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Carbon Dynamics in Rewetted Tropical Peat Swamp Forests

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Abstract: Degraded and drained peat swamp forests (PSFs) are major sources of carbon emissions in the forestry sector. Rewetting interventions aim to reduce carbon loss and to enhance the carbon stock. However, studies of rewetting interventions in tropical PSFs are still limited. This study examined the effect of rewetting interventions on carbon dynamics at a rewetted site and an undrained site. We measured aboveground carbon (AGC), belowground carbon (BGC), litterfall, heterotrophic components of soil respiration (R_h), methane emissions (CH_4), and dissolved organic carbon (DOC) concentration at both sites. We found that the total carbon stock at the rewetted site was slightly lower than at the undrained site (1886.73 ± 87.69 and 2106.23 ± 214.33 Mg C ha^{-1}, respectively). The soil organic carbon (SOC) was 1685 ± 61 Mg C ha^{-1} and 1912 ± 190 Mg C ha^{-1} at the rewetted and undrained sites, respectively, and the carbon from litterfall was 4.68 ± 0.30 and 3.92 ± 0.34 Mg C ha^{-1} year^{-1}, respectively. The annual average R_h was 4.06 ± 0.02 Mg C ha^{-1} year^{-1} at the rewetted site and was 3.96 ± 0.16 Mg C ha^{-1} year^{-1} at the undrained site. In contrast, the annual average CH_4 emissions were −0.0015 ± 0.00 Mg C ha^{-1} year^{-1} at the rewetted site and 0.056 ± 0.000 Mg C ha^{-1} year^{-1} at the undrained site. In the rewetted condition, carbon from litter may become stable over a longer period. Consequently, carbon loss and gain mainly depend on the magnitude of peat decomposition (R_h) and CH_4 emissions.

Keywords: heterotrophic respiration (R_h); methane emissions; soil organic carbon (SOC); peatland restoration; litterfall production

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1. Introduction

Under global climate warming and drier conditions, many pristine tropical peatland ecosystems have been projected to be carbon sources rather than carbon sinks [1,2]. Moreover, tropical peatland ecosystems have been degraded and have lost their carbon due to deforestation, forest conversion, and fires [3–5]. Without immediate forest management interventions, such as peatland rewetting, degraded and drained tropical peat swamp forests (PSFs) will continue to be carbon sources [6]. Rewetting interventions in previously drained peatlands have been recommended as a significant global warming and climate change mitigation strategy in the land use sector [7]. However, unlike the drained PSFs, the field study of carbon dynamics from rewetted PSFs is limited, especially in the tropical climate zone. Hence, the availability of primary data from rewetted tropical PSFs is scarce [8–10]. In fact, primary data, such as CO_2 emissions from soil respiration (R_s), CH_4 emissions, dissolved organic carbon (DOC), litter productions, soil organic carbon (SOC), and other biophysical properties of peat soil, are needed in order to model the future carbon dynamics under rewetted conditions in tropical PSFs [11]. Therefore, this paper examines and discusses the impact of the rewetting intervention on carbon dynamics in tropical PSFs.

Rewetting interventions are mainly conducted by blocking canals/ditches [12,13]. The effective blocking of canals/ditches would raise the groundwater level (GWL) closer to the peat surface [14] and maintain the mean annual GWL at less than −30 cm below peat surface and +10 above the peat surface [10]. In rewetted conditions, where the GWL is closer to the peat surface, gas diffusion to the peat soil is minimized, the oxygen (O_2) concentration in the peat profile decreases, and the peat properties gradually change [15–17]. For example, peat bulk density (BD) and soil organic matter (SOM) properties change following rewetting [18,19]. Thus, the alteration of SOM properties is followed by a change in the soil organic carbon (SOC) content in the peat layer [20]. In addition to abiotic properties, biotic properties, such as the microbial population, also change. The methanogen community, for example, increased in the rewetted peatland, while the methanotroph community decreased [21]. Likewise, in the rewetted condition, the vegetation composition becomes more adaptable to the rewetted condition [22–24]. The changes in biotic and abiotic peat properties, then, have an effect on the biogeochemical cycling of carbon [11,25], which eventually affects carbon dynamics in the annual, decadal, and even centennial timescale for this ecosystem.

In PSF ecosystems, the carbon input mostly comes from aboveground and belowground litter [26,27]. In contrast, carbon loss is mainly caused by SOM decomposition caused by microbial activity (i.e., CO_2 emissions from heterotrophic components (R_h) and CH_4 emissions) [28] and fluvial carbon loss [29,30]. In natural PSF ecosystems, the SOM from litter is preserved due to waterlogged and highly acidic conditions, and the carbon is stored in peat soil. In contrast, in the degraded and drained PSFs, where the annual mean of GWL ranges around −50 to −100 cm from the peat surface, the carbon loss rate from SOM decomposition is higher than the carbon accumulation rate, causing a negative carbon balance or the loss of carbon from the system [31]. Therefore, rewetting the previously drained peatlands is expected to reverse the direction of carbon loss, from a carbon source to a carbon sink. From the review and meta-analysis studies, rewetting interventions have shown a decreasing effect on CO_2 emissions, but an increasing effect on CH_4 emissions, although the effects of rewetting on DOC are still inconclusive [8,25]. Furthermore, field studies from the northern peatlands have shown that a peat ecosystem could become a carbon sink or remain a carbon source after rewetting interventions [32–34]. However, the published data on carbon loss and gain from rewetted tropical PSFs are still limited [8–10]. Therefore, there is a need to conduct further studies on the carbon dynamics in rewetted tropical peatlands. To what extent the rewetted tropical peatlands affect the biogeochemical cycle of carbon and how much carbon enters the peat through plant litter and exits the peat through CO_2, CH_4 emissions, and DOC are questions that need to be answered with more field data. This study aims to measure and discuss the effect of rewetting on litterfall, the CO_2 emissions from the heterotrophic components of soil respiration (R_h), CH_4 emissions, DOC, and carbon stocks at the rewetted site. We compared the measured data with other published data from undrained and drained tropical PSFs. We hypothesized that the rewetted and undrained sites would have lower R_h but higher CH_4 emissions when compared with drained tropical PSFs

