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Review

Geographic Setting and Groundwater Table Control Carbon Emission from Indonesian Peatland: A Meta-Analysis

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Abstract: Peat restoration is a key climate mitigation action for achieving Indonesia's Nationally Determined Contribution (NDC) emission reduction target. The level of carbon reduction resulting from peat restoration is uncertain, owing in part to diverse methodologies and land covers. In this study, a meta-analysis was conducted to assess the impact of rewetting on reduction of total CO_2 in soil and heterotrophic emissions at the country level. The tier 2 emission factor associated with the land cover category in Indonesia was also calculated. The analysis included a total of 32 studies with 112 observations (data points) for total CO_2 emissions and 31 observations for heterotrophic emissions in Indonesia. The results show that the land cover category is not a significant predictor of heterotrophic and total soil emissions, but the highest observed soil emissions were found in the plantation forest. Using the random-effects model, our results suggest that an increase in the water table depth of 10 cm would result in an increase in total CO_2 emissions of 2.7 Mg CO_2 ha^{-1} year^{-1} and an increase in heterotrophic emissions of 2.3 Mg CO_2 ha^{-1} year^{-1}. Our findings show that managing water table depth in degraded peatlands in various land cover types is important to achieve Indonesia's emission reduction target by 2030.

Keywords: CO_2; emissions factor (EF); Indonesia; meta-analysis; peatland; water table

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1. Introduction

Protecting and restoring soil organic matter delivers many benefits for people and provides a comprehensive solution for climate change, in particular for tropical peatlands [1,2]. There is a growing international interest in soil carbon in international climate mitigation work, such as the "4 per 1000" Initiative in Paris in 2015 and recognition of soil organic carbon (SOC) sequestration in the United Nations Framework Convention on Climate Change (UNFCCC) process in 2017 in the COP 23 decision 4/CP.23. The SOC element with the highest potential for natural climate solutions (NCSs) in the tropics is peatland restoration, which stands at 200 $GtCO_2$eq year^{-1} [3,4]. Specifically, NCS analysis has shown that restoring peatlands is one of the most promising strategies to achieve country emission reductions by 2030 [5], with potential emission reductions of 878 $MtonCO_2$eq year^{-1} in Indonesia [4].

Peatlands are critical for climate change and the global carbon cycle. However, the function of peatlands will be switched from sink to source in this century [6]. Moreover, undrained tropical peatlands have a significant climate stabilizing effect because of the rich carbon underneath the soil [7,8]. Tropical peatlands represent an important ecosystem in the global carbon budget, accounting for 10% of global peatlands and storing 50–350 GtC [9–11]. On the other hand, drained tropical peatlands, due to land use change through drainage and fires, have completely different effects, acting as significant contributors to global greenhouse gas emissions [12–15]. They are responsible for almost 25% of global carbon emissions from the land use sector [8]. Specifically in Indonesia, emissions from peat decomposition and fires contribute to 76% of the total agriculture and forestry annual emissions [16]. As the forestry sector is the main foundation of the NDC emission reduction target, and peatlands are the major contributor in the forestry sector, exploring the potential for Indonesia to extend and push the ambitious commitment over a longer period is necessary.

Indonesia already ratified the Paris Agreement in 2016 and submitted its Nationally Determined Contribution (NDC) in the same year. Based on Indonesia's NDC, either 1.4 million ha (Counter Measure 1 scenario) or 2.9 million ha (Counter Measure 2 scenario) of degraded peatlands will be restored within the period from 2014 to 2030. Indonesia is known as the second largest tropical peatland forest in the world, with 14.9–22 million ha of peatland [11,17,18]. Therefore, to achieve the emissions reduction target, Indonesia has pledged to restore two million ha of degraded peatland [19] and established the Peat Restoration Agency in 2015, which has now been extended to become the Peat and Mangrove Restoration Agency. Rewetting, as the main component in the restoration program, should be properly quantified with robust scientific evidence. Rewetting is not only useful to restore degraded peatlands, but also to protect remaining intact forests from fire risks [17,20,21]. Studies from tropical peatland types have demonstrated that increasing the water table through rewetting reduces CO_2 emissions and subsidence [22–25].

Hoyt et al. [26] have observed an effect of soil temperature and moisture on soil heterotrophic respiration. Furthermore, Cobb et al. [27] concluded that rainfall seasonality can affect the CO_2 emissions from tropical peatlands. Despite the importance of conserving and restoring peatlands in climate change mitigation, data on the relationship between soil GHG emissions and environmental variables in tropical peatlands is limited. Hooijer et al. [22] have provided several equations to estimate carbon emissions from water table fluctuation using eight sampling points in Riau, Sumatra. These equations were used as an approved Verified Carbon Standard (VCS) methodology for rewetting drained tropical peatlands (VM0027). In a recent review, Carlson et al. [25] used a linear regression model to determine the relation between water table depth and soil respiration. This model was built upon the IPCC's tier 1 emissions factor, which is based on limited sources (12 studies and 59 sites). In this study, we aimed to improve upon these previous studies by expanding the sampling numbers from various land use and cover types for peatlands and by testing the environmental variables at the country scale. This study had two objectives:

- To provide a Tier 2 emission factor estimate for peat decomposition using recent publications in Indonesia;
- To model the relationship between total and heterotrophic respirations with significant environmental predictors (i.e., land use, land cover class, geographical coordinate, water table depth, bulk density, and air temperature) in order to quantify CO_2 emission reductions from rewetting.

2. Methodology

2.1. Scope of the Study

This meta-analysis was based on 31 peer-reviewed journal papers and 1 project report. The research works were published between 2005 and 2019 from 112 study sites located in the Sumatra and Kalimantan islands of Indonesia, covering seven provinces: Aceh, North Sumatra, Riau, Jambi, West Kalimantan, South Kalimantan, and Central Kalimantan. Figure 1 depicts the geographical scope of this study. We classified the land use category based on the degree of degradation: cropping/shrubland, drained burnt, forest, and plantation. Land cover categories for observed peatlands in this study were based on the categories from the Indonesian Ministry of Environment and Forestry (MoEF), land cover categories adapted from IPCC for wetlands supplement [28], and land management classes. A more detailed explanation about land cover categories can be found in Indonesia's first Forest Emissions Level Reference [29]. In addition, land cover categories—namely cropland and fallow, drained; cropland, drained, paddy rice; forestland and cleared forestland, drained; plantations, drained, oil palm; and plantations, drained, short rotations [28]—were also assessed in this study.

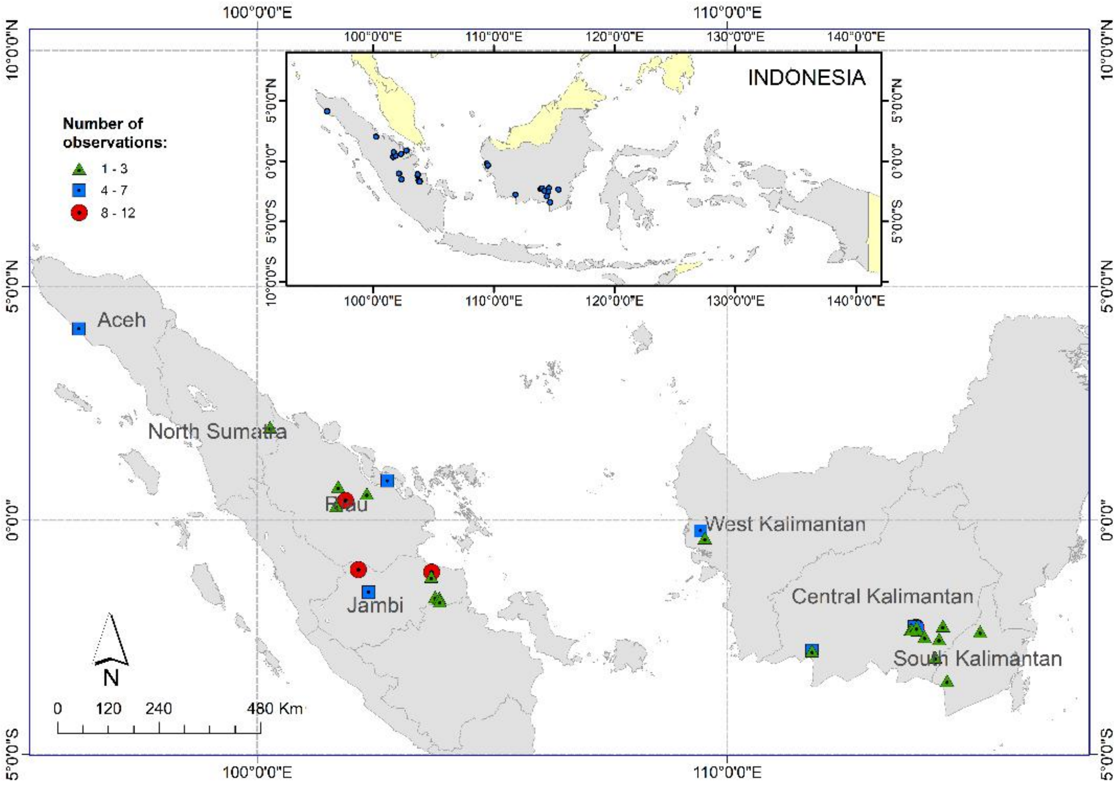


Figure 1. Geographical extent of the primary study areas used for the meta-analysis. Green diamonds, blue squares, and red circles denote the numbers of observations for 1–3 data observations, 4–7 data observations, and 8–12 data observations, respectively.

2.2. Total CO_2 and Heterotrophic Emissions Data Set

The dataset on total CO_2 and heterotrophic emissions was collected through a systematic review of publications of peatlands in Indonesia, as shown in Table 1 Additional data were also extracted from the publications to provide predictor variables (moderators) that might explain the heterogeneity of CO_2 emissions. Among others, the predictor variables used in this meta-analysis were geographical coordinates (latitude and longitude), land use class/land cover class, water table depth (cm), air temperature (°C), annual rainfall (mm year^{-1}), and bulk density (g cm^{-3}). Where necessary, the CO_2 emissions and predictor variables data were elicited by converting graphical data using the GetData Graph Digitizer (http://getdata-graph-digitizer.com (accessed on 23 February 2021)) and by accessing an online climate database (https://power.larc.nasa.gov/data-access-viewer (accessed on 24 February 2021)) when air temperature and annual rainfall data were absent in the publications. The details of the study titles and authors are provided in Table A1.

