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ORIGINAL ARTICLE

Greenhouse gas emissions in restored secondary tropical peat swamp forests

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Abstract Restoration of deforested and drained tropical peat swamp forests is globally relevant in the context of reducing emissions from deforestation and forest degradation. The seasonal flux of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) in a restoration concession in Central Kalimantan, Indonesia, was measured in the two contrasting land covers: shrubs and secondary forests growing on peatlands. We found that land covers had high, but insignificantly different, soil carbon stocks of 949 + 56 and 1126 + 147 Mg ha^{-1}, respectively. The mean annual CO_2 flux from the soil of shrub areas was 52.4 ± 4.1 Mg ha^{-1} year^{-1}, and from secondary peat swamp forests was 42.9 ± 3.6 Mg ha^{-1} year^{-1}. The significant difference in mean soil temperature in the shrubs (31.2 °C) and secondary peat swamp forests (26.3 °C) was responsible for the difference in total CO_2 fluxes of these sites. We also found the mean annual total soil respiration was almost equally partitioned between heterotrophic respiration (20.8 + 1.3 Mg ha^{-1} year^{-1}) and autotrophic respiration (22.6 + 1.5 Mg ha^{-1} year^{-1}). Lowered ground water level up to − 40 cm in both land covers caused the increase of CO_2 fluxes to 40–75%. These numbers contribute to the provision of emission factors for rewetted organic soils required in the national reporting using the 2013 Supplement of the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for wetlands as part of the obligation under the United Nations Framework Convention on Climate Change (UNFCCC).

Keywords Emission factors · REDD+ · Ground water level · Microbial biomass · Spatial variability

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1 Introduction

Peatlands are disproportionately important for the world's climate system. The area of peatlands is only 3–5% of the Earth's surface, but peatlands store more than 30% of soil carbon worldwide. Recent studies indicate that, globally, peatlands cover an area as much as three times larger than previously thought (Gumbricht et al. 2017). The study also showed that Indonesia houses more than 22 million ha of peatlands. These ecosystems store 75 Gt C of carbon (Warren et al. 2017), about 30% more carbon than the entire Indonesian forest biomass. The large amounts of carbon stored in these ecosystems bring peatlands to international attention as a potential means of climate change mitigation and adaptation.

Peat swamp forests may be considered as disturbed when they have alternating vegetation cover (structure and composition) due to logging, deforestation, and draining (the latter often followed by burning). These processes lead to the emission of greenhouse gases (GHGs). In Southeast Asia, mostly in Indonesia, such processes have occurred since the mid-1980s. Between 1990 and 2010, Southeast Asia lost an estimated 40% of its peat swamp forests (Miettinen et al., 2012). This turned the ecosystems from sinks to sources of GHGs (Miettinen et al., 2017).

The main source of water inundating peat swamp forests in Indonesia, including Sumatra and Kalimantan, is rainfall. Therefore, Indonesian peat swamp forests are categorized as ombrotrophic (rainfed) rather than minerotrophic peatlands (fed by runoff or ground water) (Lähteenoja et al. 2009, 2011). The drainage of ombrotrophic peat has significant effects on the exposure of upper peat layers to oxygen, leading to elevated decomposition rate and net soil carbon loss.

Most deforestation in the peat swamp forests of Sumatra and Kalimantan is followed by the extensive draining of land to establish pulpwood (*Acacia crassicarpa*) and agriculture development, especially oil palm (*Elaeis guineensis*) plantations. Substantial information on the effect of draining peatlands suggests that CO_2 emissions are positively correlated with ground water level. Moreover, total CO_2 emissions are partitioned into heterotrophic and autotrophic respiration. It has been demonstrated that heterotrophic respiration dominates (up to 82%) the total respiration from peat swamp (Carlson et al. 2015).