2. Methods

2.1. Study Sites

The study was conducted at rewetted and undrained sites inside the Peatland Restoration and Conservation Project Area (Katingan Mentaya Project—KMP), Central Kalimantan, Indonesia. The KMP has been implementing rewetting interventions since 2016 in the drained tropical PSFs inside the project area. The PSFs before restoration were selectively logged at both sites; the only difference between the rewetted site and the undrained site is the presence of ditch networks, which were formerly used to transport logs. The ditches have average widths of 2 m, depths of 1.5 m, and lengths of approximately 3–5 m, with a water flow speed at surface of 0.1–0.25 m/s. At the rewetted site, there are many ditches, while there are none at the undrained site. Therefore, the restoration intervention at the rewetted site involved rewetting by canal blocking, whereas only forest protection was the restoration intervention at the undrained site, and there was no revegetation activity at either site [35]. The rewetted site was located in the middle of the ditch network and 200 m from the forest edge. Meanwhile, the undrained site was located farther northward, around 3 km from the rewetted site (Figure 1b). The location of the rewetted site is at 2°55′25.93″ S, 113°9′16.19″ E, and the undrained site is at 2°54′15.54″ S, 113°9′14.92″ E. In the KMP area, the monthly mean of rainfall is 232 mm, with the lowest rainfall in July and the highest in December. The monthly mean temperature is 25.8 °C, with a minimum of 17.7 °C and a maximum of 35.3 °C.

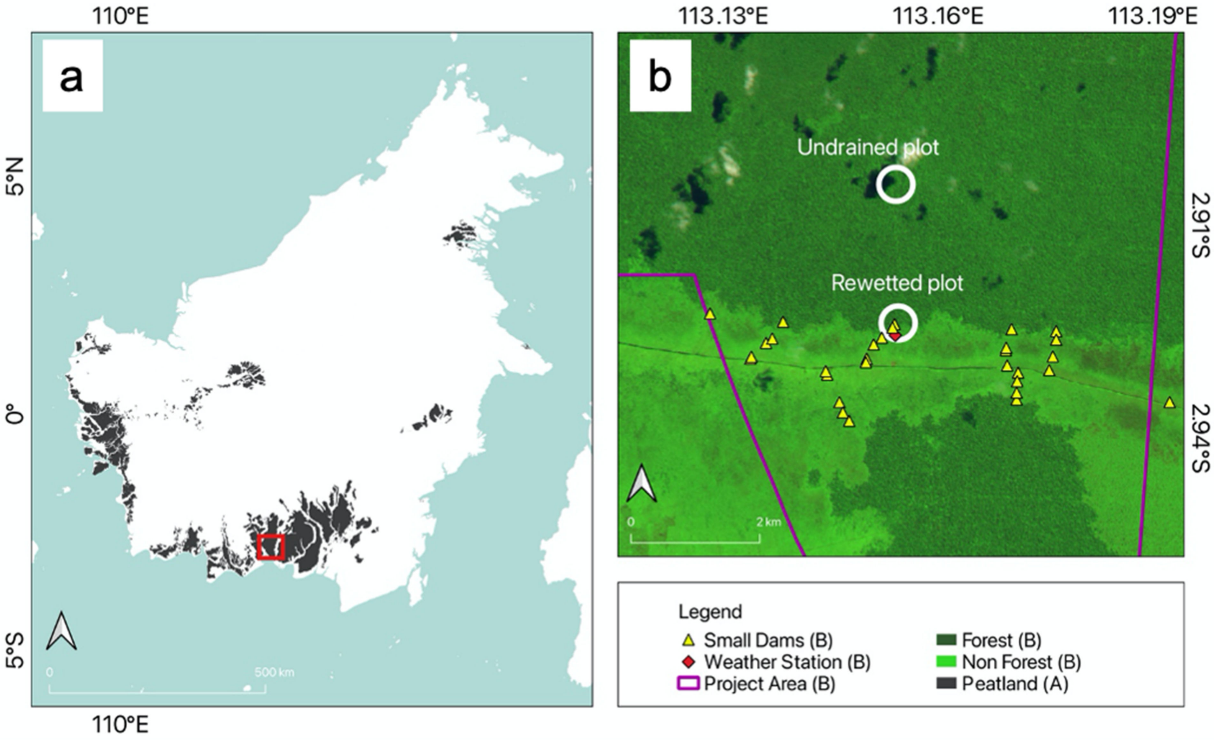

Figure 1. The study was conducted in the Katingan Mentaya Project area (red square) in Kalimantan, Indonesia (Panel **a**). The rewetted and undrained sites (hollow white circle) are around 3 km apart (Panel **b**). Yellow solid triangles indicate the ditch blocking built along the ditches. The red diamond indicates a weather station placed in an open area around 600 m from the rewetted site (Panel **b**).

2.2. Carbon Stock and Forest Composition Field Sampling

The field sampling to measure the carbon stock, aboveground carbon (AGC), belowground carbon (BGC), forest composition, and soil organic carbon (SOC) was carried out following methods described in a previous study [36,37]. The carbon stock data collection was conducted in eight rectangular 1 ha plots (40 × 250 m) (Figure 2a), with four plots at the rewetted site and four plots at the undrained site. Each plot was located 100 m apart and established in parallel rows from east to west within each site. The conversion from the tree's diameter at breast height (DBH) data to dry biomass and carbon were calculated using equations from a previous study [36] (Table S1). The root biomass was calculated using the root-to-shoot ratio and then multiplied by 0.48 to obtain the root carbon [38]. The SOC stock, defined as the amount of organic carbon mass stored within the peat layer and expressed as Mg C ha^{-1}, was estimated by multiplying peat bulk density, carbon content, and peat depth [39].

