Soil CO_2 emissions and net primary production of an oil palm plantation established on tropical peat

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SUMMARY

The C dynamics of a young (7 years old) smallholder oil palm plantation on peat soil in South Kalimantan (Indonesia) was investigated by directly assessing soil carbon dioxide (CO_2) emissions and C sequestration as net primary production (NPP) over a period of 19 months, from September 2018 to March 2020. Soil CO_2 efflux was measured monthly using a closed chamber system in 'near (1m)' and 'far (3m)' positions relative to tree bases, in order to measure total soil respiration (SR) and peat decomposition (PD), respectively. Simultaneously, litter (frond) decomposition (LD) was measured using a litter bag method. NPP was calculated as the sum of above-ground and below-ground biomass production. The C fluxes via SR, PD and LD were estimated to be 23.1 ± 6.13, 15.4 ± 4.37 (mean ± SD) and 0.38 Mg ha^{-1} yr^{-1}, respectively. NPP (as C) was estimated to be 1090 g m^{-2} yr^{-1}. NPP was low, mostly due to immaturity of the plantation. Heterotrophic respiration (HR) (= PD + LD) was 15.8 Mg ha^{-1} yr^{-1}, resulting in the plantation acting as a net C source of 4.9 Mg ha^{-1} yr^{-1} (= NPP - HR).

KEY WORDS: biomass production, carbon sequestration, frond decomposition, heterotrophic respiration

INTRODUCTION

The rapid conversion of tropical peat swamp forests to oil palm plantations has become a focus of global attention and scientific scrutiny in recent years because peat is an organic soil which stores a significant amount of carbon (C); for example, more than 50 Gt in Southeast Asia alone (Page *et al*. 2011). The conversion of peat swamp forest to oil palm plantation potentially transforms the ecosystem from a C sink to a C source due to changes in vegetation cover and the installation of drainage (Hergoualc'h & Verchot 2013). The main Southeast Asian resources of peat soil are located in Indonesia and Malaysia (Gumbricht *et al*. 2017), where population growth and economic development have driven land use changes on peatland continuously over recent decades (Miettinen *et al*. 2012). It has been estimated that the fraction of pristine peat swamp forests in Southeast Asia decreased from 76 % in 1990 to 29 % in 2015, mostly due to the establishment of new oil palm plantations (Miettinen *et al*. 2016). Therefore, it is essential to study the C dynamics of Southeast Asian tropical peatlands that are used for oil palm plantation.

Several studies of soil carbon dioxide (CO_2) emissions have been conducted in oil palm plantations on peatlands, but few of them quantify oxidative peat decomposition (PD) and heterotrophic respiration (HR) as separate components of total soil respiration (SR) (Melling *et al*. 2013, Dariah *et al*. 2014, Hergoualc'h *et al*. 2017, Ishikura *et al*. 2018, Manning *et al*. 2019). SR consists of autotrophic or root respiration (RR), PD and litter decomposition (LD). HR is usually defined as the sum of PD and LD (Hirano *et al.* 2014). Litter decomposition is a key process that regulates nutrient availability in a forest ecosystem and also a major source of C to the atmosphere (Kotowska *et al*. 2016). However, to our knowledge, there have been no previous studies of CO_2 emissions from litter (frond) decomposition in oil palm plantations on peat soil.

Soil CO_2 emissions have typically been assessed using closed chamber methods. Latterly, measurements of soil CO_2 emissions in chambers located in positions distant from the base of the oil palm tree have been reported as separate measurements of PD (i.e. without an RR contribution) (Dariah *et al*. 2014, Ishikura *et al*. 2018, Manning *et al*. 2019). Different oil palm management zones, i.e. 1) frond stack (FS) - a heap of prunings between rows which is usually rich in organic material - and 2) harvesting path (HP), which is subject to compaction, are also supposed to contribute differently to the soil CO_2 emissions (Manning *et al*. 2019).

Besides C loss, the conversion of tropical peat swamp forest to agricultural plantation changes ecosystem C storage and the C sequestration potential of primary production (Kotowska *et al*. 2015). However, carbon sequestration through net primary production (NPP) in oil palm plantations on peat soil remains poorly investigated. To our knowledge, only a limited number of publications address the NPP of oil palm plantations on either mineral soil (Kotowska *et al*. 2015) or peat soil (Melling *et al*. 2008, Basuki *et al*. 2018).

The aim of this study was to address knowledge gaps about the C balance of oil palm plantations established on peat soil. Our specific objectives were to investigate the C dynamics of an oil palm plantation on peat soil by directly measuring soil CO_2 emissions (HR) and carbon sequestration (NPP). We hypothesised that NPP in a young oil palm plantation would be low because of the low rate of fruit production.

