximity of each plot from the drainage canal; the nearer the plot is to the drainage canal, the deeper its groundwater level tends to be (Marwanto and Agus, 2014). In the context of the Sriwijaya Botanical Gardens, the Tembesu 2015 stand and secondary forest of Gelam were the nearest plots to the main drainage canal (Figure 2), exhibiting groundwater levels of  $-52.0 \pm 35.6$  and  $-60.0 \pm 24.4$  cm, respectively, both of which were deeper than those of the other two plots.

Despite these spatial differences, groundwater levels across all plots remained relatively stable during periods when rainfall ceased. This temporal stability indicates that short-term fluctuations in groundwater level were not solely controlled by precipitation inputs. Such patterns are consistent with regulated water retention within the study area, potentially associated with the operation of the water gate system that limits water outflow and helps maintain groundwater levels in the peatland.

The average groundwater levels across all peatlands in the Sriwijaya Botanical Garden fell below the critical threshold of  $-40$  cm (Dohong et al., 2017). The deep groundwater level allows for greater oxygen penetration into the peat, thereby enhancing microbial activity, accelerating peat decomposition, and ultimately increasing CO<sub>2</sub> emissions (Albert-Saiz et al., 2025). However, this deep groundwater level did not persist throughout the entire period; as the seasons changed from the dry season at the onset of the measurement period to the rainy season toward the end, the water level rose significantly (Figure 4). At the commencement of the observation (week 1), the groundwater levels in all sites were very deep (approximately  $-120$  to  $-160$  cm), indicating dry conditions. Over the first several weeks (especially between weeks 2 and 5), the groundwater level increased rapidly throughout all peatland cover types. After week 5 or so, the groundwater level fluctuated slightly while maintaining an overall upward trend (less negative) until it reached a relatively shallow depth (approximately  $-10$  to  $-20$  cm) by week 22, indicating that water approached the surface. Notably, the groundwater level approached zero in the Belangeran 2020 and 2015 stands by week 22, indicating conditions conducive to surface saturation and a potential tendency toward inundation.

Variations in groundwater levels resulted in differences in CO<sub>2</sub> emissions across peatland cover types in the Sriwijaya Botanical Gardens; however, the magnitude of this effect varied among them. The linear mixed effects model showed that groundwater level significantly affected emissions in the Tembesu 2015, Belangeran 2020, and

Belangeran 2015 stands, whereas its effects were not significant in the Gelam secondary forest stand (Table 3). This model accounted for the combined influence of environmental variables while incorporating random effects to address repeated measurements. Furthermore, a simple factor linear-effect regression models examining the relationship between groundwater level and emissions in each peatland cover type (Figure 7) demonstrated differences in both the conditional coefficient of determination (R<sup>2</sup>) and slope of the equations, despite the relationship being statistically significant ( $p$ -value < 0.01) across all covers. The highest conditional coefficient of determination was observed in the Tembesu 2015 stand, with an R<sup>2</sup> value of 0.52 ( $r = 0.72$ ) and a slope of  $-0.25$ , represented by the equation  $y = -0.25x + 23.2$ . In contrast, the lowest was observed in the secondary forest of Gelam, with an R<sup>2</sup> value of 0.28 ( $r = 0.53$ ) and a slope of  $-0.20$ , represented by the equation  $y = -0.20x + 17.68$ .

The equation delineating the relationship between groundwater levels and emissions for each peatland cover type can be interpreted in practical terms. For example, the equation in the Belangeran 2020 stand,  $y = -0.25x + 23.2$ , indicates that for every 10 cm decrease in water level, CO<sub>2</sub> emissions increase by approximately 2.5 t CO<sub>2</sub> ha<sup>-1</sup> year<sup>-1</sup>. The regression equation slopes across all peatland cover types range from  $-0.20$  in the secondary forest of Gelam to  $-0.31$  in the Belangeran 2015 stand, indicating that with each 10-cm decrease in groundwater level, CO<sub>2</sub> emissions increase by 2.0 to 3.1 t CO<sub>2</sub> ha<sup>-1</sup> year<sup>-1</sup>. These values are smaller than those reported in two previous studies, which identified increases in CO<sub>2</sub> emissions of 6.5 and 7.2 t CO<sub>2</sub> ha<sup>-1</sup> year<sup>-1</sup> for every 10-cm decrease in the groundwater level (Wakhid et al., 2017; Deshmukh et al., 2023; Prananto et al., 2020). Within the groundwater level range observed in this study, the relationship between CO<sub>2</sub> fluxes and water table depth appears largely linear, consistent with previous findings. However, the scatter pattern suggests that over a broader range of groundwater level this relationship could become non-linear, aligning with bell-shaped responses documented in peatland studies by (Norberg et al., 2018; Mäkiranta et al., 2009).