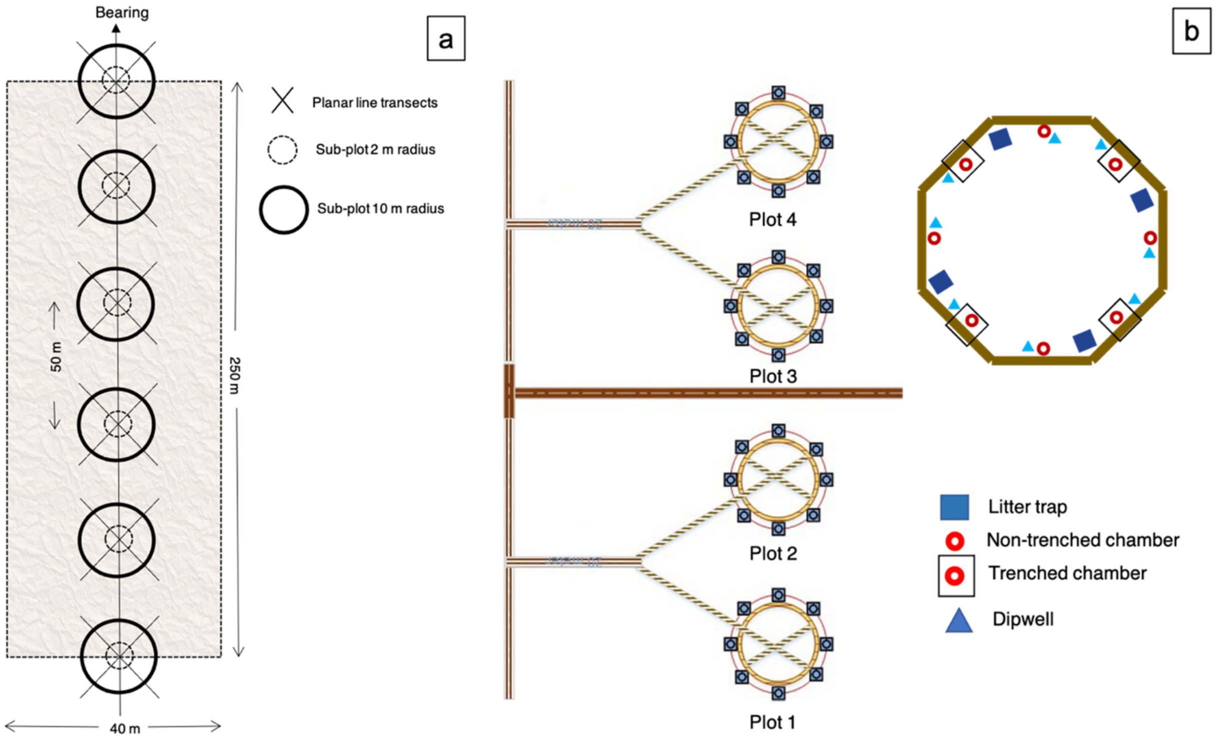

Figure 2. Panel (**a**) shows a carbon stock plot layout modified from Kauffman et al. (2016). Panel (**b**) shows the chambers and litter trap layout in each sub-plot; the distance between plots is 100 m. In each plot, there are 8 permanent chambers (4 trenched and 4 non-trenched), 4 litter traps, and 8 dipwells.

The peat samples were collected from the peat surface down to the mineral soils, with depth intervals as follows: 0–15, 15–30, 30–50, 50–100, 100–200, 200–300, and >300 cm [37]. The 5 cm-long peat samples were placed into an aluminum cup (8 × 7 cm), weighed, and wrapped with marked plastic sample bags for further analysis. All field work for carbon stock assessment was conducted in February and March 2018, and peat soil sample analysis (carbon and nitrogen content) was conducted in LIPI Cibinong during February 2019 using a Leco^{TM} CN analyzer. In terms of forest composition and structure, we used DBH and tree species data (trees with a DBH of 5–49.9 cm and trees with a DBH $\geq$ 50 cm) to analyze the forest structure and composition. The importance value (IV) of each species encountered in the plots and Shannon's diversity (H') were calculated according to a method described by Kalima and Deny (2019). The value of H' was categorized as follows: $H' \leq 1$ indicates very low, $H' \geq 1$–2 indicates low, $H' \geq 2$–3 indicates medium, $H' \geq 3$–4 indicates high, and $H' \geq 4$ indicates very high levels of diversity [40,41]. We also used principal component analysis (PCA) to compare the biophysical properties of each plot.

2.3. *Litterfall*

Litterfall was collected in 16 litter traps with dimensions of 0.5 × 0.5 m (collection area 0.25 m^2). In total, there were 32 traps for both sites. The traps, which were made from mesh cloth and a polyvinyl chloride (PVC) frame, were suspended at a height of 1 m above the peat surface and placed systematically in the plots (Figure 2b). The collection of litterfall was carried out twice a month (or every 14 days) over the whole year in 2019. The collected litterfalls were separated into twigs, leaves, and flowers/fruits, and dried at 70 °C to a constant mass [42]. The annual production of the litterfalls was derived from the mean litterfall annual production, while the branch falls were estimated by multiplying the litterfall annual production by 9.89% [43]. We used 0.48 as a carbon fraction to convert litter and branch fall dry biomass to carbon.

2.4. Heterotrophic Component of Soil Respiration (R_h) and Methane Emission

The R_h and CH_4 fluxes were measured in situ in 4 plots at the rewetted and undrained sites by using a static closed chamber method [44]. Each plot consisted of 8 chambers that were configured into an octagonally shaped plot to cover microtopography variation. In total, there were 64 chambers, with 32 chambers at the rewetted site and 32 chambers at the undrained site (Figure 2b). The chambers were made of an opaque polyvinyl chloride (PVC) cylinder with a height of 30 cm and an inner diameter of 25 cm. All chambers were inserted 5 cm deep into the peat soil and remained in the field for the entire measurement period. The distance from one chamber to another was around 5 m, and the distance from one plot to the next was 100 m. Half of the chambers in each plot were trenched using perforated corrugated plastics inserted 80 cm deep into the peat soil following a method described in a previous study [45,46]. The trenched chamber was 1 × 1 m square. The chamber was placed at the center to avoid an edge effect [45]. We manually removed the understory vegetation in the trenched chambers by hand and regularly removed plants that had regrown every two weeks [46]. However, we did not remove the litter. In addition, to prevent soil disturbance, wooden walkways were built between plots to connect the measurement points (chambers). The establishment of the plots was completed in November 2018. In the non-trenched chambers, we did not remove ground vegetation either inside or outside the chambers.

The first gas sampling was conducted in February 2019 (wet season), and the second was conducted in September 2019 (dry season). During the gas sampling, the gas in the chamber headspace was collected at 0, 10, 20, and 30 min using a 50 mL polypropylene syringe between 8:00 a.m. and 1:00 p.m. The gas sample from the syringe was then inserted directly into a labeled glass vial. The collected gas samples were then analyzed using a gas chromatograph equipped with an electron capture detector (ECD) and with a flame ionization detector (FID) for CO_2 and CH_4 analysis, respectively [47,48]. The flux rate was calculated from the concentration change rate in the chamber headspace, determined by the slope of a linear regression of gas concentration and converted to a mass unit using the ideal gas equation [44]. The R_h and CH_4 fluxes from the measurement were converted into annual cumulative data using equations for two months of data [49]. The CH_4 flux data were only collected from the non-trenched plot.