METHODS

Study site

The study was conducted in a smallholder oil palm plantation on tropical peat located about 30 km southeast of Banjarmasin, the capital city of South Kalimantan, Indonesia (3° 24' 19.0" S, 114° 46' 11" E). The study site was originally shrubland with a peat depth of 6 m on average (SD ~ 0.1 m). Small drainage canals (2.5 m wide) were constructed, then in 2013 oil palm trees were planted, in a triangular pattern with 8 m spacing between trees, at a density of 147 trees ha^{-1}. At the time of our study the oil palm trees were seven years old, and the tree height was approximately 1.5 m. Most of the planted trees leaned over because there was no artificial compaction of the soil. Compound chemical (NPK) fertiliser was applied within 1 m around the tree bases in March and September annually, giving dosages equivalent to 70 kg N ha^{-1} yr^{-1}, 70 kg P_2O_5 ha^{-1} yr^{-1}, 70 kg K_2O ha^{-1} yr^{-1}, 2 kg MgO ha^{-1} yr^{-1} and 26 kg CaO ha^{-1} yr^{-1}. In addition, organic fertiliser (manure) was applied at a rate of 50 kg per tree in 2017.

Measurement of soil CO_2 efflux

Soil CO_2 efflux was measured at monthly intervals for 19 months (from September 2018 to March 2020) using a closed chamber system which was sequentially mounted on a set of permanent chamber bases inserted about 5 cm into the peat, cutting any tree roots present. The opaque PVC chamber was 30 cm in diameter and 20 cm in height, with a portable infrared CO_2 analyser (GMP343, Vaisala, Helsinki, Finland) and a DC data logger (LR 5042, HIOKI, Nagano, Japan) installed inside it. To improve the time response, the CO_2 analyser was operated in an open-path mode by removing its air filter. CO_2 concentrations in the chamber headspace were recorded every ten seconds for three minutes on each chamber base. Simultaneously, a thermo recorder (TR-71U, T&D corporation, Matsumoto, Japan) was deployed on the chamber to measure ambient air temperature outside the chamber, which had previously been shown to be close to temperature inside the chamber throughout the three-minute measurement period (Wakhid *et al*. 2017). Soil temperature was measured at a depth of 5 cm near the chamber base, using a thermometer. Measurements were conducted in the morning (08:00–11:00 hrs), with three replications per chamber base (total of nine measurements per month). Soil CO_2 efflux (μmol m^{-2} s^{-1}) was calculated from the air temperature (T_a, ºC) and the rate of increase in CO_2 concentration (dC/dt, μmol mol^{-1} s^{-1}) using Equation 1 (Sano *et al.* 2010):

$$\mathrm{CO_2\,efflux} = \frac{dC}{dt} \cdot \frac{V}{V'\left(\frac{273.15+T_a}{273.15}\right)} \cdot \frac{1}{A} \qquad [1]$$

where V is chamber volume (0.0144 m^3), V' is the molar volume of air at 0 °C (0.0224 m^3 mol^{-1}) and A is the ground area covered by the chamber (0.0707 m^2). dC/dt was determined from CO_2 concentrations during the last two minutes of measurement using the least-square method. Also, a linearity test was applied following the approach of Aguilos *et al*. (2013) to control the quality of dC/dt.

Soil CO_2 efflux was measured in three plots at distances of 20 m, 40 m and 60 m from a drainage canal. Within each plot, chambers were installed at positions ‘near’ and ‘far’ which were 1 m and 3 m, respectively, from tree bases (Figure 1). Data from the ‘near’ (1 m) position indicated total soil respiration (SR) and data from the ‘far’ (3 m) position (where there were no palm roots in the chamber bases) corresponded to peat decomposition (PD) (Dariah *et al*. 2014, Ishikura *et al*. 2018, Manning *et al*. 2019). The ‘near’ position is also known as ‘root circle’ (RC) in oil palm plantation management. To estimate the effect of plantation management, ‘far’ bases were installed in frond stacks (FS) and harvesting paths (HP). Thus, there were three chamber bases per plot, in ‘near’ (RC) and ‘far’ (FS and HP) positions. Before each monthly measurement, palm litter and pruned fronds were removed from the RC and HP chamber bases to exclude CO_2 emissions through pruned frond decomposition. Thus, the difference between CO_2 fluxes in ‘near’ and ‘far’ positions (SR - PD) is equivalent to root respiration (RR). Annual SR and PD (as C, Mg ha^{-1} yr^{-1}) were calculated from the means of monthly measurements (g m^{-2} d^{-1}).

