

Article

Rewetting Tropical Peatlands Reduced Net Greenhouse Gas Emissions in Riau Province, Indonesia

Iska Lestari ¹, Daniel Murdiyarso ^{1,2,*} and Muh Taufik ¹

¹ Department of Geophysics and Meteorology, Faculty of Mathematics and Natural Sciences, IPB University Campus Dramaga, Bogor 16680, Indonesia; iskalestari@gmail.com (I.L.); mtaufik@apps.ipb.ac.id (M.T.)

² Center for International Forestry Research, Jl. CIFOR, Situ Gede, Sindang Barang, Bogor 16115, Indonesia

* Correspondence: d.murdiyarso@cgiar.org; Tel.: +62-811-947-165

Abstract: Draining deforested tropical peat swamp forests (PSFs) converts greenhouse gas (GHG) sinks to sources and increases the likelihood of fire hazards. Rewetting deforested and drained PSFs before revegetation is expected to reverse this outcome. This study aims to quantify the GHG emissions of deforested PSFs that have been (a) reforested, (b) converted into oil palm, or (c) replanted with rubber. Before rewetting, heterotrophic soil respiration in reforested, oil palm, and rubber plantation areas were 48.91 ± 4.75 Mg CO₂ ha⁻¹ yr⁻¹, 54.98 ± 1.53 Mg CO₂ ha⁻¹ yr⁻¹, and 67.67 ± 2.13 Mg CO₂ ha⁻¹ yr⁻¹, respectively. After rewetting, this decreased substantially by 21%, 36%, and 39%. Conversely, rewetting drained landscapes that used to be methane (CH₄) sinks converted them into CH₄ sources; almost twice as much methane was emitted after rewetting. Nitrous oxide (N₂O) emissions tended to decrease; in nitrogen-rich rubber plantations, N₂O emissions halved; in nitrogen-poor reforested areas, emissions reduced by up to a quarter after rewetting. Overall, rewetting reduced the net emissions up to 15.41 Mg CO₂-eq ha⁻¹ yr⁻¹ (25%) in reforested, 18.36 Mg CO₂-eq ha⁻¹ yr⁻¹ (18%) in oil palm, and 28.87 Mg CO₂-eq ha⁻¹ yr⁻¹ (17%) in rubber plantation areas.



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Keywords: climate change; groundwater level; land-cover change; nature-based solutions; respiration; restoration

1. Introduction

Being carbon-rich reservoirs, peat swamp forests (PSFs) can shift from sequestering to emitting carbon, thus contributing to climate change. A net atmospheric carbon exchange of ~ 0.14 Gt C yr⁻¹ is equal to $\sim 1\%$ of human-driven fossil fuel emissions or 3–10% of the current net sink for terrestrial natural ecosystems [1,2]. Tropical PSF, which accounts for 10% of the world's peatland and stores around 50–350 Gt C [3,4], is therefore a major ecosystem in the world's carbon budget.

With 15–21 Mha of PSF [5], Indonesia stores a large amount of carbon, around 57 Gt C [3]. However, peatland degradation in Indonesia, as a consequence of PSF conversion, is causing greenhouse gas (GHG) concentrations in the atmosphere to rise [6]. Previous studies showed that, over the last 25 years, as much as 427 Mg C ha⁻¹ [7–9] has been released into the atmosphere due to peatland conversion. Other damaging consequences of peatland being converted for agriculture and export-orientated commodities like oil palm, pulp, and paper are a biodiversity loss [10], as well as drained peatland, due to lower groundwater levels (GWL) [11], which can lead to peat fires, especially during the dry season [12,13].

Being naturally waterlogged ecosystems, improving water management has been one of the most effective actions to halt further peatland degradation and GHG emissions. This also reduces fire hazards and creates conditions for restoring vegetation [14]. In recent years, increasing efforts have been made to restore the hydrological function of

degraded peatlands by blocking and backfilling existing canals. This practice significantly reduces the outflow of surface runoff, increasing the GWL and storage capacity of degraded peatlands [15–19].

Extensive research on the impact of peatland drainage (following deforestation) and rewetting on GHG emissions have been conducted in Indonesia over the last decade. A range of methods have been used, from close chamber [20–23] to flux tower [24], for sample collection [20–23] and direct measurements [21–24]. These methods have enabled the assessment of total respiration [20,24], as well as the segregation of autotrophic and heterotrophic respiration [21–23].

Riau is one of the provinces prioritized for peatland restoration by the Indonesian Peatland Restoration Agency, which aimed to rewet and revegetate the landscape and support socioeconomic revitalization. In this study, the authors ask how does the singular impact of rewetting differ when compared with the combined impact of rewetting and revegetating the landscape? What type of vegetation cover is ideal for restoration efforts? Specifically, we are interested to know the effects of GHG emissions, as the fluxes of each GHG differ in response to rewetting, let alone when interacting with different revegetation treatments.