2.3. Emission Factor (EF) in Different Land Use and Land Covers Categories

The mean and SD of total CO_2 and heterotrophic emissions (Mg CO_2 ha^{-1} year^{-1}) from each site were combined across the studies to derive numbers for the tier 2 level for each land use/land cover class category. The true value of total CO_2 and heterotrophic emissions in each primary study remained unknown, but it was assumed to vary from one study area to another. The random-effects models with the restricted maximum-likelihood (REML) estimator and the Knapp and Hartung adjustment [30] were used to derive the mean total CO_2 and heterotrophic emissions (EF) at the tier 2 level with the "metafor" package of R version 3.6.3 [31,32]. The inter-study heterogeneity was assessed using the I^2 and Q statistics [30].

Table 1. List of the publications and number of observations for total CO_2 and heterotrophic emissions used in this meta-analysis [13,15,22,33–61].

No.	Author (Year)	Number of Observations	
		Total CO_2	Heterotrophic
1	Ali et al., (2006) [33]	3	
2	Astiani et al., (2018) [34]	4	
3	Batubara et al., (2019) [35]	2	
4	Comeau et al., (2016) [36]	1	
5	Dariah et al., (2014) [37]	2	2
6	Furukawa et al., (2005) [38]	12	
7	Hadi et al., (2005) [39]	3	
8	Handayani et al., (2009) [40]	7	7
9	Hergoualc'h et al., (2017) [41]	3	3
10	Hirano et al., (2007) [42]	1	
11	Hirano et al., (2009) [15]	6	
12	Hirano et al., (2014) [43]	2	
13	Hooijer et al., (2012) [22]	2	
14	Hooijer et al., (2014) [44]	1	
15	Husnain et al., (2014) [45]	1	6 *)
16	Inubushi et al., (2003) [46]	3	
17	Ishikura et al., (2017) [47]	11	
18	Ishizuka et al., (2002) [48]	8	
19	Itoh et al., (2017) [49]	3	
20	Jamaludin et al., (2020) [50]	3	3
21	Jauhiainen et al., (2005) [51]	1	
22	Jauhiainen et al., (2008) [13]	4	
23	Jauhiainen et al., (2012) [52]	8	8
24	Khasanah and van Noordwijk (2019) [53]	4	
25	Marwanto and Agus (2014) [54]	1	
26	Marwanto et al., (2019) [55]	1	
27	Saragi-Sasmito et al., (2019) [56]	1	1
28	Sundari et al., (2012) [57]	2	
29	Swails et al., (2019) [58]	6	
30	Toma et al., (2011) [59]	1	
31	Wakhid et al., (2017) [23]	1	1
32	Watanabe et al., (2009) [60]	4	
	Total	112	31

*) Husnain et al. (2014) provided 6 heterotrophic emissions data without their corresponding total CO_2 emissions for the same sites.

2.4. Model for Estimating Total CO_2 and Heterotrophic Emissions

The heterogeneity of CO_2 emissions can be influenced by various factors, including water table depth, land use types, microtopography, precipitation, temperature, and vegetation physiology [15,46]. Based on the data availability, this meta-analysis considered five predictor variables that might account for the heterogeneity of CO_2 emissions (*TE* or *HE*, Mg ha^{-1} $year^{-1}$): water table depth (*W*, cm), air temperature (*T*, °C), annual rainfall (*R*, mm $year^{-1}$), geographical location (in terms of absolute latitude, *L*), and bulk density (*B*, g cm^{-3}). These predictor variables were used to estimate total CO_2 and heterotrophic emissions using the following linear mixed-effects model [31]:

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \ldots + \beta_p B_{ki} + u_i \quad (1)$$

where Y_i is total or heterotrophic CO_2 emissions; β_0, β_1, . . . , β_p are regression parameters; X_1, X_2, . . . , X_k are predictor variables (i.e., W, T, R, L, or B); and u_i indicates the random effects of the i-th study that were assumed to be normally distributed with mean μ and variance τ^2. The "metafor" package was first used to generate a linear mixed-effects model using all predictor variables, which was then reduced into more simple models when some predictor variables were not found to be statistically significant. The maximum likelihood (ML) estimator and the Knap and Hartung adjustment methods were used to estimate the model parameters and their associated significant tests. The heterogeneity of total and heterotrophic CO_2 emissions accounted for by the predictor variables in each model was assessed using R^2 analog [30] and the comparison of model fits was based on the corrected Akaike Information Criterion (AICc) [31].

3. Results

3.1. Data Site

While all the primary studies provided total CO_2 emissions data, only eight primary studies (ca. 25%) provided heterotrophic emissions data (Table 1). Based on the spatial distribution shown in Figure 1, there were no primary studies conducted in Sulawesi and Papua, which, respectively, account for 0.3% and 26.7% of the total peatland area in Indonesia. In the future, studies on the CO_2 emissions should also cover these islands in order to provide more comprehensive data on CO_2 emissions from Indonesia's peatlands.

These 112 observations of primary studies, which were conducted at various sites, were further classified based on three definitions of land cover: land use as defined in [61], land cover as defined by the MoEF [62,63], and land cover as defined by the IPCC for wetlands [28]. When classifying the sites based on both land use as defined by Prananto et al. [61], these 112 studies were divided into four categories in each definition, with plantations and forests accounting for the highest number of total CO_2 observations for land use [61] and land cover as defined by IPCC for wetlands [28], respectively. When using the land cover classification of the MoEF, the studies were divided into nine categories with estate crops accounting for the highest number of total CO_2 observations. Categorizing the sites using the IPCC wetlands [28] definition resulted in six classifications, with forestland and cleared forestland, drained, as the category with the highest number of total CO_2 observations. There were limited observations for the MoEF bare ground and mixed dry agriculture classification, implying that more studies are needed to estimate total CO_2 and heterotrophic emissions for these land cover classes.

In order to fill the data gap for heterotrophic emissions, we calculated the ratio of heterotrophic emissions to total emissions from paired observations. The data for heterotrophic respiration were distributed across Aceh, Jambi, Central Kalimantan, and Riau, which represent the extent of peatlands across Indonesia. We found that the ratio of heterotrophic to total CO_2 emissions from paired data based on the primary studies was 78%, as depicted in Table 2.

Table 2. Ratio of heterotrophic to total CO_2 emissions from the primary studies in peatlands.

Land Use	Number of Observations	Ratio of Heterotrophic to Total CO_2 Emissions
Cropland and fallow, drained	1	0.90
Forestland and cleared forestland, drained	1	0.78
Plantations, drained, oil palm	14	0.67
Plantations, drained, short rotations	8	0.96
Total	24	0.78

3.2. *Emissions Factor of CO_2 Emissions from Tropical Peatland in Indonesia*

The random-effects models provided tier 2 estimates of the mean, standard error (SE), and 95% confidence interval (95% CI) of the total CO_2 emissions for all peatlands and each class of land use or land cover, as depicted in Figure 2. Using all observation data (n = 112), the random-effects model estimated a total CO_2 emissions of 48.22 Mg CO_2 ha^{-1} $year^{-1}$ (95% CI: 42.36–54.08 Mg CO_2 ha^{-1} $year^{-1}$) for the peatlands in Sumatra and Kalimantan. This tier 2 estimate had a lower SE of 2.96 Mg CO_2 ha^{-1} $year^{-1}$, which was attributed to the large amount of observation data. The heterogeneity of the estimate was high (I^2 = 95.5%) but statistically significant (Q = 6940, p-value < 0.01), indicating that total CO_2 emissions were considerably different among the study sites. Classifying the study sites into relevant land use and land cover classes produced specific estimates of total CO_2 emission factors, which were lower or higher than the tier 2 mean estimates. The heterogeneity of total CO_2 emissions between study sites within a land use/cover class was also high (I^2: 88.3–97.3% for land use classes, I^2: 40.1–97.6% for land cover classes). These findings confirmed that total CO_2 emissions from peatlands varied across the study sites within a particular class of land use/land cover due to variability in the environmental parameters.

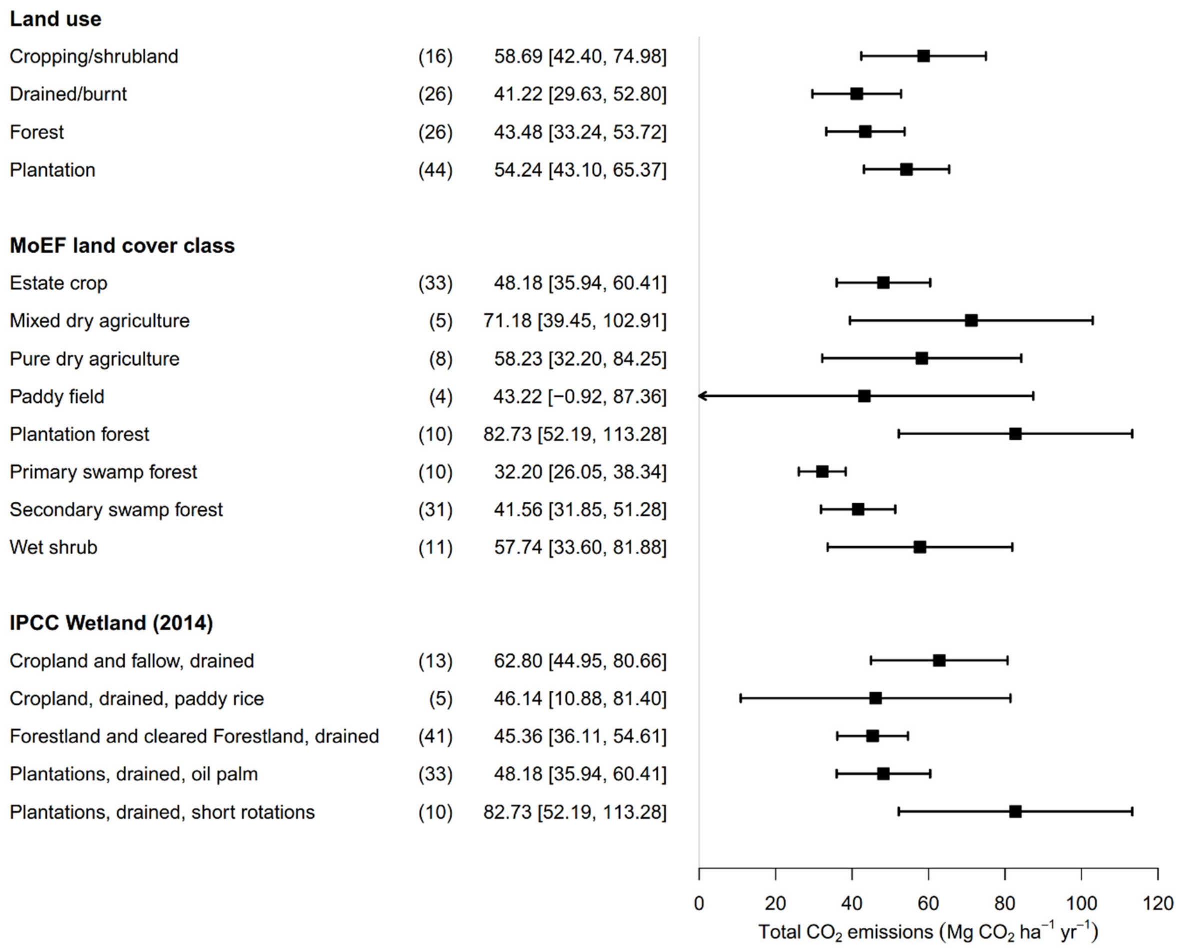


Figure 2. Total CO_2 emissions factors of Indonesia' peatlands for each land use and land cover class. The number of observations is provided in parentheses, followed by the mean and lower and upper bounds of the confidence interval in square brackets, separated by a comma.