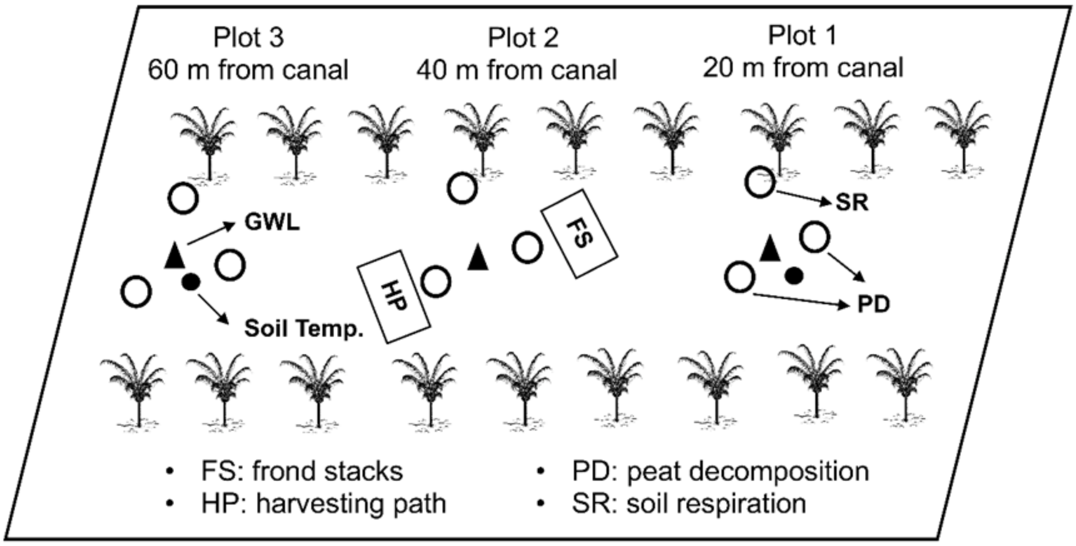

Figure 1. Arrangement of plots, chamber bases and other instruments in relation to plantation trees.

Measurement of CO_2 emissions arising from pruned frond (litter) decomposition (LD)

To measure the litter decomposition directly, old fronds (frond numbers 40–48) were cut from the trees and inserted (fresh) into litter bags of dimensions 40 cm × 80 cm, made from plastic mosquito netting with a mesh size of 2 mm. After collection, each frond was immediately separated into two parts (tip and base) to achieve a manageable size, and the fresh weight of each frond portion was recorded. In total, 24 bags of frond tips and 24 bags of frond bases, each containing about 800 g of plant material, were prepared and set on the top of frond stacks around the appropriate chamber bases in September 2018. Six bags were retrieved every two months (in November 2018, January 2019, March 2019, May 2019, July 2019, September 2019, November 2019 and January 2020). After retrieval, each litter bag was cleaned to remove soil and litter particles, then (initially) dry weight and C content were measured for each sample. C content was not measured after July 2019 because it had remained almost the same from November 2018 to July 2019; therefore, frond C content was assumed to be constant. Also, initial values of dry weight and C content of leaves and rachises were measured at the beginning (n = 3). Dry weight was measured by oven drying at 70 °C for 48 hours, and C content was determined by the loss of ignition (LoI) method with a conversion factor of 0.58 from organic matter to organic C (Agus *et al*. 2011).

The decomposition rate constant (k) was estimated by fitting a negative exponential equation to the relationship between the quotient of residual to original C amount and elapsed time (Equation 2, Moradi *et al.* 2014):

$$Y = Y_0 \exp(-kt) \qquad [2]$$

where Y is the residual ratio of carbon amount at time t (year) and Y_0 is the initial amount of carbon. C loss through frond decomposition was estimated using the k value and initial C amount with an assumption that only oxidative decomposition occurred. Then, the annual area-based CO_2 emission due to frond decomposition was calculated from the monthly emission and pruned frond production rates.

Measurement of net primary production (NPP)

NPP (Mg ha^{-1} yr^{-1}) was defined as the C content of biomass production, equal to the sum of above- and below-ground NPP (ANPP and BNPP) (Kotowska *et al*. 2016). ANPP consisted of tree canopy (trunks and attached fronds), pruned fronds, and fruit bunch production. BNPP was calculated from coarse and fine root biomass production. Tree canopy NPP was assessed as the difference in biomass between August 2018 and July 2019 of 30 trees, which corresponds to 20 % of the tree density per ha. Tree canopy biomass (Mg tree^{-1}) was calculated from tree height, using an allometric equation (Khasanah *et al*. 2015):

$$\text{Canopy biomass} = 0.0939 \times H + 0.0951 \qquad [3]$$

where H (m) is the vertical distance from ground level to the base of the lowest frond (Khasanah *et al*. 2015).

Annual fruit bunch NPP was calculated from the farmer's records using a dry weight of 50 % and a C content of 57.7 % (Wakhid *et al*. unpublished data). In oil palm plantation common practice, a frond attached just below the fruit bunch is usually pruned and stacked on the soil surface during fruit harvesting to recycle nutrients. However, there was little fruit production at this site because the oil palm trees were young and still in the initial stage of fruit production. Therefore, the average pruned frond production from one tree was estimated to be one frond nearly bimonthly. The NPP of understorey vegetation was calculated as the difference between maximum and minimum biomass of each sampling following Scurlock *et al*. (2002). The biomass of understorey vegetation was sampled in September 2018, February 2019 and June 2019, from three quadrats (0.5 m × 0.5 m) in three management areas (RC, FS, HP; nine quadrats in total).

Coarse root NPP was calculated as an annual biomass increase. Coarse root biomass (including trunk bases; Mg ha^{-1}) was calculated following the approach of Syahrinudin (2005; Equation 4):

$$\text{Coarse root biomass} = 1.45 \times \text{palm age} + 9.88 \qquad [4]$$

However, the biomass was scaled with a factor of 1.05 (147 / 140) because that Equation 4 was developed for an oil palm plantation on mineral soil with a density of 140 trees ha^{-1}. In the calculation of coarse root NPP, the value used for C content (56.7 %) was actually derived for fine roots of oil palm (Wakhid *et al*. unpublished data).