Quantifying the net effects of rewetting and revegetation based on the global warming potential of each GHG is more realistic than just accounting for rewetting alone. Raising the GWL up to 10 cm from the surface would also have a net cooling effect [25]. We expect the study results will allow for the recommendation of suitable management options in line with national and subnational efforts to reduce GHG emissions, so as to meet the emission reduction targets in the context of nationally determined contributions.

2. Materials and Methods

2.1. Study Site

Field data were collected from permanent research plots in the village of Tanjung Leban, Bengkalis Regency, Riau Province (Figure 1). This area, which has an altitude of 1–6.1 m above the mean sea level, holds the remnants of lowland peat swamp forests (PSFs). Approximately 80% of the landscape is dominated by deep peat (>3 m thick).

The plots are made up of community-initiated reforested area (RA; 5 years old), an oil palm plantation (OP; 11 years old), and rubber tree plantations (RP; 15 years old). The RA consists of a mix of native peat swamp species, like *Dyera polyphylla*, *Callophylum lowii*, *Shorea uliginosa*, *Cratogeomys arborescens*, and *Mezettia parviflora*. The OP was planted in a 9 × 9 m² in a triangular pattern with low tillage. The RP was not planted regularly but occasionally fertilized (Figure 2).

Two parallel drainage canals were constructed by the logging company whose operations are located upstream. These canals have been causing substantial drawdown of the groundwater levels during the dry season. The local community planted native species in peat swamp areas in 2013 after a peat fire incidence occurred in 2010.

According to the long-term records of a nearby weather station in Bukit Batu (see Figure 1), the region has an average annual rainfall of 2443 mm. The wettest month is November, with a monthly rainfall of 375 mm, while the driest month is June, with a monthly rainfall of 161 mm. The monthly air temperature does not fluctuate much, and the annual temperature averages at 26.9 °C (<https://en.climate-data.org/location/579424/>; accessed on 15 December 2021).