In five–six-year-old oil palm plantations in Jambi province in central Sumatra, where ground water levels ranged between 56 and 91 cm, total respiration varied between 12 and 36 Mg CO_2 ha^{-1} $year^{-1}$, of which between 10 and 31 Mg CO_2 ha^{-1} $year^{-1}$ was heterotrophic respiration (Comeau et al. 2013; Dariah et al. 2014). In neighboring Riau province, the total respiration of young (around one-year-old) drained pulpwood plantations with ground water levels of 45–108 cm was 17–42 Mg CO_2 ha^{-1} $year^{-1}$ and heterotrophic respiration was 19–38 Mg CO_2 ha^{-1} $year^{-1}$ (Jauhiainen et al. 2012). The Intergovernmental Panel on Climate Change (IPCC) methodology for national greenhouse gas inventories has adopted this information as emission factors (Hiraishi et al. 2014).

Rewetting is the process of changing a drained soil into a wet soil by blocking artificial draining canals and ditches. The effects of rewetting organic soils like peat are not exactly the opposite when they were drained both of physical and chemical properties. However, information is lacking on the effects on emissions of GHGs of rewetting degraded tropical peatlands (IPCC 2014). Rewetting will certainly increase the opportunity for peat soils to develop anoxic environments that may activate methanogen bacteria. As a result, methane may be produced and emitted; the extent of this needs to be quantified. Likewise, nitrification and denitrification bacteria may also be affected in inundated peatlands. However, only limited data are available on tropical peat GHG fluxes and their biological controls (Chimner 2004).

The current study, conducted in Katingan Regency, Central Kalimantan Province, was designed to quantify the effects of rewetting on levels of GHG emissions. Although land cover type is not a good predictor of total emissions, the root environments of different vegetation covers affect root respiration while the vegetation continues to grow. Emissions from two contrasting vegetation covers, namely secondary peat swamp forests and shrubs, were compared when canals were blocked. This information is needed to respond to the opportunity of generating carbon benefits in restored peatlands from international mechanisms such as reducing emissions from deforestation and forest degradation, known as REDD+ (Murdiyarso et al. 2010). Other ancillary parameters, such as soil temperature, ground water level, and microbial biomass, were measured and discussed in the context of their effects on the rate of GHG emissions.

2 Materials and methods

2.1 The site

The Katingan project site (2° 32′ 37″ S, 3° 01′ 44″ S and 113° 00′ 40″, 113°18′57″ E) is one of peatland restoration projects in Central Kalimantan, Indonesia. The 108,000 ha peatland site forms a dome between two large rivers—the Mentaya in the west and the Katingan in the east (Fig. 1). Most of the area was logged in the late 1980s and early 1990s. This process formed cleared areas and patches of secondary peat swamp forests with the disturbance gradient depending on the distance from the main rivers and canals. Canals were established to transport logs and drain part of the area for agriculture.

In early 2013, the artificial drainage at these sites was blocked and the ground water table was left to fluctuate naturally. Flux of GHGs and the ancillary data were collected from May and August 2014 across parts of the wet and dry seasons.

The area is part of the coastal peatlands with peat depth ranging from less than 1 m to more than 12 m in the middle of the peat dome. The peat is ombrotrophic and exposed to a mean annual rainfall of 3016 mm. The area's monsoonal rainfall pattern (with an inter-tropical convergence effect) has peaks in April and December, while August is the driest month. Surface water availability affects monthly evaporation patterns with a monthly mean of 137 mm. The mean monthly temperature of 26 °C fluctuates only slightly throughout the year (Fig. 2).

Simulated carbon dating suggests that the peat has accumulated over the past 1500–6000 years (Dommain et al. 2011). The peat drainage that took place during logging operations in the 1980s may have reduced the emissions of carbon stored over such a long period. Although we did not measure it, lateral flux to the Java Sea is very possible and takes the form of dissolved organic carbon in a large volume (Abrams et al. 2016). The blocking of the canals was expected to have increased the ground water level. This, in turn, was likely to have reduced the lateral flux of dissolved organic carbon and even the mineralized compound, (dissolved inorganic carbon) from the sources.

2.2 Carbon stocks and greenhouse gas fluxes

Measurement sites for assessing carbon stocks, GHG flux, and ground water level were set up in the shrubs and logged-over or secondary peat swamp forests in May and August 2014. Two of the sampling sites were in shrub areas and five in the secondary peat swamp forests (see Fig. 1). The sampling scheme is summarized in Table 1.