Fine root (≤ 2 mm in diameter) NPP was calculated as the sum of fine root production estimated using the simplified decision matrix method (Yuan & Chen 2013). Fine root biomass was sampled by sequential soil coring (depth 0–30 cm, using an auger 2.54 cm in diameter) conducted bimonthly in September 2018, November 2018, January 2019, March 2019, May 2019 and July 2019 near three trees at different distances from the canal (Figure 1). Soil cores were collected at 1, 2 and 3 m distance from the tree base in four directions for each tree (in total, 12 soil core samples for each tree). Soil cores were stored in plastic bags, then washed and separated into living (biomass) and dead (necromass) material by visual inspection (Makkonen & Helmisaari 1999). The fine roots of oil palm trees were distinguished from roots of understorey vegetation by their colour and shape (Leuschner *et al*. 2009).

Measurement of soil environmental factors

Precipitation was measured about 5 km distant from the study site (BMKG, South Kalimantan). GWL (relative to ground level) was measured manually once a month in conjunction with the soil CO_2 efflux measurements, in a vertical perforated PVC pipe inserted deep into mineral soil at each of the three plots. GWL was also measured using automatic sensors, but only from September 2018 to September 2019 because two sensors broke and one was stolen (data not shown here). Soil temperature was recorded hourly using two temperature data loggers (Thermochron SL type, KN laboratories, Osaka, Japan) installed at 5 cm depth in Plots 1 and 3, near the pipes for GWL measurement. Unfortunately, the soil temperature sensors malfunctioned in July 2019, and this resulted in no soil temperature data being recorded for two months (July and August) of that year.

To analyse soil C and N contents, nine peat samples (0–30 cm) were collected in September 2018, at three management areas (RC, HP, FS). The depth range was chosen because it encompasses the soil layer where fine roots are concentrated, according to literature (Syahrinudin 2005). C content was determined by the LOI method with a conversion factor of 0.58 from organic matter to organic C (Agus *et al.* 2011). N content was measured by the Kjeldahl technique. Bulk density (BD) was estimated using a gravimetric method in the laboratory. Peat samples for BD were collected at depths of 0–50, 50–100, 100–150 and 150–200 cm in the dry season (August 2018) when the groundwater level (GWL; relative to ground level) was below -1m using a peat auger (Eijkelkamp, Netherlands), following Agus *et al.* (2011) because the peat soil maturity was low.

Data analysis

Differences among treatments or components were analysed using analysis of variance, and specific differences among groups were analysed using Tukey's multiple comparison test. The correlation between soil CO_2 efflux rate and environmental factors was analysed using linear regression and the Pearson correlation method. Data analysis was conducted using Excel and R software (R Development Core Team 2019, version 3.5.3).

RESULTS

Soil environmental factors

The precipitation, soil temperature and GWL data are shown in Figure 2. Based on the criterion of monthly precipitation less than 100 mm (Malhi *et al*. 2002, Hirano *et al.* 2015), the 2019 dry season lasted from June through October (Figure 2a). Mean daily soil temperatures ranged from 26 °C to 33 °C in Plot 1 and from 27 °C to 32 °C in Plot 3 during the flux measurement period. Mean annual GWL was -0.74 m, and GWL varied seasonally between -0.39 and -1.28 m (Figure 2c). GWL followed the seasonal variation in