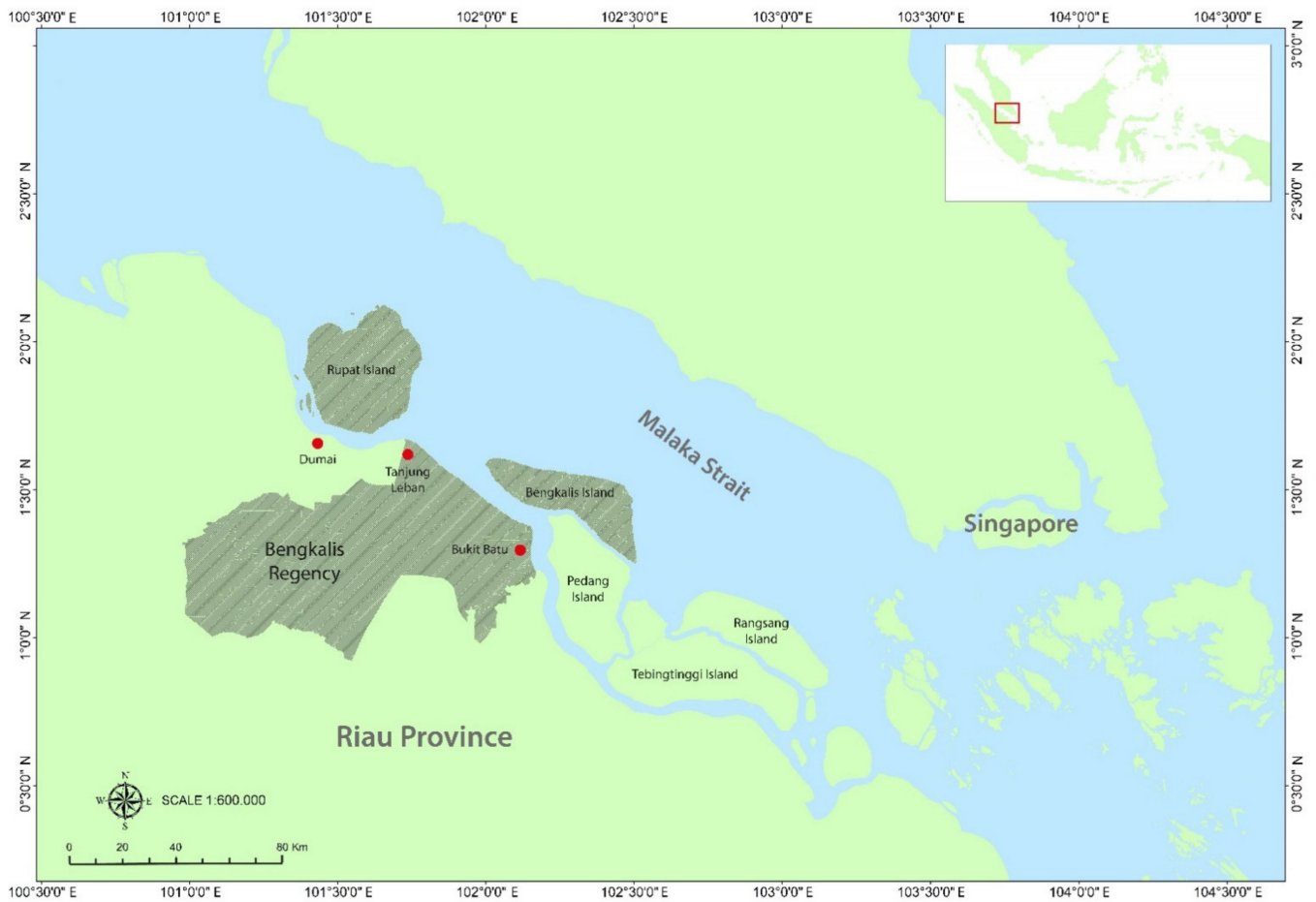


Figure 1. Study site located in Tanjung Leban Village, Bengkalis Regency (shaded area), Riau Province, Indonesia. Dumai is an industrialized zone with oil refinery and crude palm oil shipping harbor. Bukit Batu is a township with a weather station.

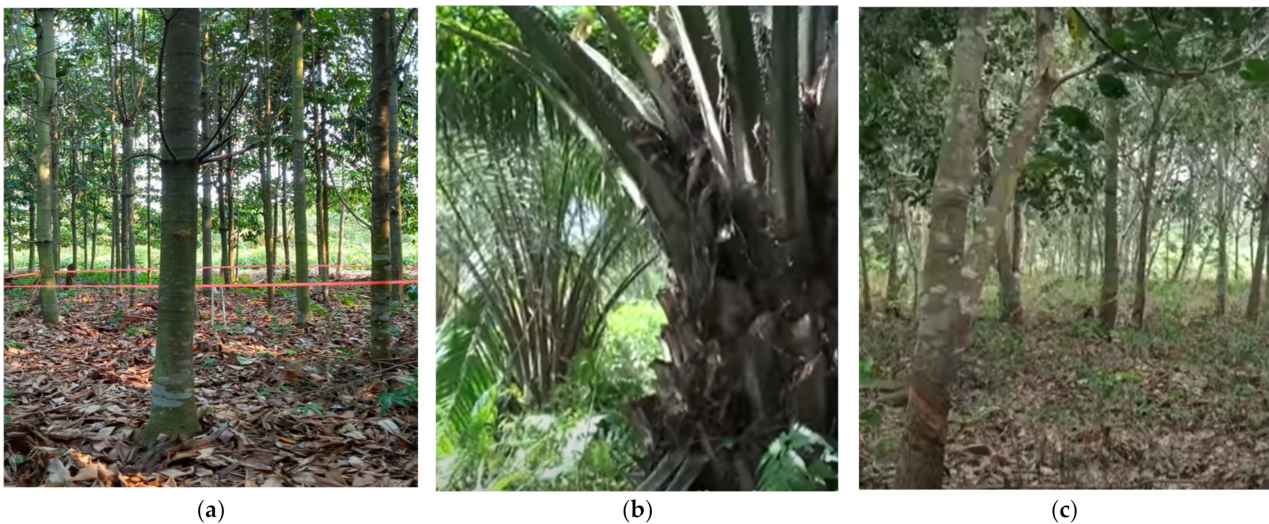


Figure 2. General features of community-initiated revegetation in degraded peatland following deforestation, fires, and drainage in (a) a reforested area (RA) with mixed native species, (b) an oil palm plantation (OP), and (c) a rubber plantation (RP).

2.2. Measurements of Greenhouse Gas Emissions

We adopted the closed-chamber method, which is widely used in carbon cycle studies, as well as other areas of environmental research [26,27]. Measurements of CO₂ emissions were carried out using an Infrared Gas Analyser (IRGA), LI-COR, Model LI-840A. A small amount of air was circulated in the dynamic chamber to measure the CO₂ concentration (ppm) and CO₂ flux (mg m⁻² h⁻¹). Total respiration (SR_t), which includes autotrophic (SR_a) and heterotrophic respiration (SR_h), was measured in untilled plots and to separate heterotrophic respiration, which signifies microbial activity in peat decomposition, measurements carried out in tilled plots of 100 × 100 × 100 cm³. The soil respiration was measured in 4-month intervals.