Based on land use classification, the total CO_2 emissions range from 41.22 to 58.69 Mg CO_2 ha^{-1} $year^{-1}$, with the lowest value observed in the drained/burnt class. If land cover classes as defined by the MoEF [63] and IPCC [28] are applied, the highest CO_2 emissions can then be observed in the plantation forest or plantation, drained, short plantation categories. Oil palm plantations (defined as estate crops based on the MoEF's land cover class or as plantations, drained, oil palm according to the IPCC [28] had average CO_2 emissions of 48.18 Mg CO_2 ha^{-1} $year^{-1}$

Due to data limitations for heterotrophic emissions, they only accounted for 31 of the 112 total measurements. Similar to the total CO_2 emission, the heterogeneity of heterotrophic emissions was also high (I^2 = 95.4%) and significant (Q = 6948, *p*-value < 0.01). The specific estimates of heterotrophic emissions for each land use or land cover type are shown in Figure 3. The results show that the average emission factor from all land use and land cover types was 38.17 Mg CO_2 ha^{-1} $year^{-1}$, with a 95% CI of 33.63–42.71 Mg CO_2 ha^{-1} $year^{-1}$. These numbers can be considered as the emission factor of heterotrophic emissions from each land cover/land use class at the country level. The heterogeneity of heterotrophic emissions was also high, both within the land use classes (I^2 = 88.3–97.3%) and within the land cover classes (I^2 = 40.6–97.6%), indicating that the heterotrophic emissions varied across the peatland sites, similar to the total CO_2 emissions.

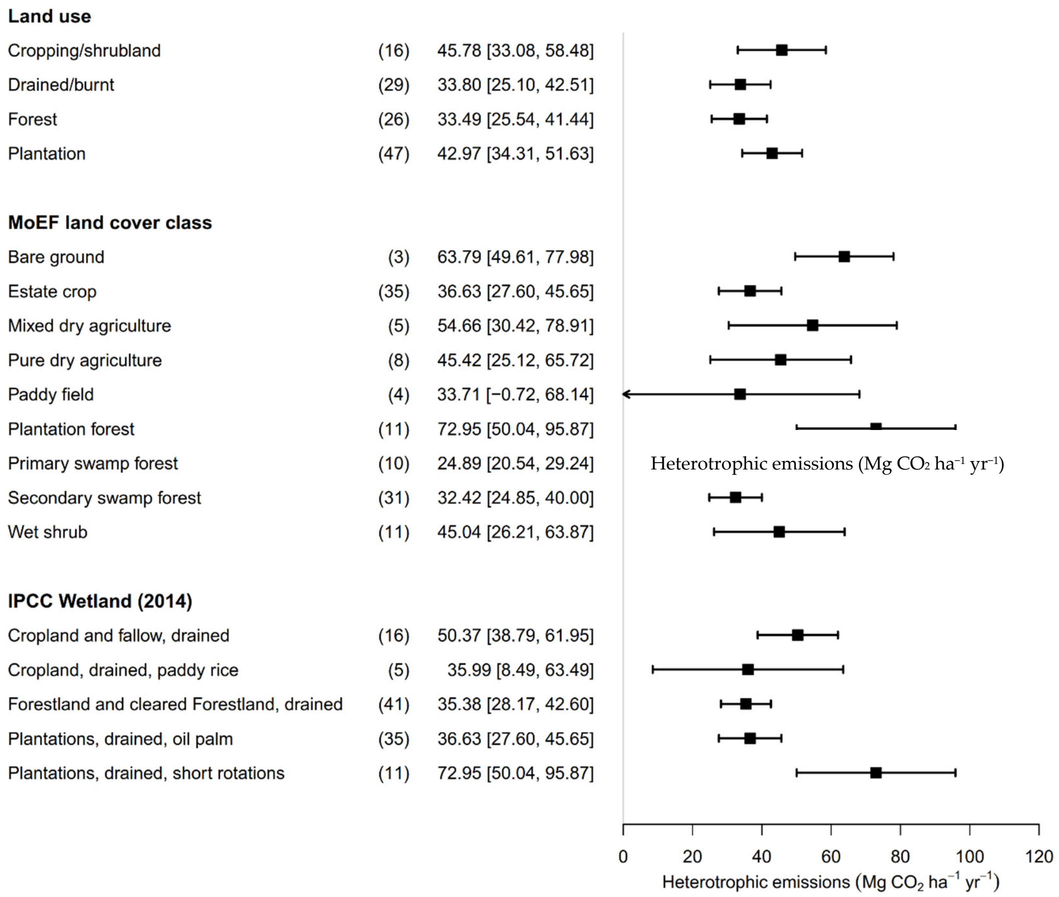


Figure 3. Heterotrophic emissions of Indonesia' peatlands. For each land use and land cover class, the number of observations is provided in parentheses, followed by the mean and lower and upper bounds of the confidence interval in square brackets, separated by a comma.

3.3. Meta-Analysis of CO_2 Emissions with Environmental Variables

We provide three alternative models to estimate total soil CO_2 emissions and other significant parameters (Table 3), including absolute latitude (L), water table depth (W), and bulk density (B). Temperature (T) and rainfall (R) were observed to be insignificant predictors; therefore, they were omitted from the model selection. Total soil emissions 1 (TE1) was developed using three parameters (L, W, and B) with an alpha of 10%; the TE1 model is a good option to estimate the total CO_2 emissions when the bulk density data are available. In the absence of field bulk density data, future studies can consider using the average bulk density data for the land use and land cover categories that were collected in this study (see Table A2). Total soil emissions 2 (TE2) was used to predict total soil emissions (Mg CO_2 ha^{-1} year^{-1}) using W and L. Total soil emissions 3 (TE3) was the simplest model, using W as the only independent predictor, but this model had the lowest R^2. Compared to TE1, the TE2 and TE3 models provide practical advantages for estimating the total CO_2 emissions, as W and L data are easy to monitor in the field. TE refers to total CO_2 emissions while HE refers to heterotrophic emissions.

Table 3. Parameter estimates and goodness of fit statistics of the general mixed-effects models for estimating total CO_2 emissions for all land uses.

Model	Parameter				SE	n	F		R^2 (%)	AICc
TE1	-	β_0	41.105	***	11.394	60	12.44	***	45.07	574.21
	W	β_1	0.565	***	0.131					
	L	β_2	−13.494	***	3.530					
	B	β_3	69.187	*	37.552					
TE2	-	β_0	56.738	***	8.057	101	8.57	***	12.32	988.85
	W	β_1	0.245	**	0.103					
	L	β_2	−9.147	***	2.828					
TE3	-	β_0	38.021	***	5.859	101	6.27	**	4.06	995.91
	W	β_1	0.269	**	0.108					

*** = highly significant at 1%, ** = significant at 5%, * = significant at 10%, n = number of observations used in the models, SE = standard error of the parameter estimates, R^2 = amount of heterogeneity accounted for by the models, AICc = corrected Akaike Information Criterion.

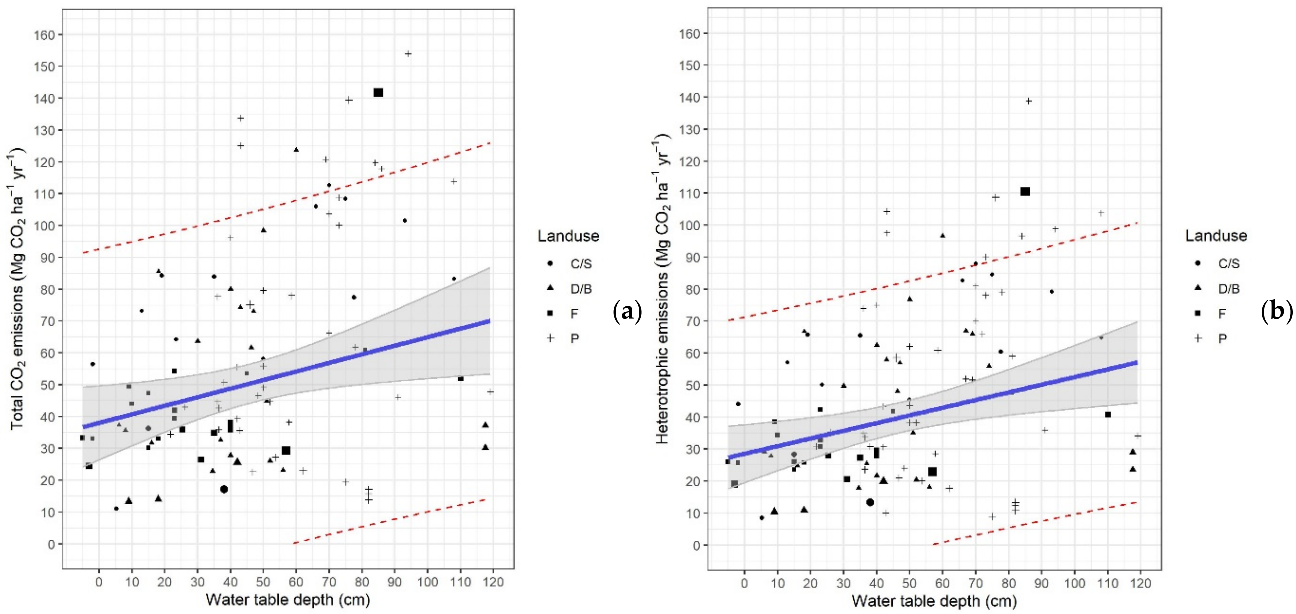
When developing suitable models for heterotrophic emissions, we found that only water table depth and latitude were significant predictors when using an alpha of 5% and 10%, as shown in Table 4. Inclusion of latitude and water table depth predictors was preferable (R^2 = 16.81%), rather than only using water table depth as a predictor (R^2 = 5.29%), as the latter only explained 5% of the heterogeneity of heterotrophic emissions. This meant that an increase in bulk density would not significantly increase the average heterotrophic emissions. HE1 was developed to describe the relationship between heterotrophic emissions (Mg CO_2 ha^{-1} year^{-1}) from W (water table level in cm) and L (absolute latitude). Using only W as a parameter to estimate heterotrophic emissions, HE2 had a lower R_2 compared to HE1. Therefore, HE1 was preferred to HE2 not only because of a higher R^2, but also because W and L were easily collected.