2.5. DOC and POC

We estimated DOC and POC at 20, 50, and 100 cm peat pore water depths. At each site, the peat water was collected at three locations and stored in a cool box (±4 °C) for transport to the field office in Sampit [50]. The samples were stored in a refrigerator (≤3 °C) before analysis. The DOC and POC were analyzed following the method described by the American Public Health Association (APHA) 5310 C (persulfate–heated oxidation method) at the Sucofindo laboratory in Banjarbaru, South Kalimantan. The application of the persulfate oxidation method for DOC and POC analysis is widely used in commercial laboratories and has an analytical range from 0.002 to 1000 mg/L [51]

2.6. Ground Water Level (GWL)

We used automatic water loggers (Model HOBO™ U20-001-02-Ti; 0.3–0.6 cm accuracy; 0.14 cm resolution) to monitor the GWL at the rewetted and undrained sites. The logger was inserted into a perforated iron galvanized pipe and sealed at the top to prevent the rainwater from entering into the pipe. GWL data were logged every 30 min and downloaded once a month. Barometric pressure was also measured in both sites to automatically convert the raw water pressure data into actual GWL data [52]. In addition to the automatic water logger, we installed a perforated PVC pipe at each measurement point immediately next to the chamber to measure the GWL concomitantly during the gas measurements. We also installed a mini weather station to monitor the rainfall and air temperature. The weather station was located 500 m from the rewetted site and 3000 m from the undrained site. To examine the rewetting intervention, we compared the GWL difference (gap) between the rewetted and undrained sites before and after the dam construction (GWLgap = GWLundrained − GWLrewetted).

2.7. Statistical Analysis

Student's *t*-test was used to compare the litterfall, R_h, CH_4 emissions, and SOC data between sites. A one-way ANOVA was also performed to test the significance of differences within the plots at each site. The GWL before and after the rewetting intervention (dam construction) was compared using a paired *t*-test. All statistical analyses were performed using the Microsoft Excel © data analysis package and Statplus™. Principal component analysis (PCA) was used to characterize the biophysical properties of each site using R version 4.0.2, and the results are visualized with the "ggbiplot" R package.

3. Results

3.1. Biophysical Properties and Carbon Stock

We encountered dominant tree species from the Anacardiaceace, Dipterocarpaceae, Ebenaceae, Fabaceae, Lauraceae, Myrtaceae, Sapotaceae, and Rutaceae families at the rewetted and undrained sites. Although these dominant tree species were found at both sites, the rewetted site was dominated by Ebenaceae, while Anacardiaceae dominated the undrained site. In terms of commercial timber, trees from the Ebenaceae and Anacardiaceae families are considered to be less valuable for timber, which explains why the tree species were still relatively abundant. In contrast, several valuable commercial trees, such as *Gonystyllus bancanus*, *Alstonia scholaris*, and *Shorea* sp., were rare, which demonstrated that the study sites had experienced selective logging activity before restoration took place. Based on the dominant tree composition encountered at both sites, the forest type at the study site could be classified as a mixed swamp forest [53].

In terms of GWL, the rewetting intervention raised the GWL at the rewetted site. The GWL's gap between undrained and rewetted site after the rewetting intervention was 6 cm shallower ($p < 0.001$). The small GWL gap suggested the effectiveness of the rewetting intervention. During the field measurement, the GWLs of the rewetted and undrained sites were 10 and 13 cm in February and −89 and −72 cm in September, respectively. Meanwhile, the annual mean of the GWL at the rewetted site was deeper from the peat surface (−21 cm) than it was at the undrained site (−12 cm) (Table S2 and Figure S1). The bulk density (BD) and carbon content (CC) of both sites were also not significantly different, but the nitrogen content (NC) was significantly higher at the rewetted site (Figure 3, see also Tables S3 and S4). This led to a lower C/N ratio at that site.

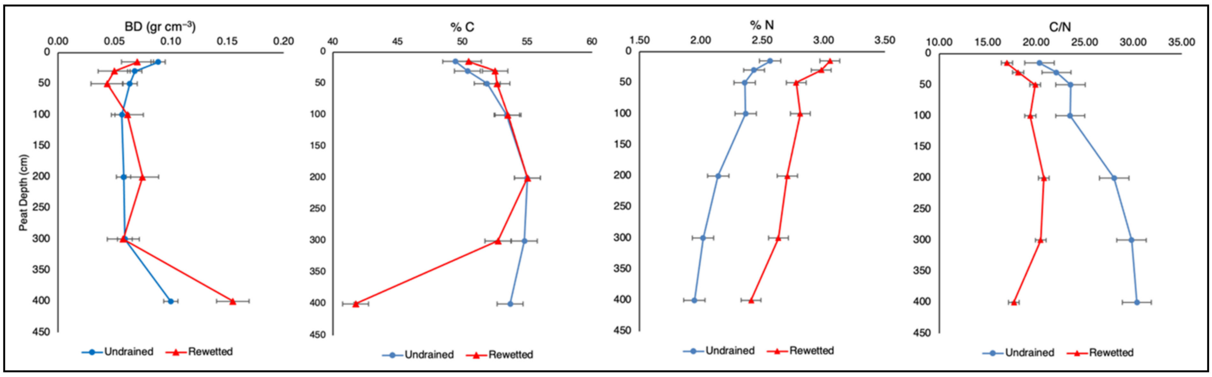

Figure 3. Relationship of bulk density (g cm^{-3}), carbon content (%), nitrogen content (%), and C/N ratio to peat depth at the undrained and rewetted sites. The solid red triangle indicates the rewetted site, and the solid blue circle indicates the undrained site. The error bars represent the standard errors (SE).

In terms of carbon stock, the mean total carbon stock at the rewetted site was not significantly lower than it was at the undrained site (1886.7 ± 87.7 and 2106.2 ± 214.3 Mg

C ha^{-1}, respectively) (p-value > 0.05). At both sites, the total BGC, which is composed of root and SOC pools, was found to be nearly 92% of the total carbon stock (Table 1). Meanwhile, in AGC, the larger carbon pool was from the overstory (5%). The remainder of the carbon pools in AGC (wood debris, sapling, and standing deadwood) only constituted less than 1%. (Figure 4) The difference in the total carbon stock between the rewetted and undrained sites was mainly due to the difference in SOC associated with the peat depth. The peat depth difference was 37 ± 6 cm or, when converted to carbon stock, approximately ~200 Mg C ha^{-1}. The overall biophysical properties and carbon stocks for the rewetted and undrained sites are shown in Table 1.