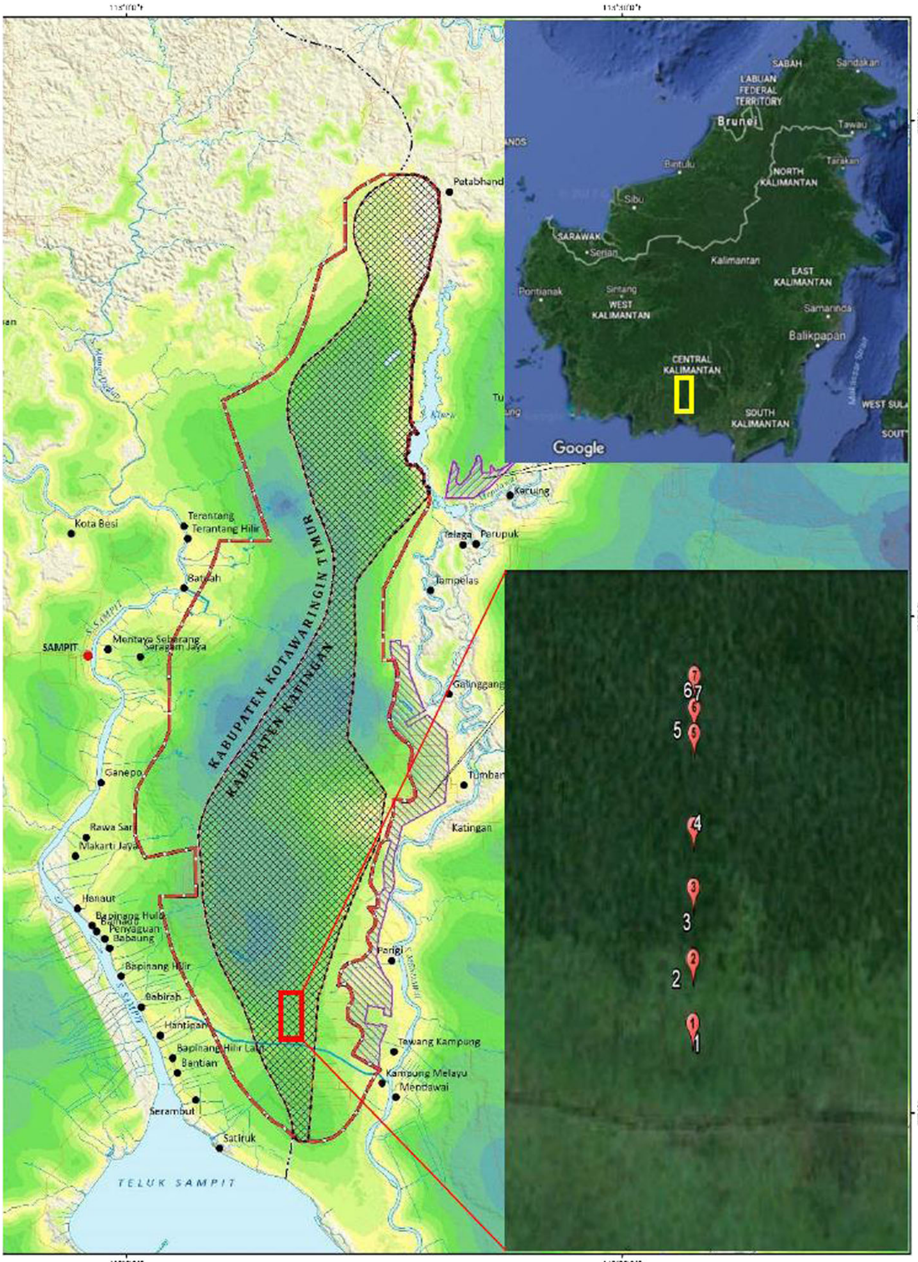

Fig. 1 The study site in the Katingan Project area in Katingan Regency, Central Kalimantan Province, Indonesia. It covers an area of 108,000 ha (within the dashed lines) of disturbed dome-forming peat swamp forest (PSF) between the Mentaya River in the west and Katingan River in the east. A transect was established in the southern part of the project site with seven plots

Carbon stocks of the shrub sites were estimated from 10 × 10 m^2 sites ($n = 2$). The carbon stocks of the secondary peat swamp forest sites were assessed in 20 × 20 m^2 sites ($n = 5$). The diameters of all trees and saplings were measured, with seedling diameters only measured in 10 × 10 m^2 sub-sites. Allometric equations (e.g., Manuri et al. 2014) were adopted to convert diameters into biomass and eventually carbon densities.