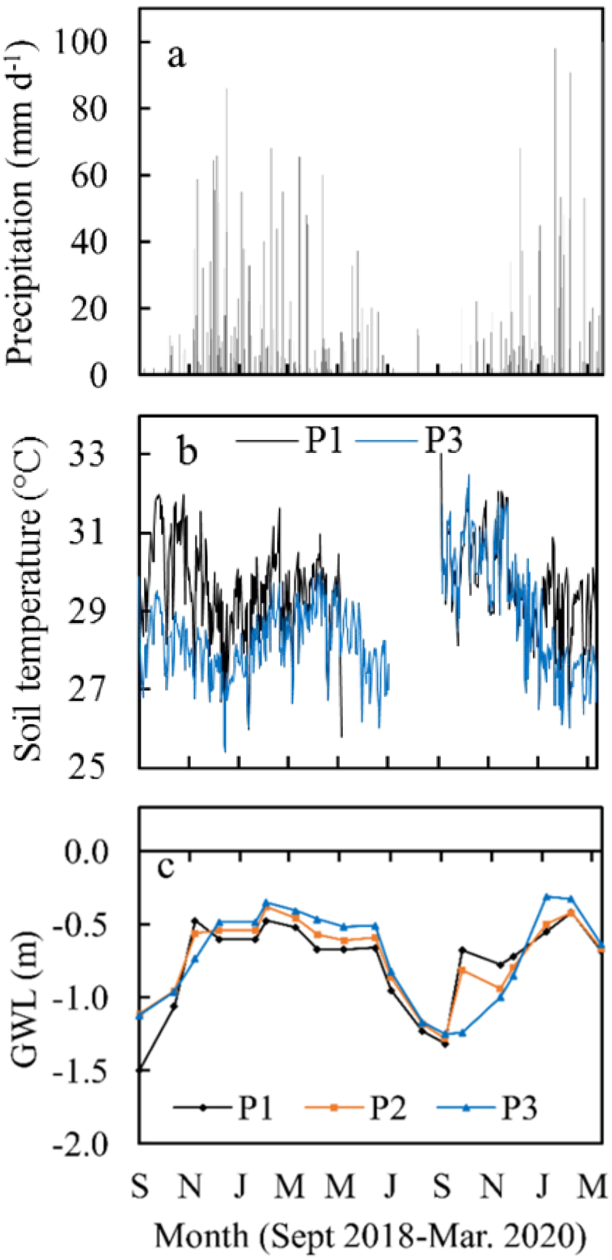

Figure 2. Variations in daily values (September 2018 to March 2020) of (a) precipitation and (b) soil temperature in Plots 1 and 3, and (c) groundwater level (GWL) from monthly manual measurements in Plots 1, 2 and 3.

precipitation; it was high (closest to, but still below, the ground surface) from November to June and declined from July to September (Figures 2a, 2c). Soil C content was not significantly different among the three management zones RC, FS and HP ($p > 0.05$; Table 1). Mean BD from the three plots was 0.14 ± 0.04, 0.12 ± 0.04, 0.11 ± 0.03 and 0.17 ± 0.05 g cm^{-3} at depths of 0–50, 50–100, 100–150 and 150–200 cm, respectively ($n = 3$).

Soil CO_2 efflux

In total, 96 % of the CO_2 efflux data were still available after quality control. Mean SR was generally higher when GWL was lower (Figures 2c, 3a) and even showed slight seasonal variation, ranging from 4.0 µmol m^{-2} s^{-1} in June 2019 to 10.6 µmol m^{-2} s^{-1} in September 2018. Vague seasonal variation was also found in PD and RR (Figures 3b, 3c). The highest SR, PD and RR were measured in September 2018, which was the month with the lowest GWL observed during the period of CO_2 efflux measurements in 2018–2020 (-1.24 and -1.28 m, respectively; Figures 2c, 3). Mean SR from three plots was significantly greater ($p < 0.001$) than the mean values of PDFS and PDHP (Table 2), although there was no significant difference between PDFS and PDHP ($p > 0.05$).

PD showed a significant relationship with GWL ($p < 0.05$, $r^2 = 0.34$, Figure 4) in FS and HP but not in SR. There was no significant relationship between PD or SR and soil temperature ($p > 0.05$, data not shown). Annual SR and PD were estimated as means of monthly measurements because their seasonal variations were small (Figure 3). Annual SR (as C) was estimated at 23.1 Mg ha^{-1} yr^{-1}, while annual mean PD in FS and HP was 15.4 Mg ha^{-1} yr^{-1}. The difference between SR and PD was 7.70 Mg ha^{-1} yr^{-1}, which almost corresponds to annual root respiration (RR). PD accounted for 67 % of SR on an annual basis.

CO_2 emission by pruned frond decomposition (LD)

The average dry weight of whole pruned fronds was 1539 ± 298 g frond^{-1}, and C content averaged 863 ± 167 g frond^{-1} (mean ± 1 SD, $n = 5$). The temporal pattern of C loss through pruned frond decomposition followed a negative exponential curve (Figure 5) with a frond decomposition rate constant (k) of 1.41 yr^{-1}. Using this k value, the pruned frond was estimated to become 90 % decomposed in 1.67 years. Annual C input to the litter of the plantation from pruned fronds was 0.76 Mg ha^{-1} yr^{-1}, calculated as the annual input of pruned fronds (6 fronds tree^{-1} yr^{-1}) × dry weight (1539 g frond^{-1}) × C content (55.4 %) × tree density (147 trees ha^{-1}); whereas the annual CO_2 emission through frond decomposition was estimated to be 0.38 Mg ha^{-1} yr^{-1}.

Net primary production (NPP)

Annual total NPP (as C) was estimated to be 10.9 Mg ha^{-1} yr^{-1} (Table 3), which was dominated by ANPP (8.51 Mg ha^{-1} yr^{-1}, 78 %). Because the rate of fruit production was small in this young plantation, the greatest contribution to NPP was tree canopy production (49 %), followed by fruit bunch production (16 %). Annual BNPP (as C) was 2.40 Mg ha^{-1} yr^{-1}, of which fine root production accounted for 64 %.

Table 1. Main characteristics of peat (mean ± SD, *n* = 3): bulk density (BD), carbon (C) and nitrogen (N).

Management zone	BD (g cm^{-3})	C content (%)	N content (%)	C/N
Root circle (RC)	0–50 cm: 0.14 ± 0.04,	48.5 ± 2.62	1.24 ± 0.39	43.1 ± 18.9
Harvesting path (HP)	50–100 cm: 0.12 ± 0.04, 100–150 cm: 0.11 ± 0.03,	50.0 ± 0.18	0.81 ± 0.10	62.1 ± 8.10
Frond stack (FS)	150-200 cm: 0.17 ± 0.05	45.9 ± 5.56	1.01 ± 0.22	45.9 ± 4.25
ANOVA (*P* value) for area		0.43	0.23	0.20