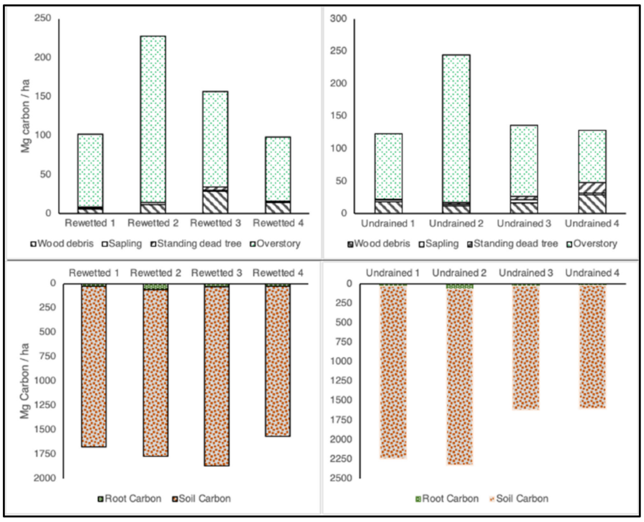

Figure 4. Aboveground carbon (AGC) and belowground carbon (BGC) stocks of the rewetted and undrained PSF plots and the contribution from each carbon pool component.

Table 1. Biophysical properties and carbon stock of the study sites (mean ± SE).

a	Properties	Rewetted Site	Undrained Site
1	Number of plots (sub-plot)	4 (24)	4 (24)
2	Annual mean GWL (cm) (January–December 2019) [a]	−22 ± 1.6	−12 ± 1.5
3	Peat depth (cm) [a]	396.7 ± 3.5	434.6 ± 5.4
4	Peat bulk density (g/cm^3) [a]	0.073 ± 0.014	0.071 ± 0.006
5	Carbon content in peat (%) [a]	51.2 ± 1.7	52.7 ± 0.8
6	Nitrogen content in peat (%) [b]	2.8 ± 0.03	2.3 ± 0.09
7	C/N ratio [b]	19.1 ± 0.6	25.4 ± 1.5
8	Number of species [b]	53	78
9	Tree Density—DBH 5–49.9 cm (tree/ha)[a]	1266 ± 38	1369 ± 127
10	Tree density—DBH > 50 cm (tree/ha)[a]	5 ± 1	8 ± 2
11	Basal area—DBH 5–49.9 cm (m^2/ha) [a]	22.0 ± 1.7	21.4 ± 2.5
12	Basal area—DBH > 50 cm (m^2/ha) [a]	1.4 ± 0.3	1.8 ± 0.6
13	Total aboveground carbon (Mg C ha^{-1}) [a]	146.3 ± 30.3	158.1 ± 28.8
14	Total belowground carbon (Mg C ha^{-1}) [a]	1720.5 ± 65.0	1948.2 ± 196.0
15	Soil organic carbon (Mg C ha^{-1}) [a]	1685 ± 61.1	1912.5 ± 190.2
16	Total carbon stock (Mg C ha^{-1}) [a]	1866.7 ± 87.7	2106.2 ± 214.3

[a] No significant difference between sites (at $p > 0.05$); [b] Significant difference between sites (at $p < 0.05$).

3.2. Litterfall Production

We observed a monthly variation in the aboveground litter production at the rewetted and undrained sites. Moreover, the litterfall showed two peaks in March and September (Figure 5). The two peaks in one year suggest that the litterfall production followed a bimodal pattern, also reported in tropical mixed PSFs in Central Kalimantan, Indonesia [54]. The annual total litterfalls were not significantly different between sites ($p > 0.05$). When converted into carbon, the carbon from the litterfall was 4.68 ± 0.30 Mg C ha^{-1} yr^{-1} at the rewetted site and 3.92 ± 0.34 Mg C ha^{-1} yr^{-1} at the undrained site. Leaves were the major component of the litterfall, although the proportion varied seasonally (Figure 5). We found that leaves constituted 80% and 82% of the total litterfall for the rewetted and undrained sites, respectively. The twigs and reproductive components constituted 14.8% and 5.3%, respectively, at the rewetted site and 13.6% and 4.6%, respectively, at the undrained site. Our finding on leaf contributions (80% to 82%) to the total the litter production were comparable with leaf contributions (70–85%) to the total litterfall from other studies on PSFs in Central Kalimantan [54–56].

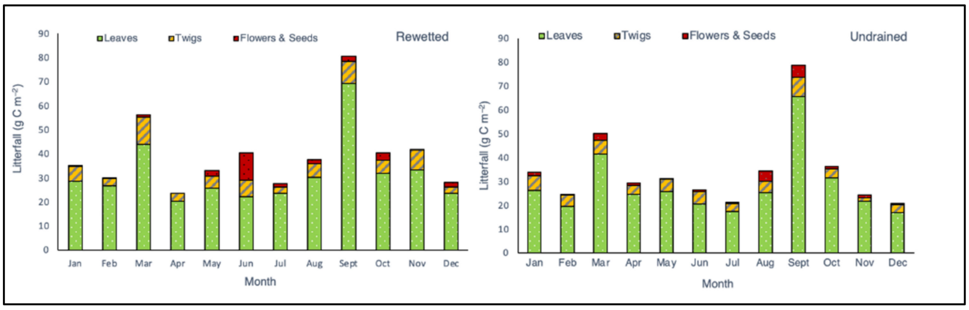

Figure 5. Monthly variation of litterfall production at the rewetted and undrained sites, Katingan, Central Kalimantan, Indonesia. The litterfall data were derived from one-year field data collection in 2019.

3.3. Heterotrophic Respiration (R_h), CH_4 Emission, and DOC

Based on the field measurements in February and September, the R_h and CH_4 emissions showed significant differences, with a p-value < 0.001 at both sites (Figure 6). The R_h in February was significantly lower, at 85.2 ± 22.5 and 77.1 ± 15.8 mg CO_2 m^{-2} h^{-1}, than the R_h in September, at 445.2 ± 39.1 and 443.3 ± 33.7 mg CO_2 m^{-2} h^{-1}, at the rewetted and undrained sites, respectively. However, the mean R_h was not significantly different between sites ($p > 0.05$), though it tended to be slightly higher at the rewetted site (265.2 ± 71.2 mg CO_2 m^{-2} h^{-1}) than at the undrained site (260.17 ± 37.7 mg CO_2 m^{-2} h^{-1}). The annual average R_h calculated from the two months of data was 14.90 ± 0.08 Mg CO_2 ha^{-1} year^{-1} at the rewetted site and 14.57 ± 0.06 Mg CO_2 ha^{-1} yr^{-1} at the undrained site. Converting this into carbon terms, R_h was 4.06 ± 0.02 Mg C ha^{-1} yr^{-1} at the rewetted site and was 3.96 ± 0.16 Mg C ha^{-1} yr^{-1} at the undrained site.