Table 4. Parameter estimates and goodness of fit statistics of the general mixed-effect models for estimating heterotrophic emissions for all land uses (n = 107).

Model	Parameter				SE	F		R^2 (%)	AICc
HE1	-	β_0	46.451	***	6.047	13.31	***	16.81	990.85
	W	β_1	0.201	**	0.077				
	L	β_2	−8.587	***	2.065				
HE2	-	β_0	28.547	***	4.568	8.4	***	5.29	1003.63
	W	β_1	0.24	***	0.083				

*** = highly significant at 1%, ** = significant at 5%, n = number of observations used in the models, SE = standard error of the parameter estimates, R^2 = amount of heterogeneity accounted for by the models, AICc = corrected Akaike Information Criterion.

This study revealed that the water table depth was positively associated with the heterogeneity of either total CO_2 or heterotrophic emissions. Based on the regression slopes (β_1) of the simplest models (TE3 and HE2), which were 0.27 for total CO_2 emissions and 0.24 for heterotrophic emissions, an increase in the water table depth by 10 cm would result in an increase in the average total CO_2 emissions by 2.7 Mg CO_2 ha^{-1} year^{-1} and the average heterotrophic emissions by 2.4 Mg CO_2 ha^{-1} year^{-1}. The water table depth effect of 2.7 Mg CO_2 ha^{-1} year^{-1} of total CO_2 emissions is comparable to that found by Hooijer et al. [22], who reported an equivalent total CO_2 emission for burnt peatland of 3.4 Mg CO_2 ha^{-1} year^{-1} when water table depth increased by 10 cm. At the water table depth of 70 cm, the TE3 model estimated total CO_2 emissions of 57 Mg CO_2 ha^{-1} year^{-1} (95% CI of 49–65 Mg CO_2 ha^{-1} year^{-1}, Figure 4a) and heterotrophic emissions of 45 Mg CO_2 ha^{-1} year^{-1} (95% CI of 39–51 Mg CO_2 ha^{-1} year^{-1}, Figure 4b). The estimates of total and heterotrophic emissions from this study were lower than those reported by Carlson et al. [25], who estimated total CO_2 emissions of 73 Mg CO_2 ha^{-1} year^{-1} (95% CI of 62–88 Mg CO_2 ha^{-1} year^{-1}) and heterotrophic emissions of 62 Mg CO_2 ha^{-1} year^{-1} (95% CI of 51–73 Mg CO_2 ha^{-1} year^{-1}) from peatland plantations at 70 cm of water table depth. This discrepancy is reasonable since this study used CO_2 emissions data from various sites across different land use classes, as depicted in Figure 4, and was not limited to plantation sites, as in the case of [25].



(**a**) (**b**)

Figure 4. Relationship between water table depth and (**a**) total CO_2 emissions and (**b**) heterotrophic emissions of all land uses. Solid blue lines represent the estimates of the population mean, shaded grey bands indicate the 95% CIs of population mean estimates, dashed red lines indicate the 95% prediction intervals for the potential CO_2 values of future samples, while the four shapes (circles, triangles, squares, and crosses) indicate the observation values in the land use classes where C/S = cropping/shrubland, D/B = drained/burnt, F = forest, and P = plantation.

Another interesting finding of this study is that absolute latitude was a significant predictor variable in all models, suggesting that absolute latitude related well to the heterogeneity of total CO_2 or heterotrophic emissions. The regression coefficients of absolute latitude in all models were negative, indicating that the decrease in the absolute latitude of peatland sites resulted in an increase in the average total or heterotrophic emissions. In other words, at a given water table depth, peatland sites closer to the equator (with a latitude of 0°, Figure 5) have greater CO_2 emissions than those farther from the equator. For example, at a 70 cm water table depth, a peatland site located at an absolute latitude of 0.5° would have an average total CO_2 emissions of 69 Mg CO_2 ha^{-1} year^{-1} (95% CI of 58–80 Mg CO_2 ha^{-1} year^{-1}, Figure 5a) or heterotrophic emissions of 56 Mg CO_2 ha^{-1} year^{-1} (95% CI of 48–64 Mg CO_2 ha^{-1} year^{-1}, Figure 5b). These CO_2 emission estimates would be higher than those for a peatland site located in an absolute latitude of 3.5° at the same water table depth, which would have average total CO_2 emissions of 42 Mg CO_2 ha^{-1} year^{-1} (95% CI of 30–54 Mg CO_2 ha^{-1} year^{-1}, Figure 5a) or heterotrophic emissions of 30 Mg CO_2 ha^{-1} year^{-1} (95% CI of 22–39 Mg CO_2 ha^{-1} year^{-1}, Figure 5b).

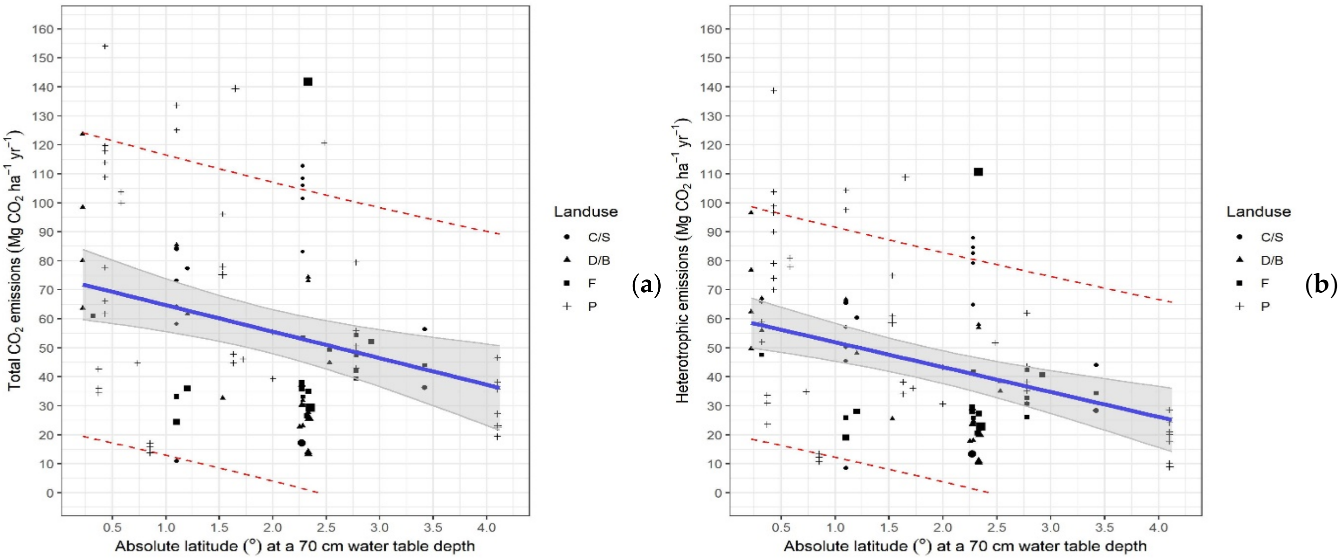


Figure 5. Relationship between absolute latitude at 70 cm water table depth and (**a**) total CO_2 emissions and (**b**) heterotrophic emissions of all land uses. Solid blue lines represent the estimates of the population mean, shaded grey bands indicate the 95% CIs of population mean estimates, dashed red lines indicate the 95% prediction intervals for the potential CO_2 values of future samples, while the four shapes (circles, triangles, squares, and crosses) indicate the observation values in the land use classes, where C/S = cropping/shrubland, D/B = drained/burnt, F = forest, and P = plantation.

3.4. Do We Need a Specific Model for Each Land Use Category?

The general mixed-effects models above provided estimates of total CO_2 emissions or heterotrophic emissions for all land use categories with a range of water table depths and bulk densities (see the summary statistics for water table depth and bulk density using land use classes in Table A3 and land cover classes in Table A4. To further clarify this issue, this study extended the mixed-effects models to include land use classes as dummy variables in the specific mixed-effects models, which could be used to estimate total CO_2 emissions for each land use class adapted from Prananto et al. [61] (CS = cropping/shrubland, DB = drained or burnt, F = primary and secondary forest, and P = oil palm, rubber and acacia plantations). Using significant predictors (W, L, and B) from the previous TE1, TE2, and T3 models, inclusion of land use classes as predictor variables increased the R^2 values only by up to 2% (Table 5).

To use the specific mixed-effects models to estimate total CO_2 at a particular land use, the other dummy variables (i.e., land use classes) were assumed to have zero effects. For example, the total CO_2 emissions of each land use class could be estimated based on the TE3-LU model as follows:

$Y = 49.950 + 0.271\ W - 17.585\ DB - 14.706\ F - 10.6096\ P$

Land use CS: $Y = 49.950 + 0.271\ W$

Land use DB: $Y_{DB} = 49.950 + 0.271\ W - 17.585\ DB$

Land use F: $Y_F = 49.950 + 0.271\ W - 14.706\ F$

Land use P: $Y_P = 49.950 + 0.271\ W - 10.6096\ P$

Using a similar approach for the total soil CO_2 emissions, where table depth (W) and Latitude (L) were significant predictors, we provide several recommended models in Table 6. Compared to the previous HE1 and HE models, the inclusion of land use categories only increased the R^2 value by 2% and 1.4%f, respectively. Therefore, similar to the total CO_2 emissions, we suggest that the HE1 or HE2 models can be applied for the various land use types in Indonesia.