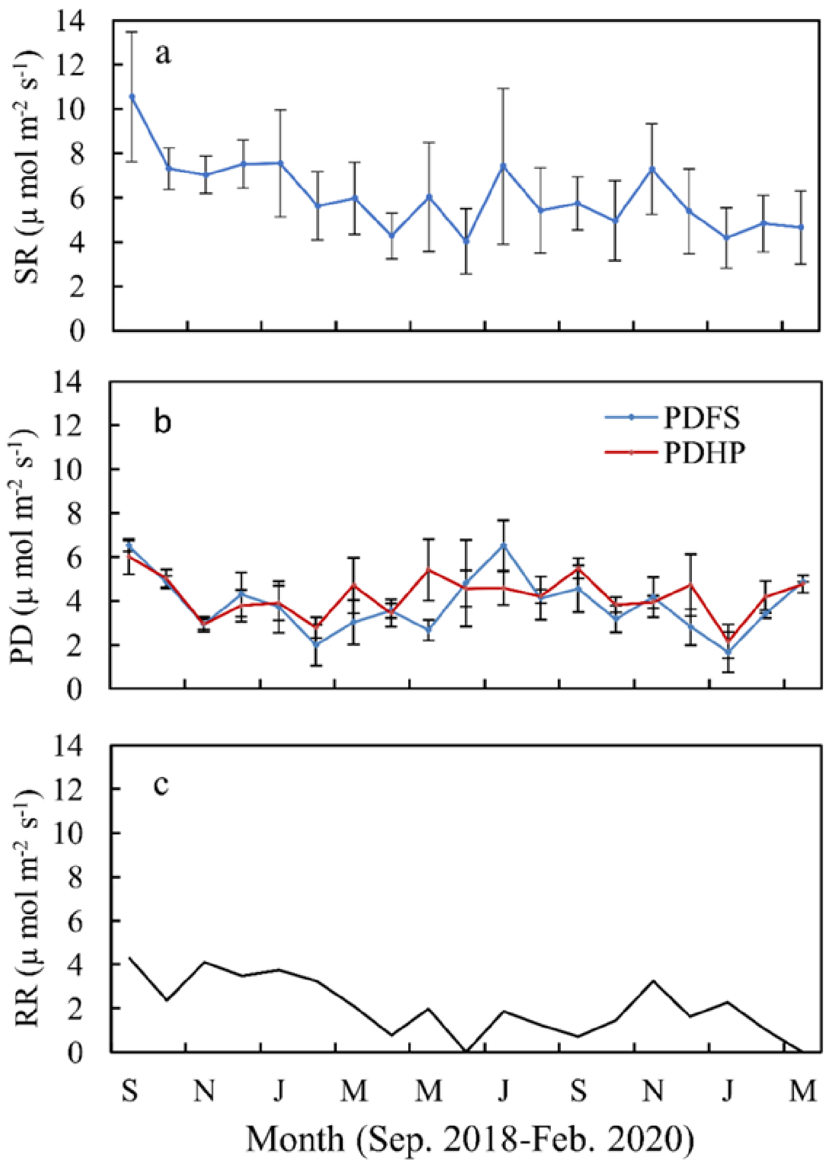

Figure 3. Mean seasonal variations in (a) total soil respiration (SR, in the root circle (RC) near the tree base, *n* = 3), (b) peat decomposition in the frond stack (PDFS) and in the harvesting path (PDHP) (*n* = 3), and (c) residual between means of SR and PD that corresponds to root respiration (RR), from September 2018 to March 2020. Vertical bars denote one standard error (SE).

Table 2. Mean soil CO_2 efflux at different management areas (mean ± SD; n = 3) from September 2018 to March 2020. Different letters denote significant difference ($P < 0.05$) between management areas (RC, FS, HP) according to Tukey HSD test following ANOVA.

Position on the management areas	CO_2 efflux (μmol m^{-2} s^{-1})	Annual C emission (as CO_2), derived from mean efflux (Mg ha^{-1} yr^{-1})
Near the tree base in the root circle (RC): corresponding to SR	5.09 ± 1.62a	23.1 ± 6.13
Far from the tree base in the frond stack (PDFS): corresponding to PD	3.88 ± 1.31b	14.7 ± 4.98
Far from the tree base in the harvesting path (PDHP): corresponding to PD	4.24 ± 0.97b	16.1 ± 3.69
Mean PD		15.4 ± 4.37
Residual: corresponding to RR		7.70 (33 % of SR)