For comparisons, the R_h values from our study were lower than the R_h values (7.1 ± 0.4 Mg C ha^{-1} yr^{-1}) from tropical PSFs in Tanjung Puting, Central Kalimantan [57], the R_h values (8.9 ± 0.4 Mg C ha^{-1} yr^{-1}) from undrained peat swamp forests in Sebangau, Central Kalimantan [58], and the R_h values (5.68 ± 0.4 Mg C ha^{-1} yr^{-1}) from restored mixed PSFs [59], and were lower than the R_h values (14.08 ± 2.1 Mg C ha^{-1} yr^{-1}) from rubber plantations and the R_h values (9.6 ± 0.8 to 24.1 ± 1.4 Mg C ha^{-1} yr^{-1}) from oil palm plantations in tropical peatlands [57,60,61]. The lower values in our results could be explained by the relatively low GWL of the peat surface at our sites (Zhong et al., 2020). The annual mean GWL at the rewetted and undrained sites in 2019 was −21 and −12 cm, respectively, lower than the annual mean GWL, ranging from −20 to −114 cm, from the peat surface reported in other studies [58].

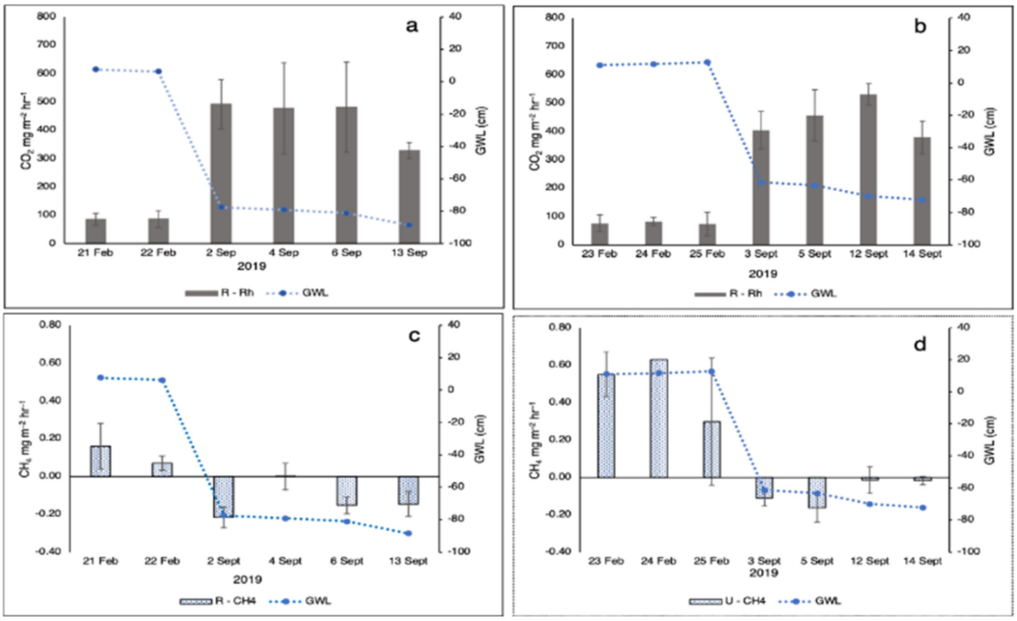

Figure 6. The fluctuation of R_h and CH_4 at the rewetted (**a**,**c**) and undrained (**b**,**d**) sites. February 2019 represents the wet season and September 2019 represents the dry season. GWL is groundwater level, and R and U indicate rewetted and undrained sites. Errors are in SE.

In contrast, CH_4 fluxes showed an opposite pattern to that of the R_h. The CH_4 fluxes were higher in February, at 0.11 ± 0.04 mg CH_4 m^{-2} h^{-1} and 0.51 ± 0.02 mg CH_4 m^{-2} h^{-1}, than in September, at -0.13 ± 0.05 mg CH_4 m^{-2} h^{-1} and -0.07 ± 0.04 mg CH_4 m^{-2} h^{-1}, at the rewetted and undrained sites, respectively. The negative sign indicates an uptake in CH_4 from the atmosphere in September. The CH_4 emissions based on the study site were not significantly different ($p > 0.05$). The annual average value of the rewetted site tended to be slightly lower (-0.00203 ± 0.00 Mg CH_4 ha^{-1} yr^{-1}) than that of the undrained site (0.0074 ± 0.00 Mg CH_4 h^{-1} yr^{-1}). Converting this into carbon, CH_4 emissions were -0.0015 ± 0.00 Mg C ha^{-1} yr^{-1} at the rewetted site and 0.056 ± 0.000 Mg C ha^{-1} yr^{-1} at the undrained site.

We estimated the DOC and POC concentration from the peat pore water at 20, 50, and 100 cm depths at the rewetted and undrained sites at the end of January. The DOC and POC concentrations were higher in the upper layer (20 cm) section. Figure 7 shows the result of the DOC and POC at various depths at the rewetted and undrained sites. The DOC concentrations in the peat pore water at the rewetted and undrained sites did not differ significantly ($p > 0.05$): they were 70.6 ± 2.56 and 69.1 ± 1.74 mg/L, respectively. Moreover, the POC concentrations in the peat pore water also did not differ significantly: they were 103.4 ± 7.59 and 88.1 ± 23.81 mg/L at the rewetted and undrained sites, respectively. Since we only measured the DOC and POC in one month (January 2019), we could not analyze the monthly variation in DOC concentration. Comparing our results with other studies, the DOC concentrations in our rewetted and undrained PSFs (Figure 7) were lower than those (79.9 ± 5.5 mg/L) in a deforested PSF [62] and a disturbed PSF (74–83 mg/L) [63], but comparable to those from undrained peatlands (16–77 mg/L) and rewetted peatlands (13–109 mg/L) [64].

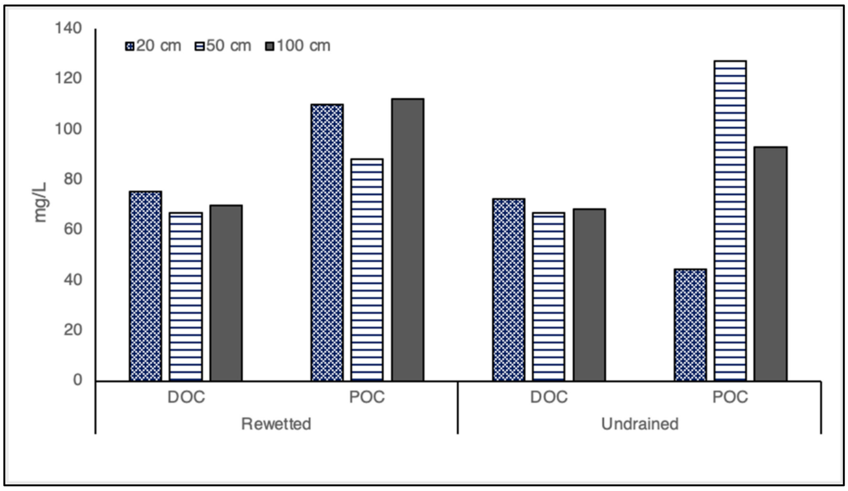

Figure 7. DOC and POC concentrations in rewetted and undrained sites.