Emissions of methane (CH₄) and nitrous oxide (N₂O) from soil were obtained using the static closed chamber system [28]. Samples were collected with four replicates for each land cover type in September 2018 to represent the conditions before rewetting. Samples that represent the rewetted conditions were collected in August 2019. Prior to gas sampling, the chamber was fanned gently for about 10 s to mix the air inside the chamber. Gas samples were collected at the closure of 0, 10, 20, and 30 min later using a 50-mL polypropylene syringe. The height of each chamber was measured at each sampling date at four different positions to calculate the headspace volume. The syringe was prepared with a three-way stopcock and connected to the outlet of the chamber hood with silicone tubes. The syringe was also equipped with a barometer as a leak indicator during air sample collections. To prevent leakage during transportation to the laboratory, the stopcocks were sealed with polycarbonate caps.

The gas samples were analyzed within 30 days with a gas chromatograph using an Electron Capture Detector (ECD) for N₂O analysis and with a Flame Ionization Detector (FID) for CH₄ analysis [29], Shimadzu, Model GC-14A. Soil N₂O and CH₄ fluxes were quantified from the rate of concentration change in the chamber hood, determined by linear regression of the change in gas concentration as a function of the incubation time. A negative rate indicated an uptake of atmospheric GHG, while a positive rate expressed GHG emissions from the peat. The slope of the best linear fit was expressed in mass units per space by using the ideal gas law [28]. The flux rate of CH₄ and N₂O per unit area was determined by the rate of gas concentration change (dc/dt) over a 10-min sampling interval. This rate is represented by the slope of CH₄ and N₂O concentration linear regression with time. The slope was related to the flux through the following equation [30]:

$$\phi = \Gamma \frac{M V}{N_0 A} \frac{\delta\theta}{\delta t} \quad (1)$$

where ϕ denotes flux (mg m⁻² h⁻¹), M is the molecular weight (g mol⁻¹), N_0 is Avogadro's number (molecule mol⁻¹), Γ demonstrates air density (molecule cm⁻³), A is the surface area covered by the chamber (cm²), V expresses the effective volume of the chamber (cm³), and $\frac{\delta\theta}{\delta t}$ is a rate of increased concentration inside a chamber (ppbv/min). The air density inside the chamber was corrected with the average air temperature inside the chamber over the 30-min sampling period (Γ):

$$\Gamma = 0.34848 \frac{P}{(273 + T)} \frac{N_0}{M_{air}} \quad (2)$$

where P is pressure (millibar), and T is the average temperature inside the chamber (°C).

The calculation of the GHG emissions, expressed in CO₂ equivalents, is based upon 100 years of perspective in global warming potential of 28 for CH₄ and 265 for N₂O [31].

2.3. Monitoring of the Groundwater Level

A semipermanent U-notch weir was constructed in December 2018 to block the canal and control the groundwater level (GWL) at 40 cm below the peat surface. The construction was designed for a medium lifetime of 2–5 years using durable-grade wood (Figure 3).

Plastic sacks containing a mixture of sands and mineral soils were placed deep into the weir body to stabilize the structure and prevent water leakage and peat erosion at the bottom and sides of the canal body. The weir is maintained regularly to prevent unnecessary damage and make sure the GWL is controlled.