DISCUSSION

Annual soil CO_2 emissions were calculated by averaging periodic CO_2 flux measurements using data for more than one year because the seasonal variation of CO_2 efflux was small. The annual PD (as C) of 15.4 Mg ha^{-1} yr^{-1} was in the range of the IPCC default CO_2 emission factor for oil palm plantation on tropical peat (11.0 Mg ha^{-1} yr^{-1} with 95 % confidence intervals or 5.60–17.0 Mg ha^{-1} yr^{-1}; IPCC 2014). PD was larger at this site than in young oil palm plantations on peat in Sarawak, Malaysia (4 years old, 6.93 Mg ha^{-1} yr^{-1}, GWL -0.58 m; method: root exclusion; Melling *et al.* 2013) and in the Indonesian provinces of Jambi (6 years old, 10.4 Mg ha^{-1} yr^{-1}, GWL -0.52 m; method: far from tree base; Dariah *et al.* 2014) and Central Kalimantan (6 years old, 8.40 Mg ha^{-1} yr^{-1}, GWL -0.34 to -0.45 m; method: root trenching; Hergoualc'h *et al.* 2017). The larger PD in our study may have been caused by the lower GWL (mean value -0.74 m). PD accounted for 67 % of SR (23.1 ± 6.13 Mg ha^{-1} yr^{-1}) on an annual basis (Table 2). The contribution of PD was similar to that observed by Hergoualc'h *et al.* (2017; 61 % of 13.8 ± 0.3 Mg ha^{-1} yr^{-1}) but lower than reported by Dariah *et al.* (2014; 86 % of 12.2 ± 3.05 Mg ha^{-1} yr^{-1}) and higher than stated by Melling *et al.* (2013; 38 % of 18.1 ± 1.98 Mg ha^{-1} yr^{-1}). RR in our site (7.70 Mg ha^{-1} yr^{-1}, BD: 0.14 g cm^{-3}) was higher than previously reported RR values (1.78 Mg ha^{-1} yr^{-1}, BD: 0.19 g cm^{-3}, Dariah *et al.* 2014; 3.60–5.40 Mg ha^{-1} yr^{-1}, BD: 0.32 g cm^{-3}, Hergoualc'h *et al.* 2017) for young oil palm plantations in Jambi and Central Kalimantan, respectively, but lower than for young oil palm plantation in Sarawak (11.2 Mg ha^{-1} yr^{-1}; Melling *et al.* 2013). The peat soil density in the latter site probably contributed to the low RR by suppressing root development (Melling *et al.* 2013). This comparison of results emphasises that available data for CO_2 emission rates on tropical peatlands are

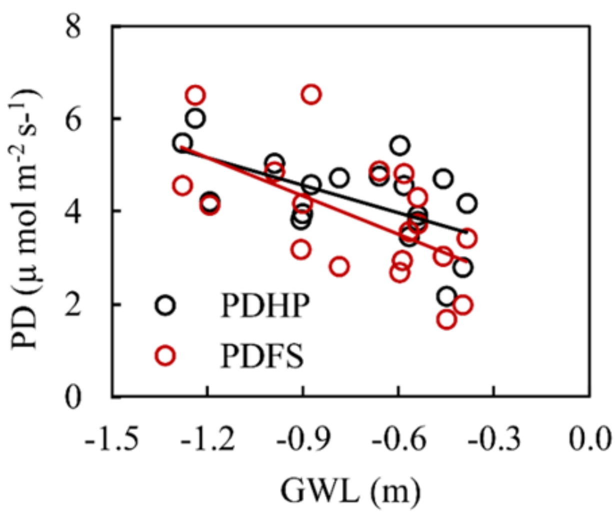

Figure 4. Relationship between peat decomposition (PD) and groundwater level (GWL) on different management areas: peat decomposition in the harvesting path (PDHP, black circle) and peat decomposition in the frond stack (PDFS, red circle). Each symbol denotes an average of 3 plots (n = 3). A line is fitted for each management area ($p < 0.01$). PDHP (black line): $y = -1.99x + 2.77$ ($r^2 = 0.34$), and PDFS (red line): $y = -2.78x + 1.84$ ($r^2 = 0.36$).

varied owing to the high variation in chemical, physical, and biological properties of the peat soil as well as the differences in research methods.

GWL has been reported to mainly control PD under various land uses on tropical peatland (Acacia, Jauhiainen *et al.* 2012; Forest, Itoh *et al.* 2017; Oil Palm, Ishikura *et al.* 2018). Similarly, in our site, a significant negative relationship between PD and GWL was found even with a low coefficient of determination (Figure 4). On the other hand, SR was not significantly correlated with GWL. It is likely that the lack of a significant relationship between SR and GWL was due to the small seasonal variation of RR, calculated as the difference of SR and PD. Moreover, there was no significant relationship between soil temperature and SR or PD. The weak relationship to soil temperature might be due to the

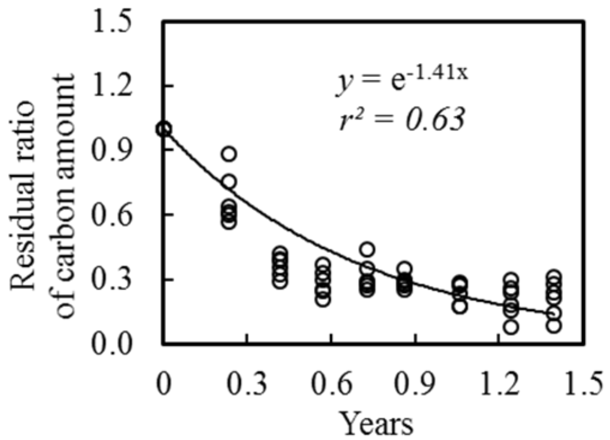

Figure 5. Pattern of C loss from pruned fronds.

small amplitude of soil temperature fluctuations, on both a daily (Wakhid *et al*. 2017) and an annual (Figure 2b) basis, in the tropical environment. SR was significantly higher than PD in both positions, which suggests that the contribution of RR to PD was minor. This is in line with the results of previous studies in oil palm plantations on peat soil, which found that RR far from tree bases was mostly negligible (Dariah *et al.* 2014, Ishikura *et al.* 2018, Manning *et al.* 2019).