4. Discussion

4.1. Carbon Stock and Peat Properties in Rewetted Tropical PSFs

Our study found that BGC, which is composed of belowground root and SOC, mainly contributes to the total carbon stock (Figure 4). It is well known that the SOC in peatland ecosystems stores more carbon than aboveground carbon (AGC) [36,55,59], which supports our results. The study showed that SOC at the rewetted site was lower than it was at the undrained site (Table 1 and Figure 4). The slightly lower SOC at the rewetted site seemed to be caused by the lower peat depth, and this was also confirmed by the principal component analysis (PCA) (Figure 8). Based on the 24 drill measurement points at each site, the peat depth at the rewetted site was on average 37 ± 6 cm lower than it was at the undrained site. The lower peat depth at the rewetted site could be due to differences in the microtopography during peat formation, or it could be the effect of the drainage that induced peat subsidence. The ditches at the rewetted site were built around the 1990s to transport logs from PSFs [35]. When we simulated the peat surface loss by applying the R_h emissions, BD, and carbon content [65], we found a peat surface loss of approximately 0.31 cm/year in the rewetted site and approximately 0.23 cm/year in the undrained site. The carbon loss from peat decomposition would lead to peat subsidence [66]. However, carbon loss from peat decomposition (R_h) is assumed to account for 60% of total peat subsidence. The other 40% comes from peat shrinkage due to compaction and consolidation [67]. Unfortunately, we did not have data on the initial peat depth before the drainage in this area. Thus, we could not estimate the depth of the peat surface loss due to forest degradation and drainage.

In terms of AGC stocks, the slightly lower AGC at the rewetted site could be due to fewer large trees (DBH > 50 cm) and a lower tree density compared with the undrained site (see Table 1), which appeared to be the result of different logging severities. The difference in tree structure and composition affected the AGC, since the overstory (trees with DBH > 5 cm) makes the largest contribution to the AGC stock. The effect of the forest structure and composition of the AGC has been discussed in previous studies as well [36,55,68]. Since there is no species-specific allometric equation for PSF trees, we calculated tree dry biomass using a general allometric equation developed for tropical PSFs [69]. Thus, the difference in tree species composition between the rewetted and undrained sites might not be accurately accounted for in the AGC estimation. In addition, the difference in the wood debris and understory will also lead to the AGC stock difference. The analysis of the carbon pool components using PCA showed that the rewetted site had a lower quantity and less variety of wood debris, understory, and standing deadwood than the undrained site (Figure 8).

The peat properties were not significantly different between the two sites (p-value < 0.05), although the nitrogen content was significantly higher at the rewetted site (Figure 3).

The PCA diagram (Figure 8) shows that all plots from the rewetted site are clustered together to the left, mostly due to their higher N content. A higher N content results in a lower C/N ratio, which indicates that the peat mineralization was higher at the rewetted site. The lower C/N ratio (less than 20) could suggest that the organic materials had decomposed faster at the rewetted site [70]. In contrast, the C/N ratio at the undrained site ranged from 25 to 30, indicating that the peat was still undisturbed or that the decomposition process was still in an earlier stage [71]. This finding raises the question of whether the higher N content at the rewetted site was caused by a peat decomposition process that took place before the rewetting intervention or a peat decomposition process that was still occurring during the rewetting intervention. If we refer to the R_h data in Figure 6, the higher N content at the rewetted site seems to be caused by the previous peat decomposition before the rewetting intervention took place. In other words, in rewetted conditions, peat mineralization is reduced or even halted. However, a longer period of C/N data is needed to answer this question.

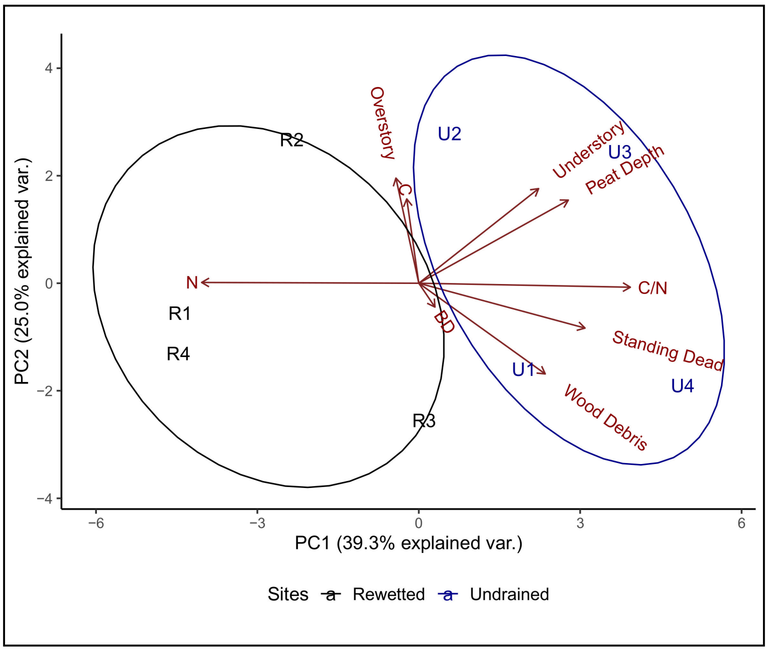

Figure 8. Principal component analysis (PCA) generated from soil property data (peat depth, bulk density (BD), carbon content (C), nitrogen content (N), C:N ratio (C/N), and carbon stocks from several pools (overstory, understory, standing dead wood, and wood debris), calculated from rewetted plots (R1, R2, R3, and R4) and undrained plots (U1, U2, U3, and U4)).

4.2. Effect of Rewetting Intervention on R_h, CH_4 Emission, and DOC

Our rewetting intervention, by blocking the ditches, raised the GWL at the rewetted site. The annual mean GWL in 2019 was −22 and −12 cm at the rewetted and undrained sites, respectively (Table 1 and Figure S1). From January to June 2019, the rewetted and undrained sites were both inundated, while the GWL was below −20 cm from July to October 2019 due to the dry season (less rainfall). However, the annual mean GWL showed that canal blocking effectively raised the GWL compared to previously drained PSFs [14].