Following Kauffman et al. (2016), soil samples were collected by coring the soil at intervals of 0–15, 15–30, 30–50, 50–100, and 100–300 cm. The carbon content was determined using Elemental CNS Analyzer (Leco™).

CO_2 fluxes were measured directly using a portable infrared gas analyzer, IRGA (EGM™), while CH_4 and N_2O were measured by air sampling using the closed chamber method combined with gas chromatography (GC). The first samplings were taken in May and August 2014 to differentiate greenhouse gas flux rates between shrubs and secondary peat swamp forests land cover.

The second measurements focused on separating the heterotrophic respiration from the total respiration in the secondary peat swamp forest sites took place almost in the same period of 2014 (June and August 2015). The 1 × 1-m^2 plots were trenched by digging very narrow and deep ditches to separate peat soil from respiring roots. To ensure isolation, the fine wire mesh (4 × 4 mm^2) was inserted in the ditch and buried. Autotrophic respiration was calculated by deducting total respiration from heterotrophic respiration. Trenching was not carried out in the shrub sites where only total respiration was assessed.

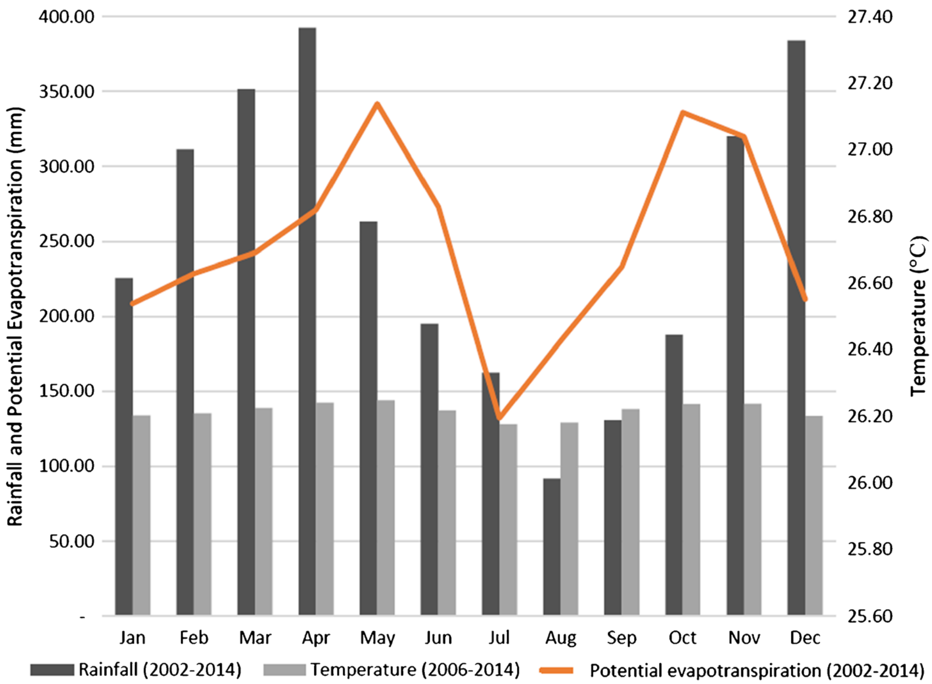

Fig. 2 Rainfall pattern at the study sites. The site has rainfall peaks in April and December and relatively constant temperatures throughout the year

Table 1 Sampling scheme in the shrubs and secondary peat swamp forests to assess carbon stocks, greenhouse gas fluxes, and ground water level