The C loss by CO_2 emission through pruned frond decomposition (LD) was estimated to be 0.38 Mg ha^{-1} yr^{-1}, which contributed 2.4 % of PD. No results for comparison were found because most previous studies in forests or plantations did not assess emissions arising from PD and LD for separate land uses. LD depended on the *k* value and frond production. The *k* value in this site (1.41) was lower than that in an oil palm plantation on mineral soil in Malaysia (1.80 yr^{-1}; Moradi *et al.* 2014) where, commonly, the fronds were pruned and stacked on the soil surface during fruit harvesting or other irregular pruning, to recycle the nutrients. Therefore, pruned frond production probably differed between the plantations depending on the farmers' activity.

NPP in this study (10.9 Mg ha^{-1} yr^{-1}) was lower than the value estimated using a model for a 5-year-old oil palm plantation on peat soil in Malaysia (12.0 Mg ha^{-1} yr^{-1}) by Melling *et al.* (2008). The site of Melling *et al*. (2008) was an industrial plantation, and differences between industrial and smallholder management practice most probably played a role in this discrepancy. Our NPP was also lower than in mature oil palm plantations on mineral soil in Jambi

Table 3. Net primary production (NPP) in terms of biomass and carbon.

Components		NPP based on biomass (Mg ha^{-1} yr^{-1})	NPP based on carbon (Mg ha^{-1}yr^{-1})
Above-ground NPP (ANPP)	tree canopy	9.29	5.30
	pruned frond	1.36	0.76
	fruit bunch	3.00	1.73
	understorey vegetation	1.34	0.72
	Total	*15.0*	*8.51*
Below-ground NPP (BNPP)	coarse root	1.52	0.86
	fine root	2.70	1.53
	Total	*4.23*	*2.40*
Total NPP	(ANPP + BNPP)	19.2	10.9

(17.3 and 15.1 Mg ha^{-1} yr^{-1}; Kotowska *et al*. 2015). However, our result was much higher than that obtained from 2–3 year old smallholder oil palm plantations on peat in Jambi (3.70 Mg ha^{-1} yr^{-1}) by Basuki *et al*. (2018), who did not measure the contribution to NPP from palm fruit because the plantations were immature. It is most likely that the NPP of oil palm plantations depends on the age of the oil palm trees, and mature oil palm plantations tend to have higher NPP than young plantations.

Heterotrophic respiration (HR) has been reported as a major agent of C loss and a key component of the soil C balance in tropical peatlands (Hergoualc'h & Verchot 2013). However, some studies have equated total soil respiration (SR) including root respiration (RR) with heterotrophic respiration (HR) or peat decomposition (PD) without measuring litter decomposition (LD) as a part of HR (Jauhiainen *et al*. 2012, Hergoualc'h & Verchot 2013, Hergoualc'h *et al*. 2017). In our study, HR (15.8 Mg ha^{-1} yr^{-1}) was estimated as the sum of PD and LD (15.4 + 0.38 Mg ha^{-1} yr^{-1}). The contribution of LD was small but would be larger for oil palm trees in their production growth phase. In a mature plantation the size and weight of a frond would be larger than in a young plantation. Also, the pruned frond production in a mature plantation would be higher than in a young plantation. Consequently, the contribution of LD is expected to be high in a mature plantation.

Carbon sequestration through NPP (10.9 Mg ha^{-1} yr^{-1}; Table 3) was lower than the C loss by soil CO_2 emissions through HR (15.8 Mg ha^{-1} yr^{-1}). Thus, our results show that the oil palm plantation at this site was a net C source of 4.86 Mg ha^{-1} yr^{-1} (= NPP - HR), i.e. it had a negative C balance. This finding is consistent even with the higher result reported by Melling *et al*. (2008) that a 5-year-old oil palm plantation in Malaysia was a net C source (2.01 Mg ha^{-1} yr^{-1}). The low NPP at our site was probably attributable in part to mortality but mostly to reduced canopy and fruit bunch biomass production due to plantation immaturity and, indeed, NPP is likely to be consistently lower than HR in young oil palm plantations. The leaning of trees in this plantation may also have played a role in suppressing the production of canopy and fruit bunch biomass. The C balance in this study might be different if C leaching via water discharge is considered. Cook *et al*. (2018) reported that the loss of dissolved organic C in the drainage waters of oil palm plantation areas on peat in Sarawak, Malaysia was in the range 0.31–0.52 Mg ha^{-1} yr^{-1}. To reduce uncertainty about soil CO_2 emissions and NPP in oil palm plantations, further field studies in oil palm plantations of different ages are necessary. Also, studies in industrial plantations on peat soil are needed, because industrial oil palm plantations potentially have higher NPP than smallholder plantations.

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AUTHOR CONTRIBUTIONS

The study design, field research, and data analysis were conducted by NW under the supervision of TH. NW wrote the draft manuscript and TH provided significant comments and suggestions during the writing and editing.

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