It is well known from previous studies that the GWL is a significant factor in controlling carbon emissions from peat soil [72,73]. A deeper GWL from the peat surface creates a larger aerobic zone, increasing the aerobic microbial activities and soil respiration. Conversely, when the GWL is lower (near the peat surface), the peat layer becomes anoxic, and oxygen concentration decreases, reducing the organic material oxidation process. However, anaerobic microbial activity, such as methanogens (methane-producing bacteria), increases in anoxic conditions, resulting in higher CH_4 emissions in rewetted peatlands [16].

Our measurements showed that R_h was higher in September 2019 when the GWL was deeper, and the R_h decreased in February 2019 when the GWL was near the peat surface (Figure 6). Our study demonstrated a negative correlation between GWL and R_h. The negative correlation between GWL and R_h has been demonstrated in previous studies in undrained, drained, and burned tropical PSFs [46,74,75]. A similar pattern was also reported from drained peatlands on acacia and oil palm plantations [76], where the GWL strongly affected the R_h. Since the R_h values represent the carbon loss from the peat soil [56], the higher the R_h, the higher the rate of carbon loss from the peat soil. However, since the rewetting intervention can reduce the R_h emissions, an effective rewetting intervention will reduce the carbon loss. From this study, we found that the annual cumulative CO_2 emissions from R_h at this rewetted site were lower than those in drained secondary PSFs (40.85 Mg CO_2 ha^{-1} $year^{-1}$), oil palm plantations (31 Mg CO_2 ha^{-1} $year^{-1}$), and acacia/rubber plantations (60 Mg CO_2 ha^{-1} $year^{-1}$) [77]. On the basis of these data, it is demonstrated that rewetting interventions in previously drained PSFs have the potential to reduce carbon emissions by around 52%, 63%, and 75% compared with oil palm plantations, drained PSFs, and acacia plantations, respectively.

In contrast, raising the GWL closer to the peat surface increases CH_4 emissions (Figure 6). In other words, there is a positive correlation between GWL and CH_4 emissions. The CH_4 emissions from our results were sampled in February (wet season; shallower GWL) and September (dry season; deeper GWL). In February 2019, the chambers at the rewetted and undrained sites were mainly inundated, with an average GWL of around 10 cm above the peat surface. This condition, a GWL of around 10 cm, has been demonstrated to create hotspots of CH_4 emissions, which can be nearly 10 times greater compared with the dry season [32,72,73]. In the flooded condition, the number of aerobic microbes is decreased, but the number of anaerobic microbes is increased. Therefore, the availability of labile substrates for CH_4 production by anaerobic microbes, e.g., methanogens, is abundant, while CH_4 oxidation by aerobic microbes is limited [78]. Consequently, an effective rewetting intervention that keeps the GWL close to the peat surface will increase the CH_4 emissions.

This study measured the DOC only in January 2020, when the GWL was above the peat surface. We found that the DOC concentrations were higher in the upper section, as reported in previous studies [50,62]. The higher DOC in the upper layer (0–20 cm) implied that the decomposition of organic matter mainly occurred in this layer. However, the effect of rewetting on DOC is still unclear [25]. Some studies have reported that rewetting increased the DOC concentration [79,80]. On the other hand, other studies have reported that rewetting reduces it [81,82]. More DOC data are needed from rewetted sites.

4.3. Effect of Rewetting on Litter Productions

Plant litter is a dominant carbon source for peat soil [83,84]. Therefore, decreasing or increasing litterfall productions may affect the carbon balance in peat soil [85]. A previous study on aboveground litterfall production from an intact tropical PSF showed that aboveground litterfall production had two peaks. The first peak was in February–March, and the second was in August–September [54]. This two-peak pattern (bimodal peaks) was also found in our study (Figure 5). In contrast, another study on a secondary tropical PSF reported that aboveground litterfall production was lowest in February–March but highest in August–September [55]. In general, the aboveground litterfall production in our study was comparable to that of other studies in pristine PSF ecosystems, with values ranging from 3.14 to 5.67 Mg C ha^{-1} $year^{-1}$ [43,54,55]. The litterfall production at the rewetted site in our study (4.68 ± 0.30 Mg C ha^{-1} $year^{-1}$) was comparable to the litterfall production of other studies in tropical peat forests, with a mean value of 4.27 ± 0.21 Mg C ha^{-1} $year^{-1}$ ($n = 18$). Therefore, the carbon input of rewetted PSFs seems to be similar to that of other PSFs, as long as the peatland remains forested.

We only measured the aboveground litterfall, which may only reflect part of the carbon input into the ecosystem. We did not measure the root litter, which also contributes to the soil carbon. A recent study indicated that the contribution of the root litter to the

SOC is substantial and could outweigh the carbon input from aboveground litterfall [86]. Studies that specifically discuss the effect of rewetting on litter production are rare [83]. Nevertheless, in a rewetted PSF, where the GWL is supposedly close to the peat surface, the growth and penetration of roots to a deeper layer of peat soil are limited by the GWL [11]. Therefore, the contribution of root litter, especially from fine roots, may be limited in the upper layer of peat soil.

5. Conclusions

In this study, we observed that rewetted PSFs can reduce the carbon loss from heterotrophic respiration (R_h) and can potentially gain carbon, since the carbon input from plant litter is preserved in waterlogged conditions. In the rewetted condition, carbon input from litter (aboveground and belowground) may become stable over a longer period of rewetting intervention, as long as the peat is forested. Consequently, the carbon loss and gain mainly depend on the magnitude of peat decomposition (R_h) and CH_4 emissions. it could be predicted that a rewetting intervention in previously drained tropical PSFs has a positive effect on carbon balance.

Long-term monitoring is required to observe whether the peat continues to be a C source or has changed to be a C sink in rewetted PSFs, especially in relation to the increase in CH_4 emissions. In addition, root litter is needed to provide a comprehensive understanding of carbon cycling from rewetted PSFs. Although there are limitations, this study can enrich the discussion on the carbon dynamics of tropical PSFs, especially rewetted and undrained logged PSFs.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/cli10030035/s1, Figure S1: Daily ground water table and daily rainfall in the study site from Mid-July 2018–March 2020; Table S1: List of formula to convert tree DBH and wood debris data into dry biomass; Table S2: Before and after dam building ground water table in rewetted site and undrained site. The rainfall data was collected from the Katingan-Mentaya project weather station; Table S3: The properties of peat in the undrained site. The data was expressed in mean ± SE; Table S4. The properties of peat in the rewetted site. The data was expressed in mean SE.

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