Sampling point	Land cover	Biomass C stocks	Peat depth	CO_2 flux (IRGA)	CH_4 and N_2O flux (GC)	CO_2 incubator	Ground water level
1	Shrubs	10×10 m^2	320 cm $n = 6$	Untrenched $n = 8$	Air samples $n = 4$	$n = 3$	Logger
2	Shrubs	10×10 m^2	400 cm $n = 6$	Untrenched $n = 8$	Air samples $n = 4$	$n = 3$	Logger
3	Secondary peat swamp forests	20×20 m^2	400 cm $n = 6$	Trenched $n = 4$ Untrenched $n = 4$	Air samples $n = 4$	$n = 3$	Logger
4	Secondary peat swamp forests	20×20 m^2	380 cm $n = 6$	Trenched $n = 4$ Untrenched $n = 4$	Air samples $n = 4$	$n = 3$	Logger
5	Secondary peat swamp forests	20×20 m^2	380 cm $n = 6$	–	–	–	–
6	Secondary peat swamp forests	20×20 m^2	320 cm $n = 6$	–	–	–	–
7	Secondary peat swamp forests	20×20 m^2	400 cm $n = 6$	–	–	–	–

IRGA portable infrared gas analyzer, *GC* gas chromatography

2.3 Ground water level and hydraulic conductivity

Automatic water level data loggers, commonly known as divers (HOBO™), were installed in monitoring wells to record ground water levels at equilibrium conditions. The wells were made of 2 m-long PVC pipe with a diameter of 5 cm. Four wells were installed in a transect perpendicular to the river or contours with an interval of 500 m in sites 1, 2, 3, and 4. Two of the wells were located in the shrub areas and the other two in the secondary peat swamp forests.

A slug test estimated hydraulic conductivity. Following Bouwer and Rice (1976), hydraulic conductivity of the aquifer was determined from the rate of water-level increases in the monitoring wells after a certain volume of water was suddenly removed by "slug." The slugs were 50 cm lengths of 5 cm diameter PVC pipes filled with sand as ballast.

2.4 Microbial biomass

Using the plate count method, the microbial biomass affecting peat decomposition or biodegradation in the shrub and secondary peat swamp forest areas was quantified as colony-forming units of bacteria and fungi (Kim et al. 2012). The samples were collected from 0 to 10- and 10 to 20-cm layers at the two contrasting sites. Three replicates were made at each site and each layer. Five samples of 50 g were composited from each of the three replicates for laboratory analysis.

2.5 Effects of water-filled pore spaces

Laboratory incubation experiments were carried out to understand the effects of water-filled pore spaces (WFPS) on the emissions of CO_2. Undisturbed peat samples were collected from two shrub sites and two secondary peat swamp forest sites with three replicates at each site. The incubated samples were treated with four levels of WFPS (40, 60, 80, and 100%). Thus, 48 samples were collected for these incubation experiments.

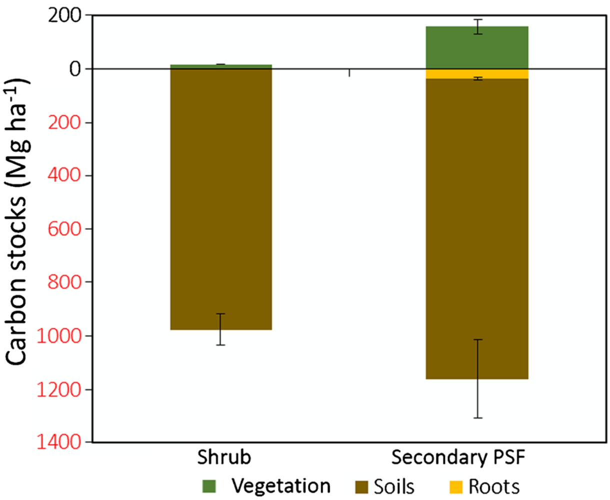

Fig. 3 Ecosystem carbon stocks in shrub and secondary peat swamp forest. Most carbon is stored in the soil although the above ground carbon has been removed

3 Results

3.1 Carbon stocks

Although the secondary peat swamp forest sites had been over-logged, the carbon stocks above the ground ranged between 132 and 333 Mg C ha^{-1}. This is relatively high compared with the carbon stocks from unlogged peat swamp forests in the neighboring Tanjung Puting National Park of 168 + 31 Mg C ha^{-1} (Novita, 2016). The clear-felled sites, however, had lost substantial above ground biomass carbon; remaining stocks had only 16.9 + 1.5 Mg C ha^{-1} as shrub biomass.