Table 5. Parameter estimates and goodness of fit statistics of the general mixed-effects models for estimating total CO_2 emissions for all land uses.

Model	Parameter				SE	n	F		R^2 (%)	AICc
TE1-LU	-	β_0	59.139	**	30.076	60	6.41	***	47.71	580.3
	W	β_1	0.478	***	0.153					
	L	β_2	−11.599	***	4.19					
	B	β_3	37.758		50.016					
	DB	β_4	−14.608		22.303					
	F	β_5	−17.556		23.719					
	P	β_6	−5.955		20.555					
TE2-LU	-	β_0	67.808	***	10.852	101	4.05	***	14.49	992.71
	W	β_1	0.258	**	0.111					
	L	β_2	−9.287	***	2.851					
	DB	β_3	−18.55		10.588					
	F	β_4	−11.864		10.27					
	P	β_5	−10.431		10.203					
TE3-LU	-	β_0	49.95	***	9.759	101	2.27 *		5.62	999.88
	W	β_1	0.271	**	0.117					
	DB	β_2	−17.585		11.079					
	F	β_3	−14.706		10.74					
	P	β_4	−10.609		10.661					

*** = highly significant at 1%, ** = significant at 5%, * = significant at 10%, n = number of observations used in the models, SE = standard error of the parameter estimates, R^2 = amount of heterogeneity accounted for by the models, AICc = corrected Akaike Information Criterion.

Table 6. Parameter estimates and goodness of fit statistics of the specific mixed-effects models for estimating heterotrophic emissions for each land use class.

Model	Parameter				SE	n	F		R^2 (%)	AICc
HE1-LU	-	β_0	55.176	***	8.259	107	5.93	***	18.81	994.74
	W	β_1	0.218	***	0.084					
	L	β_2	−8.758	***	2.088					
	DB	β_3	−14.210	*	8.060					
	F	β_4	−9.104		7.852					
	P	β_5	−8.979		7.758					
HE2-LU	-	β_0	37.908	***	7.678	107	2.71	**	6.65	1007.84
	W	β_1	0.244	***	0.091					
	DB	β_2	−12.658		8.660					
	F	β_3	−11.902		8.450					
	P	β_4	−8.968		8.331					

*** = highly significant at 1%, ** = significant at 5%, * = significant at 10%, n = number of observations used in the models, SE = standard error of the parameter estimates, R^2 = amount of heterogeneity accounted for by the models, AICc = corrected Akaike Information Criterion.

4. Discussions

4.1. Recommendation for Tier 2 Emission Factor

Based on our analysis, we recommend emission factor values of peat decomposition based on various land uses and land cover types in Indonesia because each class has specific environmental characteristics. In addition, this land cover classification is used as a basis for national forest monitoring system and REDD+ projects in Indonesia. Based on Indonesia's first FREL [62], the emission factor values of peat decomposition can be calculated based on Table 2.1 in the IPCC Wetlands Supplement (2014) [28]. This study provides recommendations to improve the emission factor values for peat decomposition, since Indonesia is currently revising its second FREL. Our mean value was within the range of total soil respiration from three different ecosystems, namely forests, sago, and palm oil (14–171 Mg CO_2 year^{-1}), located in Sarawak, Malaysia, obtained by Melling et al., (2005) [64]. Our estimate was lower than a review result for tropical peatlands in the work by Hatano et al., (2019) [65], who reported 27 and 47 Mg CO_2 year^{-1} of mean total CO_2 emissions for unfertilized and fertilized areas, respectively. Hatano et al., (2019) [65] used a smaller number of observations (42 datasets) and the data were distributed across not only Indonesia, but also Malaysia.

4.2. Estimating CO_2 Emissions from Water Table Depth and Latitude

Absolute latitude is a significant predictor variable in the model because sites near the equator may have higher oscillating temperatures between day and night than those further from equator. Hoyt et al. [26] have explained that oscillating temperatures may push fluxes of CO_2 from the peat surface to the air through a gas transport mechanism. As the peat warms during daytime, soil gas expands, which drives a higher gas flux from the peat surface to the atmosphere on sites near the equator. This finding suggests that spatial variability of peatland sites should also be considered when managing tropical peatlands in Indonesia.

The model from this study can be applied to estimate the effects of peat rewetting on total and heterotrophic CO_2 emissions in Indonesia. We did not include bulk density, air temperature, or rainfall in the models because these parameters were not found to be significant predictors to estimate heterotrophic emissions. This suggests that an increase in bulk density does not significantly increase the average heterotrophic emissions. The use of bulk density data for a predictor variable is also not practical because lab measurement is needed to obtain this data. Unlike land use and land cover as categorical variables, the data for other continuous variables (i.e., water table depth, air temperature, annual rainfall, and bulk density) were not available for all primary studies. These missing data could not be inferred from the publications because the authors did not measure all of the variables used in their studies, specifically water table depth and bulk density.

Our models suggest that the significantly different CO_2 emissions for different land use categories are influenced more by the water table depth and latitude position for those locations relative to other observed parameters, such as bulk density, air temperature, and rainfall. The three models described in this study still represented only part of the variation in the total (4.1–45.1%) and heterotrophic (5.3–16.8%) CO_2 emissions, suggesting that there are other environmental variables that need to be included in future studies. Kardol and Wardle (2010) [66] have suggested that aboveground and belowground linkages, such as composition of plants and soil microbes, may contribute to the functioning of ecosystems in terms of carbon sequestration and emission. These are relevant variables to be included in the modeling of CO_2 emissions from peatlands in the future.

The use of an extensive dataset for the model development in this study may have resulted in better estimates of emission reduction potential from peat rewetting in Indonesia. Water table management is one of the most important strategies in peatland restoration. Hence, restoring the hydrological function of degraded peat ecosystems is key to successful revegetation, reducing fire risks, and reducing the potential CO_2 emissions associated with peat oxidation [17,22,67–69]. Several studies have reported that peat rewetting, which generally consists of canal blocking and canal infilling, can increase the groundwater table, hence reducing CO_2 emissions [13,24,67–69]. However, the number of observations remains limited.

Our study revealed that predictors such as water table depth and latitude were positively associated with the heterogeneity of either total or heterotrophic CO_2 emissions. This finding suggests that the spatial variability of peatland sites should also be considered, along with the water table depth, when reducing the CO_2 emissions from tropical peatlands in Indonesia. This study also confirmed that there is no impact from the land use category on the total and heterotrophic emissions. Further, similar to Carlson et al. [25], this result confirmed that land use classes do not actually influence the average total CO_2 emissions.

5. Conclusions

The study was conducted to apply the tier 2 emission factor for peat decomposition to recent publications in Indonesia and to model the relationship between total and heterotrophic respiration with significant environmental predictors (i.e., land use, land cover class, geographical coordinate, water table depth, bulk density, and air temperature). Our study revealed that predictors such as water table depth and latitude were positively associated with the heterogeneity of either total CO_2 or heterotrophic emissions. The random-effects models provided tier 2 estimates of the mean, standard error (SE), and 95% confidence interval (95% CI) of the total CO_2 emissions for all peatlands and each class of the land use or land cover. Using all observation data (n = 112) the random-effects model estimated total CO_2 emissions of 48.22 Mg CO_2 ha^{-1} year^{-1} (95% CI: 42.36–54.08 Mg CO_2 ha^{-1} year^{-1}) for the peatlands in Sumatra and Kalimantan. At a given water table depth, peatland sites closer to the equator (with a latitude of 0°) have greater CO_2 emissions than those farther from the equator. This finding suggests that the spatial variability of peatland could influence soil CO_2 emission and this variable should be considered when managing and restoring degraded tropical peatlands in Indonesia. While land use and land cover categories do not necessarily affect the total CO_2 and heterotrophic emissions, the water table depth and latitude position are directly linked within the CO_2 emission dynamic. Given the limitations of the heterotrophic data in this study, further research is needed to improve our understanding of the relative contribution of heterotrophic and autotrophic emissions under different systems of peatland management.

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Appendix A

Table A1. Systematic Review.

No	Citation	Literature	Title of Publication
1	Ali et al., 2006	Journal	Effect of environmental variations on CO_2 Efflux from a tropical peatlands in eastern Sumatera
2	Astiani et al., 2018	Journal	Soil CO_2 respiration along annual crops or land-cover type gradients on West Kalimantan degraded peatland forest
3	Batubara et al., 2019	Journal	Impact of soil collar insertion depth on microbial respiration measurements from tropical peat under an oil palm plantation
4	Comeau et al., 2016	Journal	How do the heterotrophic and the total soil respiration of an oil palm plantation on peat respond to nitrogen fertilizer application?
5	Dariah et al., 2013	Journal	Root and peat based CO_2 emissions from oil palm plantations
6	Furukawa et al., 2005	Journal	Effect of changing groundwater levels caused by land-use changes on greenhouse gas fluxes from tropical peat lands

Table A1. *Cont.*

No	Citation	Literature	Title of Publication
7	Hadi et al., 2005	Journal	Greenhouse gas emissions from tropical peatlands of Kalimantan, Indonesia
8	Handayani et al., 2009	Journal	Carbon Dioxide (CO_2) Emission of Oil Palm Plantation on Peatland: The evaluation CO_2 flux on inside and outside Rhyzosphere
9	Hergoualc'h et al., 2017	Journal	Total and heterotrophic soil respiration in a swamp forest and oil palm plantations on peat in Central Kalimantan
10	Hirano et al., 2007	Journal	Carbon dioxide balance of a tropical peat swamp forest in Kalimantan, Indonesia
11	Hirano et al., 2009	Journal	Controls on the Carbon Balance of Tropical Peatlands
12	Hirano et al., 2014	Journal	Carbon dioxide emissions through oxidative peat decomposition on a burnt tropical peatland
13	Hooijer et al., 2012	Journal	Subsidence and carbon loss in drained tropical peatlands
14	Hooijer et al., 2014	Report	Carbon emissions from drained and degraded peatland in Indonesia and emission factors for measurement, reporting and verification (MRV) of peatland greenhouse gas emissions
15	Husnain et al., 2014	Journal	CO_2 emissions from tropical drained peat in Sumatera, Indonesia
16	Inubushi et al., 2003	Journal	Seasonal changes of CO_2, CH_4 and N_2O fluxes in relation to land-use change in tropical peatlands located in coastal area of South Kalimantan
17	Ishikura et al., 2017	Journal	Effect of groundwater level fluctuation on soil respiration rate of tropical peatland in Central Kalimantan, Indonesia
18	Ishizuka et al., 2002	Journal	An intensive field study on CO_2, CH_4, and N_2O emissions from soils at four land-use types in Sumatra, Indonesia
19	Itoh et al., 2017	Journal	Factors affecting oxidative peat decomposition due to land use in tropical peat swamp forests in Indonesia
20	Jamaludin et al., 2020	Journal	Emisi karbon dioksida (CO_2) dari pertanian skala kecil di lahan gambut
21	Jauhiainen et al., 2005	Journal	Carbon fluxes from a tropical peat swamp forest floor
22	Jauhiainen et al., 2008	Journal	Carbon dioxide and methane fluxes in drained tropical peat before and after hydrological restoration
23	Jauhiainen et al., 2012	Journal	Carbon dioxide emissions from an Acacia plantation on peatland in Sumatera, Indonesia