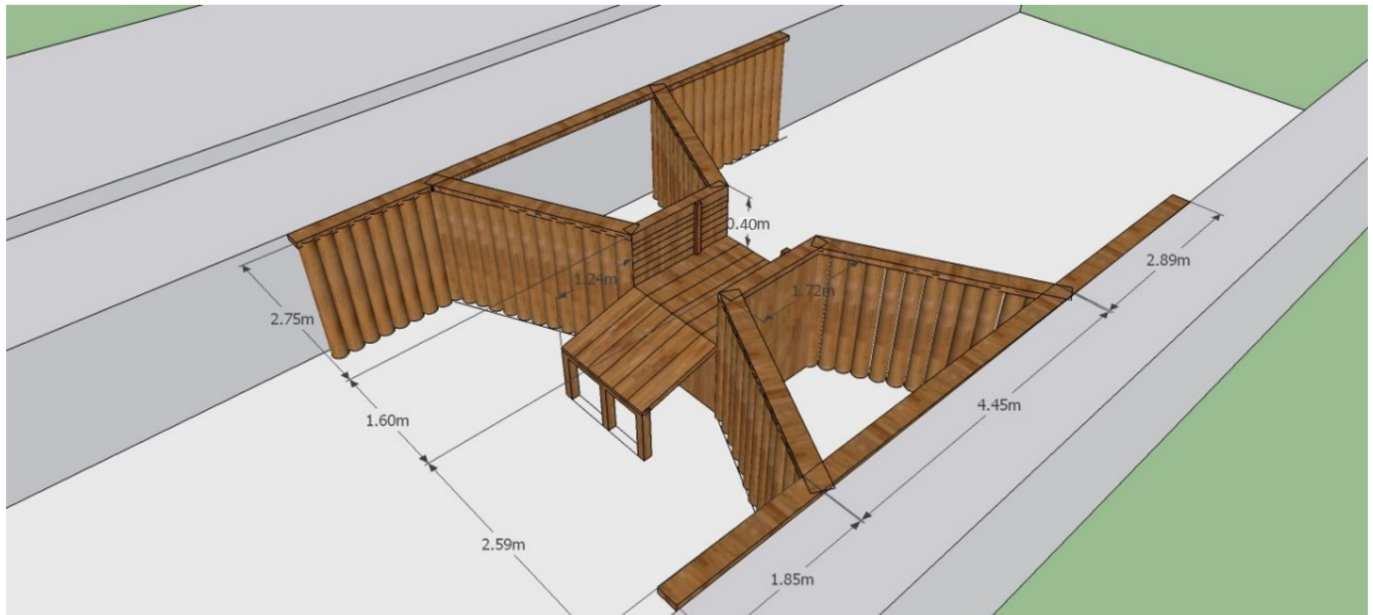


Figure 3. The standard design of a U-notch weir to block canals adopted to ensure a constant groundwater level of 40 cm (Source: Sutikno, Personal communication).

The GWL was automatically recorded using data loggers (Model HOBOTM U20-001-02-Ti, Onset Computer Corporation, Bourne, MA, USA) with 0.3–0.6 cm of accuracy and 0.14 cm of resolution. The sensor was set to record GWL fluctuations at 30-min intervals. The data loggers were installed in piezometers in the three land covers, with five points in RA, four points in OP, and four points in RP. The distribution of the piezometer was perpendicular to the canal.

2.4. Statistical Analysis

Shapiro–Wilk tests were used to verify the normality of data distribution for the soil GHG fluxes (CO_2 , CH_4 , and N_2O) and groundwater level among the different land cover types. Differences in the variables among the land cover types (if data were normally distributed) were tested with analysis of variance (ANOVA). The Kruskal–Wallis H test was used for abnormally distributed data. A multiple linear regression model was applied to see the relationship between soil respiration before and after rewetting and the correlation with the groundwater levels in three land covers. The Pearson’s correlation analysis was used to find out the correlation of the groundwater level and CH_4 or N_2O fluxes. IBM SPSS statistical software (22.0 Version) was used for all statistical analyses. All graphs were prepared using SigmaPlot (12.5 Version) and Microsoft Excel (2019 Version). To capture the range of uncertainty in the findings, a 95% confidence interval was used.

3. Results

3.1. Effects of Rewetting on Greenhouse Gas Fluxes

Figure 4 shows the fluctuation of GWL over a one-year observation period and its effect on the CO_2 fluxes. Our data generally shows that, after a drainage canal is blocked, peatland rewetting reduces CO_2 fluxes in the form of total respiration (SR_t) and heterotrophic respiration (SR_h). Statistically, the reduction was significant for both SR_t and SR_h values ($p < 0.05$). Although the effect on the SR_t values was not significantly different across the

different land cover types ($p > 0.05$), there was a significant difference in SR_h between the land cover types ($p < 0.05$). This suggests that differences between the land cover types may be due to diverse combinations of both the quantity and quality of organic carbon produced by standing vegetation and microbial activities in decomposing organic materials.