In contrast, logging seems to have not significantly changed the level of carbon stored in the soils (see Fig. 3). The mean carbon stocks in the shrub sites was 949 + 56 Mg C ha^{-1}, slightly lower than in the secondary peat swamp forest sites—1126 + 147 Mg C ha^{-1}.

3.2 Factors affecting daily and annual fluxes of greenhouse gas

Figure 4 shows the fluctuation of CO_2 over the months of May and August 2014. In general, the shrub sites had higher total soil CO_2 emissions than the secondary peat swamp forest sites. This was especially the case in the drier weather of August when soil temperatures were higher in the more open shrub areas compared to the more shaded peat swamp forest areas. This fluctuation in secondary peat swamp forests is slightly lower than in the shrub area. This is because the mean maximum soil temperature in the shrub areas (31.2 °C) was higher than shrub areas (26.3 °C).

The mean CO_2 fluxes in May were 448 + 112 mg m^{-2} h^{-1} in the shrub sites and 524 + 131 mg m^{-2} h^{-1} in the secondary peat swamp forests. In August, when air temperature was higher, they were 750 + 187 mg m^{-2} h^{-1} in the shrub sites and 456 + 114 mg m^{-2} h^{-1} in the

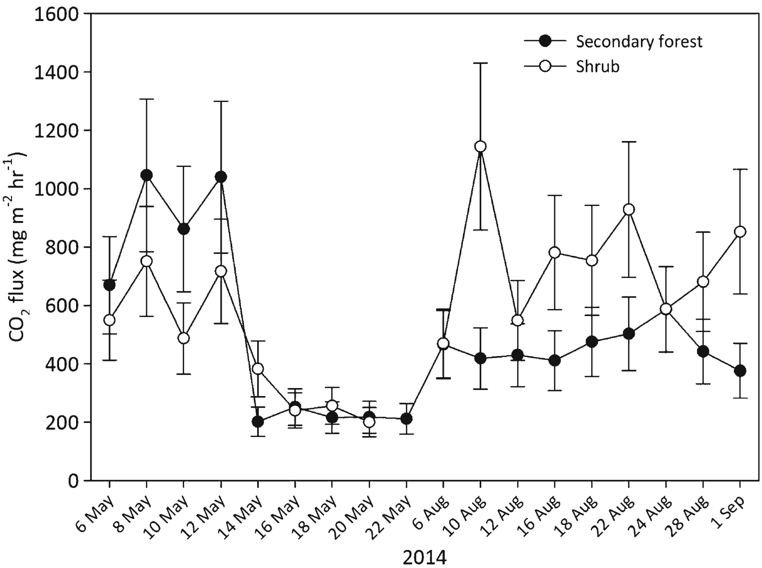

Fig. 4 The fluctuation of CO_2 in May and August 2014, representing wet and dry months, respectively. The relatively open shrub areas have higher fluxes of CO_2 than secondary peat swamp forests, which are more shaded

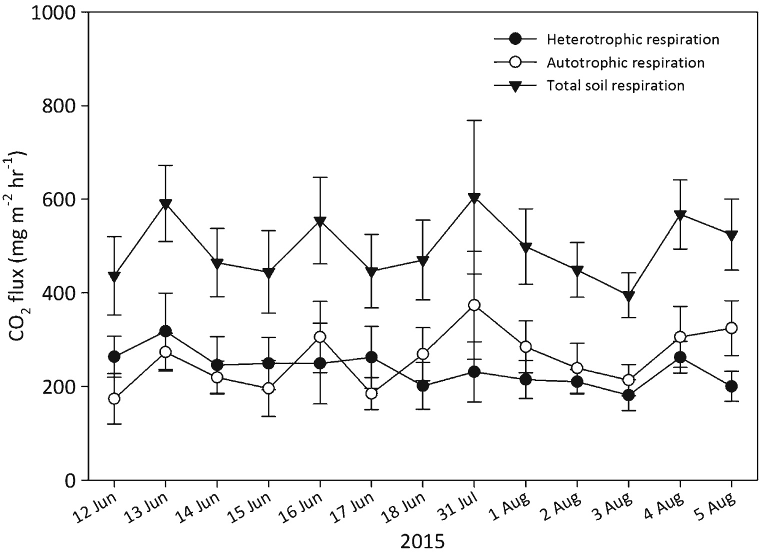

Fig. 5 Fluctuation of autotrophic, heterotrophic, and total respiration in June and August 2015. Throughout these months, the total respiration was almost equally partitioned between autotrophic and heterotrophic respiration