Table A1. *Cont.*

No	Citation	Literature	Title of Publication
24	Khasanah & Noordwijk, 2017	Journal	Subsidence and carbon dioxide emissions in a smallholder peatland mosaic in Sumatra, Indonesia
25	Marwanto & Agus, 2013	Journal	Is CO_2 flux from oil palm plantations on peatland controlled by soil moisture and/or soil and air temperatures
26	Marwanto et al., 2019	Journal	Importance of CO_2 production in subsoil layers of drained tropical peatland under mature oil palm plantation
27	Saragi-Sasmito et al., 2018	Journal	Carbon stocks, emissions, and aboveground productivity in restored secondary tropical peat swamp forest
28	Sundari et al., 2012	Journal	Effect of groundwater level on soil respiration in tropical peat swamp forests
29	Swails et al., 2018	Journal	The response of soil respiration to climatic drivers in undrained forest and drained oil palm plantations in a Indonesia peatland
30	Toma et al., 2011	Journal	Nitrous oxide emission derived from soil organic matter decomposition from tropical agricultural peat soil in central Kalimantan, Indonesia
31	Wakhid et al., 2017	Journal	Soil carbon dioxide emissions from a rubber plantation on tropical peat
32	Watanabe et al., 2009	Journal	Methane and CO_2 fluxes from an Indonesian peatland used for sago palm (Metroxylon sagu Rottb.) cultivation: Effects of fertilizer and groundwater level management

Table A2. Datasets.

No.	Authors	Site Name		Land Use	Land Cover	Province	Latitude	Longitude	Total CO_2		Heterotrophic			WTD	Temp.	Rainfall	BD
									Mean	SD	Mean	SD					
1	Ali et al., (2006)	Site 01	Agriculture land	C/S	Mixed dry agriculture	Jambi	−1.2	103.7	77.45	18.64	60.41	14.54		77.5	28	2490	0.4
2	Ali et al., (2006)	Site 02	Logged forest	F	Secondary swamp forest	Jambi	−1.2	103.7	35.95	3.05	28.04	2.38		25.3	26.8	2490	0.28
3	Ali et al., (2006)	Site 03	Recently burned	D/B	Secondary swamp forest	Jambi	−1.2	103.7	61.63	16.11	48.07	12.57		46.3	27.8	2490	0.32
4	Astiani et al., (2018)	Site 01	Drained and cleared swamp forest	D/B	Wet shrub	West Kalimantan	−0.22	109.43	63.7	10.2	49.69	7.96		30	26.5	3171	0.15
5	Astiani et al., (2018)	Site 02	Drained and cleared swamp forest	D/B	Wet shrub	West Kalimantan	−0.22	109.43	80.1	11.8	62.48	9.2		40	26.5	3171	0.15
6	Astiani et al., (2018)	Site 03	Drained and cleared swamp forest	D/B	Wet shrub	West Kalimantan	−0.22	109.43	98.5	11.9	76.83	9.28		50	26.5	3171	0.15
7	Astiani et al., (2018)	Site 04	Drained and cleared swamp forest	D/B	Wet shrub	West Kalimantan	−0.22	109.43	123.7	12.5	96.49	9.75		60	26.5	3171	0.15
8	Batubara et al., (2019)	Site 01	Oil palm plantation	P	Estate crop	North Sumatra	2	100.27	39.3	18.67	30.65	14.56		42	26	3467	0.15
9	Batubara et al., (2019)	Site 02	Oil palm plantation	P	Estate crop	North Sumatra	2	100.27	55.5	22.06	43.29	17.21		42	26	3467	0.15
10	Comeau et al., (2016)	Site 01	Oil palm plantation	P	Estate crop	Jambi	−1.65	103.87	139.4	5.66	108.73	4.41		76	27.5	2466	0.23
11	Dariah et al., (2014)	Site 01	Oil palm plantation	P	Estate crop	Jambi	−1.63	103.78	44.7	11.12	38.2	9.47	a	52	26.2	2500	0.16
12	Dariah et al., (2014)	Site 02	Oil palm plantation	P	Estate crop	Jambi	−1.63	103.78	47.8	21.36	34.1	15.84	a	119	26.2	2500	0.19
13	Furukawa et al., (2005)	Site 01	Cassava field	C/S	Pure dry agriculture	Jambi	−1.1	103.71	64.3	32.04	50.15	24.99		23.5	26.7	2582	na
14	Furukawa et al., (2005)	Site 02	Coconut field	P	Estate crop	Jambi	−1.1	103.71	133.7	36.55	104.29	28.51		43	26.7	2582	na
15	Furukawa et al., (2005)	Site 03	Coconut field	P	Estate crop	Jambi	−1.1	103.71	125.1	31.99	97.58	24.95		43	26.7	2582	na
16	Furukawa et al., (2005)	Site 04	Drained forest	D/B	Secondary swamp forest	Jambi	−1.1	103.71	85.54	37.38	66.72	29.16		18.1	26.7	2582	na
17	Furukawa et al., (2005)	Site 05	Lowland paddy field	C/S	Paddy field	Jambi	−1.1	103.71	11.05	11.47	8.62	8.95		5.2	26.7	2582	na
18	Furukawa et al., (2005)	Site 06	Pineapple field	C/S	Pure dry agriculture	Jambi	−1.1	103.71	84.38	10.51	65.82	8.2		19	26.7	2582	na
19	Furukawa et al., (2005)	Site 07	Pineapple field	C/S	Pure dry agriculture	Jambi	−1.1	103.71	84.03	18.03	65.54	14.06		35	26.7	2582	na
20	Furukawa et al., (2005)	Site 08	Pineapple field	C/S	Pure dry agriculture	Jambi	−1.1	103.71	58.2	22.36	45.4	17.44		50	26.7	2582	na
21	Furukawa et al., (2005)	Site 09	Swampy forest	F	Secondary swamp forest	Jambi	−1.1	103.71	33.31	8.63	25.98	6.73		−5	26.7	2582	na
22	Furukawa et al., (2005)	Site 10	Swampy forest	F	Secondary swamp forest	Jambi	−1.1	103.71	24.41	2.37	19.04	1.85		−3	26.7	2582	na
23	Furukawa et al., (2005)	Site 11	Swampy forest	F	Secondary swamp forest	Jambi	−1.1	103.71	33.02	16.3	25.76	12.71		−2	26.7	2582	na

Table A2. *Cont.*

No.	Authors	Site Name		Land Use	Land Cover	Province	Latitude	Longitude	Total CO_2		Heterotrophic			WTD	Temp.	Rainfall	BD
									Mean	SD	Mean	SD					
24	Furukawa et al., (2005)	Site 12	Upland paddy field	C/S	Paddy field	Jambi	−1.1	103.71	73.2	34.71	57.1	27.07		13	26.7	2582	na
25	Hadi et al., (2005)	Site 01	Abandoned paddy-crop field	F	Secondary swamp forest	South Kaliman-tan	−2.37	115.37	87.63	29.12	68.35	22.71		na	26.5	2756	na
26	Hadi et al., (2005)	Site 02	Paddy field	C/S	Paddy field	South Kaliman-tan	−2.37	115.37	57.76	30.16	45.05	23.52		na	26.5	2756	na
27	Hadi et al., (2005)	Site 03	Secondary forest	F	Secondary swamp forest	South Kaliman-tan	−2.37	115.37	46.05	25.1	35.92	19.58		na	26.5	2756	na
28	Handayani et al., (2009)	Site 01	Oil palm plantation	P	Estate crop	Aceh	4.1	96.21	22.99	4.94	17.75	6.4	a	62	36.2	2789	na
29	Handayani et al., (2009)	Site 02	Oil palm plantation	P	Estate crop	Aceh	4.1	96.21	19.39	9.91	8.89	5.25	a	75	36.2	2789	na
30	Handayani et al., (2009)	Site 03	Oil palm plantation	P	Estate crop	Aceh	4.1	96.21	46.57	23.3	24.1	26.79	a	48.4	36.2	2789	na
31	Handayani et al., (2009)	Site 04	Oil palm plantation	P	Estate crop	Aceh	4.1	96.21	27.22	8.07	20.05	6.24	a	53.6	36.2	2789	na
32	Handayani et al., (2009)	Site 05	Oil palm plantation	P	Estate crop	Aceh	4.1	96.21	38.19	25.16	28.55	16.97	a	57.8	36.2	2789	na
33	Handayani et al., (2009)	Site 06	Oil palm plantation	P	Estate crop	Aceh	4.1	96.21	22.58	7.33	20.97	7.72	a	46.7	36.2	2789	na
34	Handayani et al., (2009)	Site 07	Oil palm plantation	P	Estate crop	Aceh	4.1	96.21	35.59	25.41	10.04	7.98	a	42.7	36.2	2789	na
35	Hergoualc'h et al., (2017)	Site 01	Oil palm plantation	P	Estate crop	Central Kaliman-tan	−2.78	111.8	50.65	12.92	30.8	18.64	a	38	29.7	2058	0.31
36	Hergoualc'h et al., (2017)	Site 02	Oil palm plantation	P	Estate crop	Central Kaliman-tan	−2.78	111.8	42.94	30.2	35.23	10.18	a	26	36.8	2058	0.33
37	Hergoualc'h et al., (2017)	Site 03	Primary peat forest	F	Primary swamp forest	Central Kaliman-tan	−2.78	111.8	47.34	21.02	26.06	5.09	a	15	29.6	2058	0.17
38	Hirano et al., (2007)	Site 01	Secondary forest	F	Secondary swamp forest	Central Kaliman-tan	−2.33	114.04	141.77	1.33	110.58	1.04		85	26.3	2235	na
39	Hirano et al., (2009)	Site 01	Crop-free agric land	C/S	Pure dry agriculture	Central Kaliman-tan	−2.27	113.98	17.2	1.6	13.42	1.25		38	26.3	2331	na
40	Hirano et al., (2009)	Site 02	Drained regenerating forest	D/B	Secondary swamp forest	Central Kaliman-tan	−2.27	113.98	37.2	3.8	29.02	2.96		117.5	26.3	2560	na
41	Hirano et al., (2009)	Site 03	Drained regenerating forest	D/B	Secondary swamp forest	Central Kaliman-tan	−2.27	113.98	30.2	3.6	23.56	2.81		117.5	26.3	2331	na
42	Hirano et al., (2009)	Site 04	Secondary forest	F	Secondary swamp forest	Central Kaliman-tan	−2.27	113.98	35.7	5.8	27.85	4.52		40	26.3	1852	na