A clear pattern suggests that deeper groundwater levels are typically correlated with higher CO<sub>2</sub> emissions resulting from increased aerobic peat decomposition (Rh). Therefore, water table management is important for the conservation and restoration of degraded peatlands (Irfan et al., 2025). Upgrading canal blocking systems and intensifying water gate regulations are urgently needed to elevate groundwater levels, mitigate peat degradation, and thereby decrease CO<sub>2</sub> emissions. Hooijer et al. (2024) reported that the construction of 257 peat dams throughout a degraded peatland area of 4,800 ha successfully elevated the groundwater level from  $-60$  cm to  $-30$  cm and reduced subsidence rates by 50%.

## 4.3 Dynamics and effects of soil temperatures

Soil temperature is an environmental factor influencing CO<sub>2</sub> emissions (Marwanto et al., 2019); however, its effects are not always significant (Pacaldo and Aydin, 2023). Recent research has shown a significant variation in soil temperature across the various peatland cover types in the Sriwijaya Botanical Gardens, with measurements ranging from  $26.7 \pm 1.6$  °C in the Tembesu 2015 stand to  $30.2 \pm 3.0$  °C in the Belangeran 2020 stand (Figure 5). The magnitude of the soil temperature in a peatland is influenced by the extent of sunlight penetration to the ground surface, increased sunlight penetration results

in elevated soil temperatures. The elevated temperature in the Belangeran 2020 stand may be attributed to several factors, including fire occurrence in 2019 that eradicated the undergrowth and lower canopy cover due to the young age of the stand. These conditions facilitate increased sunlight penetration into the peat soil. In contrast, the reduced soil temperature in the Tembesu 2015 stand may be attributed to its dense canopy cover, which restricts sunlight penetration to the peat surface.

Soil temperatures across all peatland cover types in the Sriwijaya Botanical Gardens exhibited significant relationships with CO<sub>2</sub> emissions, with *p*-values < 0.01 (Figure 8). However, the conditional coefficients of determinant (R<sup>2</sup>) were relatively low, ranging from 0.27 (*r* = 0.52) in the Belangeran 2015 stand to 0.48 (*r* = 0.69) in the Tembesu 2015 stand. The strongest effect of soil temperature on CO<sub>2</sub> emissions was noted in the Tembesu 2015 stand, represented by the equation  $y = 5.64x - 114.58$  (R<sup>2</sup> = 0.48; *r* = 0.69; *p*-value < 0.01). This equation indicates that for each 1 °C increase in soil temperature, CO<sub>2</sub> emissions rise by approximately 5.64 t ha<sup>-1</sup> year<sup>-1</sup>; conversely, a 1 °C decrease in soil temperature results in a corresponding decline in emissions by the same amount. As plant growth and canopy development progress, sunlight penetration to the soil surface diminishes, resulting in decreased soil temperatures and reduced CO<sub>2</sub> emissions (De Frenne et al., 2021). While these linear relationships provide a useful approximation within the observed soil temperature range, the relatively high scatter and low R<sup>2</sup> values suggest that the temperature CO<sub>2</sub> emission relationship may not be strictly linear across broader thermal gradients. In peatland ecosystems, temperature effects on respiration often exhibit non-linear or threshold responses due to interactions with soil moisture, oxygen availability, and substrate limitation.

Weekly fluctuations in soil temperatures across four peatland cover types indicated that the Belangeran 2020 stand consistently exhibited the highest temperatures, with peaks exceeding 30 °C, especially between weeks 6–12. This thermal profile was correlated with its elevated CO<sub>2</sub> emissions, especially during the early measurement period. In contrast, the Belangeran 2015 stand maintained cooler and more stable soil temperatures, predominantly within the 26–30 °C range, and exhibited the lowest overall emission rates. The mature vegetation in this stand likely enhances shading, buffers temperature extremes, and inhibits decomposition. In contrast, the Tembesu 2015 stand showed relatively low soil temperatures, similar to those in the Belangeran 2015 stand; however, its emissions remained high and variable. This suggests that other factors, such as root respiration and low groundwater table depth, play major roles in CO<sub>2</sub> emissions from this stand. The secondary forest of Gelam exhibited intermediate soil temperatures and displayed moderate emission levels.