secondary peat swamp forest sites. If May and August represent wet and dry months, respectively, the mean annual fluxes of CO_2 would be 599 + 150 and 490 + 123 mg m^{-2} h^{-1} in shrub areas and in secondary peat swamp forests, respectively. These are equal to 52.4 ± 4.1 and 42.9 ± 3.6 Mg CO_2 ha^{-1} year^{-1} in shrub areas and in secondary peat swamp forests, respectively.

Table S2 summarizes the daily heterotrophic and autotrophic respiration in secondary peat swamp forests. Figure 5 shows the fluctuation of total, heterotrophic, and autotrophic respiration.

The mean seasonal flux was found to be 236 + 20 mg m^{-2} h^{-1} for heterotrophic and 261 + 24 mg m^{-2} h^{-1} for autotrophic respiration. On an annual basis, the total respiration of 43.4 ± 2.1 Mg CO_2 ha^{-1} year^{-1} was partitioned into heterotrophic respiration of 20.8 ± 1.3 Mg CO_2 ha^{-1} year^{-1} and autotrophic respiration of 22.6 ± 1.5 Mg CO_2 ha^{-1} year^{-1}. These suggest that the respiration rate in secondary peat swamp forests was almost equally partitioned between heterotrophic (48%) and autotrophic (52%) respiration.

On the non-CO_2 greenhouse gases (CH_4 and N_2O), following Tables S3 and S4, mean annual emissions of CH_4 in the secondary peat swamp forest sites were 21.44 + 7.46 kg ha^{-1} year^{-1}, while in the shrub sites they were 39.55 + 15.02 kg ha^{-1} year^{-1}. For N_2O, the mean annual emissions were 2.48 + 4.47 kg ha^{-1} year^{-1} of secondary peat swamp forests, and 4.51 + 4.35 kg ha^{-1} year^{-1} of shrub areas. Flux from shrub are higher than those found in secondary forests for both CH_4 and N_2O. This may be caused by higher air and soil temperature since the water table in both sites was relatively stable over the same period. Daily fluctuations of CH_4 and N_2O during May and August 2014 are shown in Figs. 6 and 7, respectively.

The spatial variability of CH_4 and N_2O flux was relatively high. This may be affected by the distribution and population of micro-organism affecting the emissions of these gases. Table 2 summarizes the populations of bacteria and fungi at two different layers as expressed

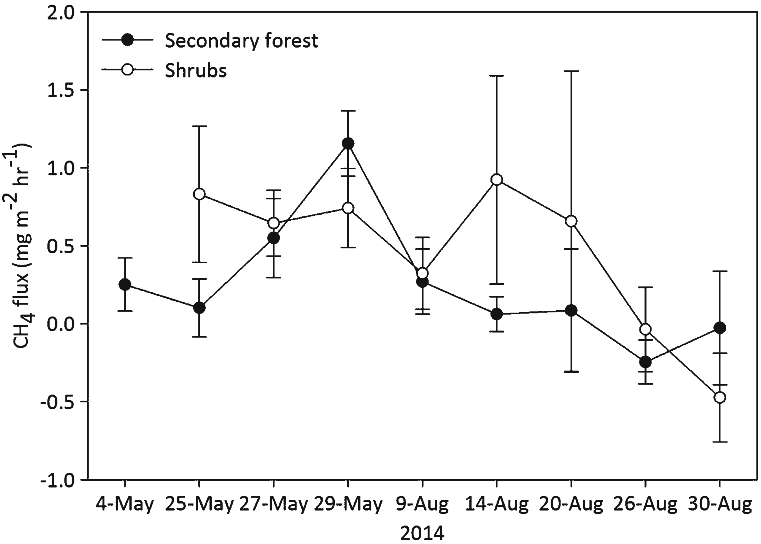

Fig. 6 The fluctuation of CH_4 in May and August 2014 representing wet and dry months, respectively. The relatively open shrub areas have higher fluxes of CH_4 than secondary peat swamp forests, which are more shaded