Table A2. *Cont.*

No.	Authors	Site Name		Land Use	Land Cover	Province	Latitude	Longitude	Total CO_2		Heterotrophic			WTD	Temp.	Rainfall	BD
									Mean	SD	Mean	SD					
43	Hirano et al., (2009)	Site 05	Secondary forest	F	Secondary swamp forest	Central Kaliman-tan	−2.27	113.98	37.1	5.2	28.94	4.06		40	26.3	2292	na
44	Hirano et al., (2009)	Site 06	Secondary forest	F	Secondary swamp forest	Central Kaliman-tan	−2.27	113.98	38	4.9	29.64	3.82		40	26.3	2560	na
45	Hirano et al., (2014)	Site 01	Burned forest	D/B	Secondary swamp forest	Central Kaliman-tan	−2.33	114.03	14	2.99	10.92	2.33		18	26.2	2540	na
46	Hirano et al., (2014)	Site 02	Burned forest	D/B	Secondary swamp forest	Central Kaliman-tan	−2.33	114.03	13.3	2.69	10.37	2.1		9	26.2	2540	na
47	Hooijer et al., (2012)	Site 01	Acacia plantation	P	Plantation forest	Riau	0.58	102.33	103.75	50.3	80.93	39.23		70	30	2500	0.09
48	Hooijer et al., (2012)	Site 02	Oil palm plantation	P	Estate crop	Jambi	0.58	102.33	100	17.9	78	13.96		73	30	2500	0.09
49	Hooijer et al., (2014)	Site 01	Burnt and drained peatland	D/B	Secondary swamp forest	Central Kaliman-tan	−2.25	114.58	22.75	8.82	17.75	6.88		34.5	25.9	2842	0.09
50	Husnain et al., (2014)	Site 01	Acacia plantation	P	Plantation forest	Riau	0.32	101.68	na	na	59	19.02	a	81	31.9	2492	0.12
51	Husnain et al., (2014)	Site 02	Bare ground	D/B	Bare ground	Riau	0.32	101.68	na	na	67	23.97	a	67	31.9	2492	0.12
52	Husnain et al., (2014)	Site 03	Bare ground	D/B	Bare ground	Riau	0.32	101.68	na	na	56	30.06	a	74	31.9	2492	0.12
53	Husnain et al., (2014)	Site 04	Bare ground	D/B	Bare ground	Riau	0.32	101.68	na	na	66	26.95	a	69	31.9	2492	0.12
54	Husnain et al., (2014)	Site 05	Oil palm plantation	P	Estate crop	Riau	0.32	101.68	na	na	66	25.03	a	72	31.9	2492	0.15
55	Husnain et al., (2014)	Site 07	Rubber plantation	P	Estate crop	Riau	0.32	101.68	na	na	52	16.97	a	67	31.9	2492	0.12
56	Husnain et al., (2014)	Site 08	Secondary forest	F	Secondary swamp forest	Riau	0.32	101.68	61	25.03	47.58	19.52		81	31.9	2492	0.12
57	Inubushi et al., (2003)	Site 01	Abandoned cropland	C/S	Pure dry agriculture	South Kaliman-tan	−3.42	114.67	36.3	4.04	28.31	3.15		15	26.5	3133	na
58	Inubushi et al., (2003)	Site 02	Abandoned paddy	C/S	Paddy field	South Kaliman-tan	−3.42	114.67	56.5	10.63	44.07	8.29		−2	26.5	3133	na
59	Inubushi et al., (2003)	Site 03	Secondary forest	F	Secondary swamp forest	South Kaliman-tan	−3.42	114.67	44	15.76	34.32	12.29		10	26.5	3133	na
60	Ishikura et al., (2017)	Site 01	Burned land	D/B	Wet shrub	Central Kaliman-tan	−2.28	114.01	31.8	22.24	24.8	17.35		16	26.3	2235	0.22
61	Ishikura et al., (2017)	Site 02	Burned land	D/B	Wet shrub	Central Kaliman-tan	−2.28	114.01	23.1	10.61	18.02	8.28		56	26.3	2235	0.22

Table A2. *Cont.*

No.	Authors	Site Name		Land Use	Land Cover	Province	Latitude	Longitude	Total CO_2		Heterotrophic		WTD	Temp.	Rainfall	BD
									Mean	SD	Mean	SD				
62	Ishikura et al., (2017)	Site 03	Burned land	D/B	Wet shrub	Central Kaliman-tan	−2.28	114.01	37.3	45.88	29.09	35.79	6	26.3	2235	0.13
63	Ishikura et al., (2017)	Site 04	Burned land	D/B	Wet shrub	Central Kaliman-tan	−2.28	114.01	35.7	28.61	27.85	22.32	8	26.3	2235	0.13
64	Ishikura et al., (2017)	Site 05	Crop land	C/S	Pure dry agriculture	Central Kaliman-tan	−2.28	114.01	112.7	59.37	87.91	46.31	70	26.3	2235	0.38
65	Ishikura et al., (2017)	Site 06	Crop land	C/S	Mixed dry agriculture	Central Kaliman-tan	−2.28	114.01	101.5	55.61	79.17	43.38	93	26.3	2235	0.38
66	Ishikura et al., (2017)	Site 07	Crop land	C/S	Pure dry agriculture	Central Kaliman-tan	−2.28	114.01	106	56.17	82.68	43.81	66	26.3	2235	0.42
67	Ishikura et al., (2017)	Site 08	Forest land	F	Secondary swamp forest	Central Kaliman-tan	−2.28	114.01	53.6	20.86	41.81	16.27	45	26.3	2235	0.13
68	Ishikura et al., (2017)	Site 09	Forest land	F	Primary swamp forest	Central Kaliman-tan	−2.28	114.01	30.2	18.58	23.56	14.49	15	26.3	2235	0.12
69	Ishikura et al., (2017)	Site 10	Forest land	F	Primary swamp forest	Central Kaliman-tan	−2.28	114.01	33.1	16.07	25.82	12.53	18	26.3	2235	0.12
70	Ishikura et al., (2017)	Site 11	Grass land	C/S	Wet shrub	Central Kaliman-tan	−2.28	114.01	83.2	48.48	64.9	37.81	108	26.3	2235	0.33
71	Ishizuka et al., (2002)	Site 01	Deforested area	D/B	Plantation forest	Jambi	−1.05	102.15	16.48	8.79	12.85	6.86	na	25.7	2060	1.19
72	Ishizuka et al., (2002)	Site 02	Logged-over forest	D/B	Secondary swamp forest	Jambi	−1.05	102.15	20.97	5.67	16.36	4.42	na	25.7	2060	1.14
73	Ishizuka et al., (2002)	Site 03	Logged-over forest	D/B	Secondary swamp forest	Jambi	−1.05	102.15	26.05	7.53	20.32	5.87	na	25.7	2060	1.14
74	Ishizuka et al., (2002)	Site 04	Logged-over forest	D/B	Secondary swamp forest	Jambi	−1.05	102.15	37.26	12.52	29.06	9.77	na	25.7	2060	1.08
75	Ishizuka et al., (2002)	Site 05	Oil palm plantation	P	Estate crop	Jambi	−1.05	102.15	18.31	4.17	14.28	3.25	na	25.7	2060	1.18
76	Ishizuka et al., (2002)	Site 06	Primary forest	F	Primary swamp forest	Jambi	−1.05	102.15	20.33	4.95	15.86	3.86	na	25.7	2060	1.17
77	Ishizuka et al., (2002)	Site 07	Primary forest	F	Primary swamp forest	Jambi	−1.05	102.15	30.1	8.64	23.48	6.74	na	25.7	2060	1.17
78	Ishizuka et al., (2002)	Site 08	Rubber plantation	P	Estate crop	Jambi	−1.05	102.15	23.96	8.52	18.69	6.65	na	25.7	2060	1.12
79	Itoh et al., (2017)	Site 01	Drained and burnt forest	D/B	Secondary swamp forest	Central Kaliman-tan	−2.34	114.04	25.57	2.42	19.94	1.89	42	26.2	2546	0.24
80	Itoh et al., (2017)	Site 02	Drained forest	F	Secondary swamp forest	Central Kaliman-tan	−2.35	114.04	29.32	1.35	22.87	1.05	57	26.2	2546	0.14