#### 4.4 Dynamics and effects of air temperatures

Similar to soil temperatures, the variation in air temperature between peatland cover types in the Sriwijaya Botanical Gardens correlated with the amount of sunlight penetrating the canopy cover and soil surface. Therefore, the fluctuation in air temperatures between the peatland cover types and their dynamics during the measurement period mirrored the pattern observed for soil temperatures. The highest air temperature recorded in the Belangeran 2020 stand may be attributed to substantial sunlight penetration within the stand, resulting from a fire in 2019 that rendered this stand younger than its counterparts. In contrast, the lowest air temperatures recorded in the

Tembesu 2015 and Belangeran 2015 stands may be attributed to their denser canopy, which reduces solar radiation and wind speed, thereby impacting the air temperature. Adaptive species, such as Belangeran, Tembesu, and other native species, have been reported to be associated with more favorable microclimate conditions in degraded peatlands, including lower temperatures and higher humidity following their establishment (Dharmawan et al., 2024; Jaya et al., 2024).

The relationship between air temperature and CO<sub>2</sub> emissions across all peatland cover types in the Sriwijaya Botanical Garden was statistically significant (*p*-value < 0.01); however, it exhibited a low magnitude of effect, with conditional coefficients of determination (R<sup>2</sup>) ranging from 0.21 to 0.43 and coefficients of correlation varying between 0.46 and 0.66 (Figure 9). Linear mixed-effects models indicates that air temperature significantly affects CO<sub>2</sub> emissions in the Belangeran 2015 and 2020 stands, while its effect is not significant in the other stands. This suggests that, similar to soil temperature, the influence of air temperature on peatland emissions is context-dependent and may be influenced by other interacting environmental factors. In some cases, the air temperature exhibits a strong positive correlation with CO<sub>2</sub> emissions, whereas in other cases, the relationship appears weak or statistically insignificant (Pacaldo and Aydin, 2023; Yahya et al., 2019).

The low R<sup>2</sup> values and inconsistent significance across sites suggest that the air temperature and CO<sub>2</sub> emissions relationship may not be strictly linear and could involve non-linear or threshold-type responses, particularly when evaluated over broader temperature ranges or under varying hydrological conditions. The observed inconsistency may be attributed to the complex interplay between temperature and various environmental factors, such as microbial activity, peat and water table depth, oxygen availability, and substrate quality. While these findings provide valuable insight, the limited of sample size restricts the extent to which them can be generalized.

#### 4.5 Implication for peatland management

This study provides empirical evidence that the hydrological condition is the dominant control of CO<sub>2</sub> emissions from peat soil, while vegetation type primarily modifies emission magnitude through its effects on microclimate and root respiration. These findings have direct relevance to Indonesian's FOLU Net Sink 2030 framework, which prioritizes peatland rewetting and fire prevention as key mitigation strategies for achieving net carbon sequestration in the land use sector. The consistently strong negative relationship between groundwater level and CO<sub>2</sub> emissions across peatland cover types indicates that maintaining a high level of groundwater table is more critical for emissions reduction than vegetation composition alone. This supports national mitigation strategies under FOLU Net Sink 2030 that emphasize canal blocking, water gate management, and hydrological rehabilitation as the primary interventions for reducing peat carbon losses.

Although vegetation types influence soil and air temperature and contributed to variation in CO<sub>2</sub> emissions, particularly through canopy openness and root respiration, these effects were secondary to hydrological control. This finding has important implications for national greenhouse gas (GHG) inventory development. Current emission factor approaches often stratify peat emissions by land cover or vegetation classes, however, the results of this study suggest that a common emission factor for rewetted or hydrologically managed peatlands may be appropriate, with vegetation type incorporated as secondary or modifying factor rather than a primary determinant. Such an approach would better reflect the underlying biogeochemical drivers of emissions and reduce

uncertainty in national reporting, particularly for peatlands under rehabilitation or conservation management.

It is also important to clarify the terminology used to describe peatland condition in this study. While the Sriwijaya Botanical Gardens have undergone extensive revegetation and partial hydrological intervention, groundwater levels during the early observation period (−120 to −160 cm) indicate that the site does not meet widely accepted definitions of fully restored peatlands which typically require sustained water table depths near the surface (approximately −40 cm) to suppress aerobic decomposition and fire risk. Therefore, the site is more accurately described as rehabilitated or revegetated peatland under ongoing hydrological recovery, rather than fully restored peatland. This distinction is critical for both scientific accuracy and policy relevance, as emission factors and mitigation outcomes differ substantially between restored, rehabilitated, and degraded peatlands.