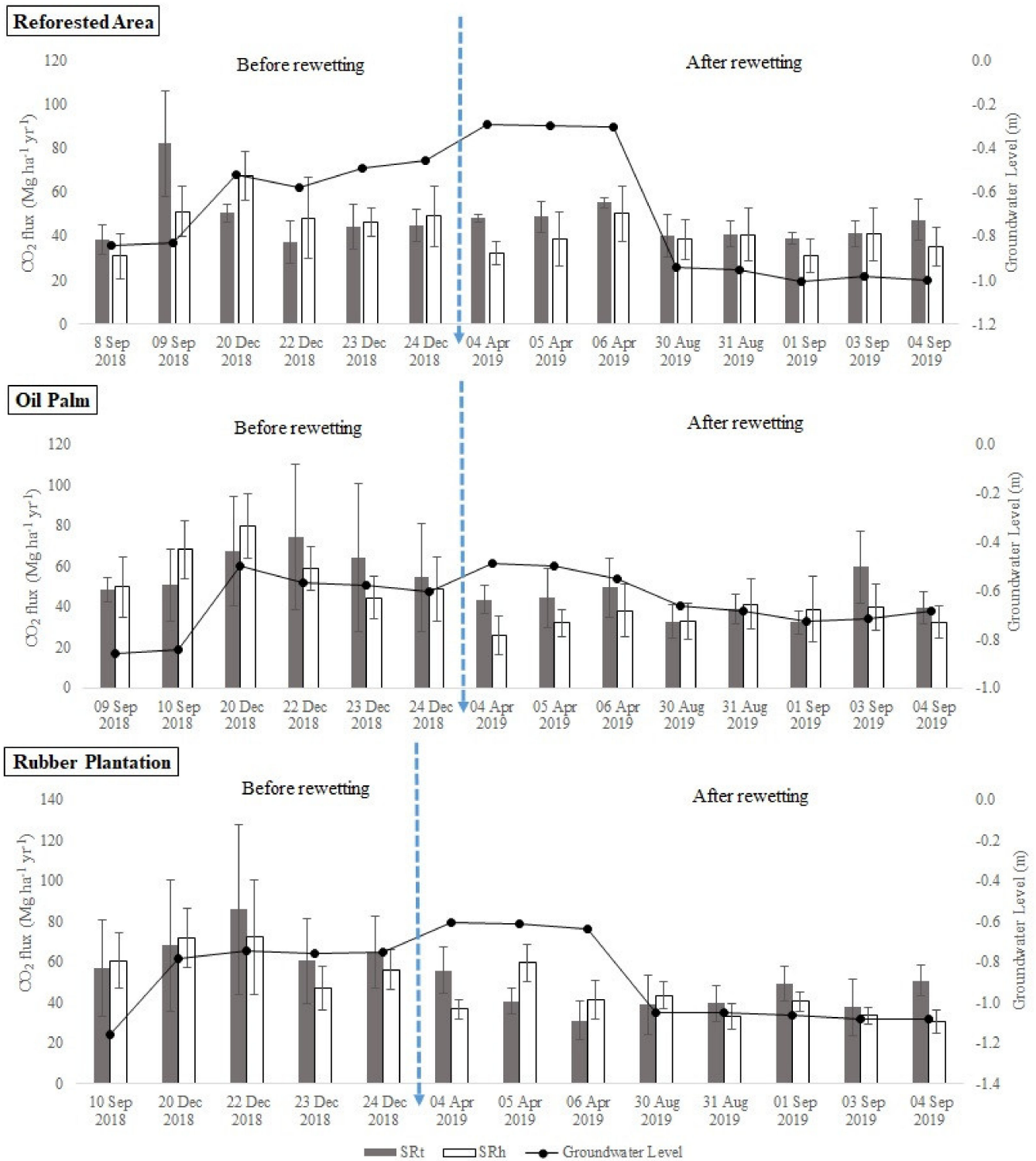


Figure 4. CO₂ flux responses to the groundwater levels in reforested, oil palm, and rubber plantation areas of rewetted peatlands in Bengkalis Regency, Riau Province, Indonesia.

As shown in Table 1, the proportion of SR_h in the reforested and oil palm areas (48.91 ± 4.75 and 54.98 ± 1.53 $Mg\ CO_2\ ha^{-1}\ yr^{-1}$, respectively) to SR_t (49.68 ± 6.84 and 55.71 ± 5.54 $Mg\ CO_2\ ha^{-1}\ yr^{-1}$, respectively) was as high as 98% before rewetting. Even after rewetting, it was still relatively high (85% and 83%, respectively). This indicates an abundance of organic materials. However, it is rather peculiar to report that the SR_h value in the rubber plantation (67.67 ± 2.13 $Mg\ CO_2\ ha^{-1}\ yr^{-1}$) was higher than the SR_t value (61.36 ± 7.28 $Mg\ CO_2\ ha^{-1}\ yr^{-1}$). It is very likely that fertilizer applied in the rubber plantation has enhanced the mineralization of organic matter in the untrenched plots and increased SR_h , while, in the trenched plots, SR_h has been up taken by roots and reduced SR_t , as was found in an earlier study of the fertilizer's effects on respiration [32].

Table 1. Annual CO_2 fluxes in the form of total soil respiration (SR_t) and heterotrophic soil respiration (SR_h) across three different land covers before and after rewetting.

Land Cover Types	CO_2 Flux ($Mg\ CO_2\ ha^{-1}\ yr^{-1}$)			
	Before Rewetting		After Rewetting	
	SR_t	SR_h	SR_t	SR_h
Reforested Area	49.68 ± 6.84	48.91 ± 4.75	45.18 ± 2.02	38.51 ± 2.13
Oil Palm Plantation	55.71 ± 5.54	54.98 ± 1.53	42.49 ± 3.18	35.17 ± 1.81
Rubber Plantation	61.36 ± 7.28	67.67 ± 2.13	41.84 ± 2.31	41.26 ± 2.94

Table 2 shows the effect of rewetting on CH_4 and N_2O fluxes. In the reforested area (RA) and rubber plantation (RP), the increased GWL of rewetted peatlands, which stimulated the activity of soil microbes, including methanogenic bacteria, enhanced the release of CH_4 into the atmosphere more than 100 times. In RA, CH_4 release increased from -0.10 ± 6.46 to 8.02 ± 3.28 $mg\ m^{-2}\ h^{-1}$ ($p > 0.05$); in OP, it increased from 0.34 ± 3.06 to 5.36 ± 8.67 $mg\ m^{-2}\ h^{-1}$ ($p > 0.05$); and in RP, it increased from -0.19 ± 3.82 to 3.47 ± 7.93 $mg\ m^{-2}\ h^{-1}$ ($p > 0.05$). These relatively low emissions were confirmed by a large body of literature from the tropics, which conclude an average CH_4 release rate around $3\ mg\ m^{-2}\ h^{-1}$ [33].