Table A2. *Cont.*

No.	Authors	Site Name		Land Use	Land Cover	Province	Latitude	Longitude	Total CO_2		Heterotrophic			WTD	Temp.	Rainfall	BD
									Mean	SD	Mean	SD					
81	Itoh et al., (2017)	Site 03	Undrained forest	F	Primary swamp forest	Central Kaliman-tan	−2.32	113.9	26.44	3.65	20.62	2.85		31	26.2	2546	0.11
82	Jamaludin et al. (2020)	Site 01	Ginger	P	Mixed dry agriculture	West Kali-mantan	−0.37	109.52	34.41	17.92	30.87	9.38	a	21.8	31.6	na	0.14
83	Jamaludin et al. (2020)	Site 02	Oil palm plantation	P	Estate crop	West Kali-mantan	−0.37	109.52	35.93	14.17	23.56	8.15	a	36.4	30.6	na	0.21
84	Jamaludin et al., (2020)	Site 03	Rubber plantation	P	Estate crop	West Kali-mantan	−0.37	109.52	42.63	12.57	33.67	11.85	a	36.4	30.3	na	0.17
85	Jauhiainen et al., (2005)	Site 03	Undrained peat swamp forest	F	Primary swamp forest	Central Kaliman-tan	−2.33	113.92	34.93	3.2	27.25	2.5		35	25.5	2528	0.15
86	Jauhiainen et al., (2008)	Site 01	Deforested, drained, and burned peat forest	D/B	Wet shrub	Central Kaliman-tan	−2.33	114.03	27.81	8.16	21.69	6.36		40	33.5	2331	na
87	Jauhiainen et al., (2008)	Site 02	Deforested, drained, and burned peat forest	D/B	Wet shrub	Central Kaliman-tan	−2.33	114.03	26.08	7.71	20.34	6.01		52	33.5	2560	na
88	Jauhiainen et al., (2008)	Site 03	Drained and selectively logged peat swamp	D/B	Secondary swamp forest	Central Kaliman-tan	−2.33	114.03	73.05	39.94	56.98	31.15		47	29.3	2331	na
89	Jauhiainen et al., (2008)	Site 04	Drained and selectively logged peat swamp	D/B	Secondary swamp forest	Central Kaliman-tan	−2.33	114.03	74.4	42.85	58.03	33.42		43	29.3	2560	na
90	Jauhiainen et al., (2012)	Site 01	Acacia plantation	P	Plantation forest	Riau	0.43	101.88	154	56.79	98.81	25.62	a	94	26.2	2500	0.11
91	Jauhiainen et al., (2012)	Site 02	Acacia plantation	P	Plantation forest	Riau	0.43	101.88	108.8	37.3	90.05	31.88	a	73	26.2	2500	0.12
92	Jauhiainen et al., (2012)	Site 03	Acacia plantation	P	Plantation forest	Riau	0.43	101.88	113.88	52.15	103.81	44.4	a	108	26.2	2500	0.08
93	Jauhiainen et al., (2012)	Site 04	Acacia plantation	P	Plantation forest	Riau	0.43	101.88	61.76	27.97	79.1	22.16	a	78	26.2	2500	0.08
94	Jauhiainen et al., (2012)	Site 05	Acacia plantation	P	Plantation forest	Riau	0.43	101.88	66.14	66.13	69.99	34.36	a	70	26.2	2500	0.07
95	Jauhiainen et al., (2012)	Site 06	Acacia plantation	P	Plantation forest	Riau	0.43	101.88	119.66	42.07	96.62	36.48	a	84	26.2	2500	0.06
96	Jauhiainen et al., (2012)	Site 07	Acacia plantation	P	Plantation forest	Riau	0.43	101.88	77.7	23.72	73.93	24.81	a	36	26.2	2500	0.06
97	Jauhiainen et al., (2012)	Site 08	Acacia plantation	P	Plantation forest	Riau	0.43	101.88	117.82	34.84	138.76	43.46	a	86	26.2	2500	0.06
98	Khasanah & Noordwijk (2018)	Site 01	Logged-over forest	D/B	Secondary swamp forest	Jambi	−1.53	102.37	32.63	19.83	25.45	15.47		37	30	2349	0.12
99	Khasanah & Noordwijk (2018)	Site 02	Mixed betel nut, coconut and coffee	P	Mixed dry agriculture	Jambi	−1.53	102.37	78	9.9	60.84	7.72		58.5	30	2349	0.17

Table A2. *Cont.*

No.	Authors	Site Name		Land Use	Land Cover	Province	Latitude	Longitude	Total CO_2 Mean	Total CO_2 SD	Heterotrophic Mean	Heterotrophic SD		WTD	Temp.	Rainfall	BD
100	Khasanah & Noordwijk (2018)	Site 03	Oil palm plantation	P	Estate crop	Jambi	−1.53	102.37	96.13	29.65	74.98	23.13		40	30	2349	0.14
101	Khasanah & Noordwijk (2018)	Site 04	Rubber plantation	P	Estate crop	Jambi	−1.53	102.37	75.17	3.55	58.63	2.77		46	30	2349	0.19
102	Marwanto & Agus (2014)	Site 01	Oil palm plantation	P	Estate crop	Jambi	−1.72	103.88	46.1	30.02	35.96	23.42		91	26.7	2349	0.21
103	Marwanto et al., (2019)	Site 01	Oil palm plantation	P	Estate crop	Riau	0.73	101.72	44.66	25.63	34.83	19.99		36	26.3	1830	0.25
104	Saragi-Sasmito et al., (2019)	Site 01	Secondary forest	F	Secondary swamp forest	Central Kaliman-tan	−2.92	114.42	52.11	4.04	40.74	3.3	a	110	27	1600	0.01
105	Sundari et al., (2012)	Site 01	Drained forest	D/B	Secondary swamp forest	Central Kaliman-tan	−2.53	114.5	44.92	14.08	35.04	10.98		51	26.2	2005	na
106	Sundari et al., (2012)	Site 03	Undrained forest	F	Primary swamp forest	Central Kaliman-tan	−2.53	114.5	49.39	13.52	38.52	10.55		9	26.2	2005	na
107	Swails et al., (2019)	Site 01	Oil palm plantation	P	Estate crop	Central Kaliman-tan	−2.78	111.8	55.9	13.58	43.6	10.59		50	27.4	2058	0.34
108	Swails et al., (2019)	Site 02	Oil palm plantation	P	Estate crop	Central Kaliman-tan	−2.78	111.8	79.5	15.7	62.01	12.25		50	27.4	2058	0.34
109	Swails et al., (2019)	Site 03	Oil palm plantation	P	Estate crop	Central Kaliman-tan	−2.78	111.8	49.1	19.94	38.3	15.55		50	27.4	2058	0.34
110	Swails et al., (2019)	Site 04	Primary forest	F	Primary swamp forest	Central Kaliman-tan	−2.78	111.8	42	6.36	32.76	4.96		23	27.4	2058	0.2
111	Swails et al., (2019)	Site 05	Primary forest	F	Primary swamp forest	Central Kaliman-tan	−2.78	111.8	39.4	11.88	30.73	9.27		23	27.4	2058	0.2
112	Swails et al., (2019)	Site 06	Secondary forest	F	Secondary swamp forest	Central Kaliman-tan	−2.78	111.8	54.3	16.12	42.35	12.57		23	27.4	2058	0.2
113	Toma et al., (2011)	Site 01	Crop- and grassland	C/S	Mixed dry agriculture	Central Kaliman-tan	−2.28	114.02	108.41	35.22	84.56	27.47		75	25.9	2734	0.4
114	Wakhid et al., (2017)	Site 01	Rubber plantation	P	Estate crop	Central Kaliman-tan	−2.48	114.19	120.74	38.11	51.63	7.85	a	69	26.9	2506	0.23
115	Watanabe et al., (2009)	Site 01	Sago plantation	P	Estate crop	Riau	0.85	102.77	13.81	6.76	10.77	5.27		82	27.6	1700	na
116	Watanabe et al., (2009)	Site 02	Sago plantation	P	Estate crop	Riau	0.85	102.77	13.81	8.03	10.77	6.26		82	27.6	1700	na
117	Watanabe et al., (2009)	Site 03	Sago plantation	P	Estate crop	Riau	0.85	102.77	15.74	8.03	12.28	6.26		82	27.6	1700	na
118	Watanabe et al., (2009)	Site 04	Sago plantation	P	Estate crop	Riau	0.85	102.77	17.02	5.46	13.28	4.26		82	27.6	1700	na

Remarks: Latitude and longitude are in degrees (°), T-CO_2: total CO_2 emissions (Mg ha^{-1} $year^{-1}$), H-CO_2: heterotrophic CO_2 emissions (Mg ha^{-1} $year^{-1}$), SE = standard error, WTD: water table depth (cm), Temp.: air temperature (°C), Rainfall: annual rainfall (mm $year^{-1}$), BD: bulk density (g cm^{-3}), na: not available, a: actual data of heterotrophic emissions.

Table A3. Summary statistics of water table depth and bulk density for each land cover class as defined by Prananto et al. [61].

Predictor Variable	Land Use	*n*	Mean	SD	Min.	Max.
Water table depth (*W*)	CS	15	45.75	34.14	−2	108
	DB	25	45.96	28.72	6	117.5
	F	22	32.51	29.37	−5	110
	P	45	61.61	21.97	21.8	119
Bulk density (*B*)	CS	6	0.39	0.03	0.33	0.42
	DB	19	0.37	0.41	0.09	1.19
	F	15	0.29	0.36	0.01	1.17
	P	34	0.23	0.25	0.06	1.18

Remarks: *n* = number of observations, SD = standard deviation, Min. = minimum value, Max. = maximum value.

Table A4. Summary statistics of water table depth and bulk density for each land cover class as defined by the MOEF [62].

Variable	Land Cover	*n*	Mean	SD	Min.	Max.
Water table depth (*W*. cm)	Bare ground (BG)	3	70	3.61	67	74
	Estate crop (EC)	33	57.94	20.42	26	119
	Mixed dry agriculture (MDA)	5	65.16	27.15	21.8	93
	Paddy field (PDF)	3	5.4	7.5	−2	13
	Plantation forest (PF)	10	78	18.8	36	108
	Primary swamp forest (PSF)	8	21.13	8.69	9	35
	Pure dry agriculture (PDA)	8	39.56	20.85	15	70
	Secondary swamp forest (SSF)	26	43.35	34.57	−5	117.5
	Wet shrub (WS)	11	42.36	28.84	6	108
Bulk density (*B*. g cm^{-3})	Bare ground (BG)	3	0.12	0	0.12	0.12
	Estate crop (EC)	22	0.3	0.29	0.09	1.18
	Mixed dry agriculture (MDA)	5	0.3	0.13	0.14	0.4
	Plantation forest (PF)	11	0.19	0.33	0.06	1.19
	Primary swamp forest (PSF)	9	0.38	0.45	0.11	1.17
	Pure dry agriculture (PDA)	2	0.4	0.03	0.38	0.42
	Secondary swamp forest (SSF)	13	0.39	0.43	0.01	1.14
	Wet shrub (WS)	9	0.18	0.07	0.13	0.33

Remarks: *n* = number of observations, SD = standard deviation, Min. = minimum value, Max. = maximum value.

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