## 4.6 Study limitations

The limited spatial replication in this study ( $n = 3$  per peatland cover type) constrains statistical power and may not fully capture the fine-scale heterogeneity typical of peatland ecosystems. Microsite variability, including hummock–hollow microtopography, vegetation clumping, root density, and peat physical structure, can strongly influence CO<sub>2</sub> fluxes; therefore, the reported mean values may be sensitive to the specific placement of collars and plots. In addition, revegetated peatlands undergoing recovery are often spatially patchy in both hydrological conditions and vegetation structure, reflecting differences in water-table dynamics, species composition, and management history. As a result, the current sampling design may not represent the full range of environmental conditions present across the peatland, and the findings should be interpreted as representative of local conditions within the monitored plots rather than of the entire landscape.

Beyond spatial considerations, the weekly temporal resolution of flux measurements may not capture short-lived but potentially important emission events, such as rapid post-inundation degassing, storm-driven pulses, transient temperature extremes, or management-related disturbances. The omission of such episodic events could influence annual emission estimates if their contributions are not adequately represented by the sampling frequency. Future studies could reduce this uncertainty by increasing measurement frequency or by pairing flux observations with continuous groundwater-level monitoring.

The extrapolation of weekly measurements to annual CO<sub>2</sub> fluxes further requires several assumptions, including temporal stationarity within sampling intervals, representativeness of sampling days, and interpolation across hydrological transitions. These assumptions introduce additional uncertainty into annual estimates. Incorporating uncertainty propagation approaches, such as confidence intervals around annual totals, would strengthen future assessments and improve comparability across studies.

Finally, mechanistic interpretation of the observed CO<sub>2</sub> flux variability is constrained by the absence of partitioning measurements. Without separating autotrophic and heterotrophic respiration, the study cannot definitively attribute observed flux patterns to root activity, microbial decomposition, temperature effects, or water-table dynamics. Accordingly, mechanistic explanations presented here should be regarded as hypotheses supported by existing literature rather than confirmed causal relationships. Moreover, because peatlands differ widely in restoration stage, vegetation composition, drainage intensity, climate, and management regimes, the findings should

not be generalized beyond the study site. Instead, they provide site-specific evidence and pathway-aware flux estimates within the context of a revegetated peatland undergoing hydrological recovery.

## 5 Conclusion

The highest CO<sub>2</sub> emission was recorded in the Belangeran 2020 stand, closely followed by the Tembesu 2015 stand, with nearly identical values of 36.6 and 36.0 t CO<sub>2</sub> ha<sup>−1</sup> year<sup>−1</sup>, respectively. However, these values were not significantly different from emissions measured in other peatland cover types. The relatively higher emissions in the Belangeran 2020 stand correlate with elevated annual average soil and air temperatures (30.2 °C and 31.1 °C, respectively), likely resulting from a fire event in 2019. In the Tembesu 2015 stand, emissions are primarily associated with a deeper groundwater level (−52 cm) and potential contributions from root respiration. Collectively, these findings indicate that hydrological condition exerts a stronger control on peat CO<sub>2</sub> emissions than vegetation type alone. Accordingly, this study suggests that the application of a common emission factor for rewetted or hydrologically managed peatlands may be appropriate, with vegetation type incorporated as a secondary or modifying factor rather than as the primary determinant of emissions.

Environmental variables, such as groundwater level, soil temperature, and air temperature, were significantly correlated with CO<sub>2</sub> emissions across all peatland cover types in the Sriwijaya Botanical Gardens, although the effects of each variable differed. These findings highlight the important influence of groundwater level on peatland CO<sub>2</sub> emissions, while also underscoring the contributions of vegetation type, stand diameter and volume, canopy development, fire history, and surface litter in modulating emission dynamics. Therefore, effective peatland management should integrate hydrological restoration and strategic vegetation planning to enhance carbon retention. Overall, this study highlights that progress toward Indonesia's FOLU Net Sink 2030 target depend primarily on effective and sustained hydrological management, while revegetation and vegetation development play an essential supporting role in stabilizing microclimate, reducing fire susceptibility, and enhancing long-term ecosystem recovery.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

## Author contributions

HS: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. RAS: Conceptualization, Methodology, Resources, Supervision, Validation, Visualization, Writing – review & editing. MSI:

Conceptualization, Formal analysis, Supervision, Validation, Visualization, Writing – review & editing. MBP: Conceptualization, Formal analysis, Methodology, Supervision, Validation, Writing – review & editing. SL: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. EC: Conceptualization, Funding acquisition, Methodology, Supervision, Validation, Writing – review & editing.

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