Table 2. CH_4 and N_2O fluxes in reforested area (RA), oil palm (OP), and rubber plantation (RP) before and after rewetting (mean \pm SE; $n = 4$).

Land Cover Type	CH_4 Flux ($mg\ m^{-2}\ h^{-1}$)		N_2O Flux ($mg\ m^{-2}\ h^{-1}$)	
	Before Rewetting	After Rewetting	Before Rewetting	After Rewetting
	Reforested Area	-0.10 ± 6.46	8.02 ± 3.28	0.40 ± 0.84
Oil Palm Plantation	0.34 ± 3.06	5.36 ± 8.67	1.70 ± 1.33	-0.45 ± 1.52
Rubber Plantation	-0.19 ± 3.82	3.47 ± 7.93	7.25 ± 2.28	4.68 ± 2.31

While no significant differences in CH_4 fluxes were seen across the land cover types before or after rewetting, the correlation between GWL and increased CH_4 fluxes was weak in RA ($r^2 = 0.14$, $p > 0.05$) but strong in OP ($r^2 = 0.76$, $p > 0.05$) and very strong in RP ($r^2 = 0.99$, $p > 0.05$). Before rewetting, both RA and RP were sinks for CH_4 , but OP remained a CH_4 source, although not a particularly strong one.

Likewise, in the case of N_2O fluxes, no significant differences were seen between RA, OP, and RP either before rewetting (0.40 ± 0.84 , 1.70 ± 1.33 , and 7.25 ± 2.28 $mg\ m^{-2}\ h^{-1}$, respectively) or after rewetting (-0.20 ± 0.52 , -0.45 ± 1.52 , and 4.68 ± 2.31 $mg\ m^{-2}\ h^{-1}$, respectively) ($p > 0.05$). Our findings also suggest that the correlation between N_2O flux and GWL was stronger after rewetting. Using Pearson's correlation analysis, the coefficients of correlation (r^2) for RA, OP, and RP were 0.57, 0.50, and 0.69, respectively ($p > 0.05$), before rewetting, while, after rewetting, were 0.57 and 0.64 in RA and OP, respectively, with

a strong but negative correlation of 0.73 in RP. This could be due to the fact that rubber plantation was occasionally fertilized with urea.

3.2. Global Warming Potential and Net Greenhouse Gas Emissions

The contributions of CO₂, CH₄, and N₂O emissions to soil GHG emissions were calculated based on their Global Warming Potential (GWP). Following Reference [31], we adopted 28 for CH₄ and 265 for N₂O over a time horizon of 100 years. The contribution of each gas and the total emissions (in Mg CO₂-eq) are shown in Table 3. Statistically, these fluxes were not significantly different from those of the conditions before rewetting ($p > 0.05$), but a decrease of 25%, 18%, and 17% in RA, OP, and RP, respectively, is worth considering when the revegetation program is to be implemented to control GHG emissions.

Table 3. Total net greenhouse gas emissions expressed in CO₂ equivalent in the reforested area (RA), oil palm (OP), and rubber plantation (RP) before and after rewetting (mean ± SE).

Land Cover Type	CO ₂		CH ₄		N ₂ O		Total Net GHG Emissions	
	Mg CO ₂ -eq ha ⁻¹ yr ⁻¹							
	Before Rewetting	After Rewetting	Before Rewetting	After Rewetting	Before Rewetting	After Rewetting	Before Rewetting	After Rewetting
RA	49.68 ± 6.84	45.18 ± 2.02	−19.67 ± 8.05	23.69 ± 8.02	31.20 ± 9.28	−17.17 ± 7.47	61.21 ± 8.07	51.70 ± 2.57
OP	55.71 ± 5.54	42.49 ± 3.18	10.32 ± 4.59	25.22 ± 17.27	39.52 ± 21.61	26.07 ± 14.41	105.55 ± 31.74	93.78 ± 34.86
RP	61.36 ± 7.28	41.48 ± 2.31	−16.03 ± 1.50	29.52 ± 10.58	98.60 ± 33.13	50.59 ± 20.05	143.93 ± 38.91	121.59 ± 32.94

4. Discussion

4.1. The Interplay between Vegetation and Anoxic Soil Environment

The CO₂ fluxes found in this study in drained and rewetted peatland fall within the range of similar studies in other places in Indonesia; with oil palm, acacia, and rubber plantations being commonly studied manmade ecosystems [32,34–39]. Native species have been suggested to be the best vegetation choice for peatland restoration [40]. Most recently, the practice has been to follow the system of paludiculture, as improving hydrology is a prerequisite, especially in naturally waterlogged environments [40]. Combining native species would not only contribute towards halting GHG emissions; this would also enhance local livelihoods, as species such as Jelutung (*Dyera polyphylla*) have long been known to be economically important, as well as a secure biodiversity [40–42].

While the specific figures varied greatly between this and previous studies [43–45]—since the control mechanism between rewetting and draining can neither be made simple nor identical, our findings similarly demonstrated that soil respiration was controlled by GWL. This study shows that increasing GWL reduced the respiration by around 21–39%; meanwhile, a decrease in GWL was seen to increase respiration by 40–75% [22]. Overall, a positive impact was demonstrated when using canal blocking to maintain the GWL and, hence, control CO₂ emissions.

The fact that heterotrophic respiration dominated emissions from both drained and rewetted peatland is also consistent with other studies [14]. These suggest that the interplay between vegetation or land cover types and emissions from an anoxic environment or rewetted peatland matters. With around 80% of respiration being heterotrophic, rewetting even shrubby or completely deforested PSF would be a wise first step to take, especially in socially and biophysically fire-prone regions like Riau.

4.2. Net Emissions and Global Warming

This study shows that, in drained conditions, peatlands were sinks of CH₄, but the flux was substantially increased when GWL was elevated. In natural systems, CH₄ emissions from peat soils are strongly affected by the groundwater levels; emissions were found to be at their maximum rates during the rainy months in pristine Kalimantan peatlands when GWL is close to the peat surface [46]. In addition, CH₄ fluxes from wet, low-lying hollows were observed to be higher than those of dry, higher hummocks in the pristine

peat forests of Indonesia and the Peruvian Amazon [46–48]. However, such relatively small emissions are overridden by largely reduced CO₂ emissions, even if CH₄ has a larger global warming potential.

Emissions of N₂O are more complex. A number of abiotic factors, including mineralized organic matter, used nitrogen fertilizer, and deposited lateral fixation, may affect emissions, in addition to biotic factors like plant–microbial interactions and abiotic factors like soil humidity and temperature, which influence the production of soil N₂O [49]. While this study demonstrated an increase in N₂O fluxes when the GWL was elevated, natural peatland with high water levels is not a source of N₂O due to low nitrogen mineralization and nitrification activities and high denitrification activity in reductive conditions [50]. However, by draining peatland for agricultural use, N₂O emissions increase, along with CO₂ emissions [51]. In the rainy season, N₂O peat flows were found to be more elevated in Indonesian peatlands than during the dry season [52].

It is therefore considered to be more practical to consider the net effects of rewetting on the overall GHG emissions, expressed in CO₂ equivalents by considering the global warming potential of each GHG. Although reforestation with native forest species is the most effective way to reduce global warming effects (25%), compared with oil palm plantation (18%) and rubber plantation (17%), the choices around what to plant on degraded peatland will also be influenced by the socioeconomic context.

4.3. Subnational Mitigation Actions

Among other approaches to mitigate climate change, we find ‘nature-based solutions’ (NbS). This approach involves working with nature, such as with unique yet threatened ecosystems like peatlands, to address human well-being, including local livelihoods, as well as to promote biodiversity conservation. Peatland restoration efforts that reduce GHG emissions through replanting with native species that are economically important for society, as we discuss here, could be good candidates for NbS that are within reach of all stakeholders.

Indonesia can use its position as the top-ranked tropical country for using nature, especially wetlands, to resolve climate change mitigation in a cost-effective manner [53] to promote peatland conservation and restoration. The government of Riau Province is in a good position to take the lead in promoting its vast peatland ecosystems as subnational contributions to the national climate agenda. Internal trading and financial compensation may also be generated through recently enacted regulations around carbon economic values. Initiatives can equally go beyond national emission reduction targets when programs are interlinked with transboundary issues, like fire emissions and haze pollution.

5. Conclusions

It is too simplistic to assume that, just because the CO₂ flux is affected by the groundwater levels, rewetting will reduce emissions; Indonesia’s mass peatland restoration efforts must also introduce socially, economically, and environmentally appropriate vegetation at the same time. Vegetation grown on converted peat swamp forest has a significant role when it comes to supplying organic materials. In this case, restoration with native peat species seems to have the potential to control GHG emissions when peatland is rewetted. Communities in affected areas should therefore benefit from restoration programs.

Although it will not zero CO₂ emissions, rewetting degraded peatlands has a substantial positive effect on net GHG emissions. All kinds of efforts to increase groundwater levels should therefore be supported, without jeopardizing the economic development objectives. Global agendas with national and local implications, like the Nationally Determined Contributions, should be supported through broader stakeholder participation. Climate change mitigation measures could be implemented at the subnational level, including in Bengkalis Regency and Riau Province.

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