in plate counts of colony-forming unit (CFU) in shrubs and secondary peat swamp forests. Shrub areas had higher bacteria population near the surface and 20 cm below than secondary peat swamp forests. But the fungi population is much less, especially near the surface.

Physical properties of soil regulate aeration-dependent microbial activities. Aeration that allows oxygen uptake is a key factor (Linn and Doran 1984; Skopp et al. 1990). We did not identify the microbe species. However, the shrub areas, which had more bacteria but less fungi than the secondary peat swamp forests, had lower CH_4 emissions. Nevertheless, N_2O

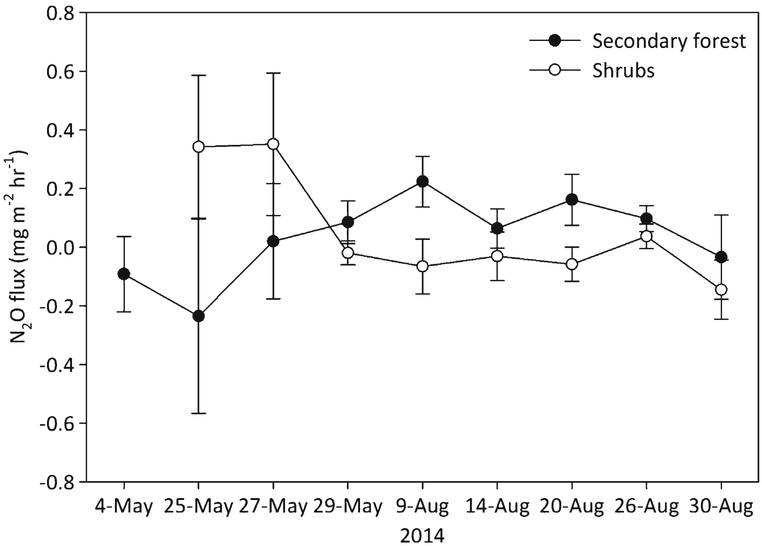

Fig. 7 The fluctuation of N_2O in May and August 2014 representing wet and dry months, respectively. The relatively open shrub areas have higher fluxes of N_2O than secondary peat swamp forests, which are more shaded

Table 2 Colony plate count (× 1000 CFU/g) of bacteria and fungi in two types of land cover at two different layers in Katingan Project site

Microbe	Secondary peat swamp forests		Shrubs	
	0–10 cm	0–10 cm	10–20 cm	10–20 cm
Bacteria	83	200	44	36
Fungi	16	< 1	7	11

emissions in more degraded shrub are unusually higher than in secondary forests. This may be caused by the drainage severity in shrub areas and water-logged secondary peat swamp forests, which defined nitrification and denitrification potentials in the opposite direction to uplands (Meurer et al. 2016).

In aerobic conditions, microbial activities are positively correlated with water content or water-filled pore spaces (WFPS). In incubated soils, linear relationships were demonstrated for CO_2 and N_2O production with WFPS values of 30 to 70% with maximum activity at 60% WFPS (Linn and Doran 1984). In aerobic and anaerobic conditions, denitrification was responsible for 79–98% of N_2O emissions at 70 and 80% WFPS, respectively (Baral et al. 2016).

Based on incubation experiments, the highest CO_2 flux was found at WFPS 80% (166 ppm) for peat samples from shrubs and 40% (120 ppm) for samples from secondary peat swamp forests.

3.3 Ground water levels and hydraulic conductivity

Figure 8 shows the results of the continuous measurement of ground water levels from May to August 2014. Fluctuation of ground water levels positively correlated with the amount of rainfall. The wet months of May and June caused inundation and high ground water levels at all sites, with lower levels when rainfall decreased in July and August. The lowering of ground

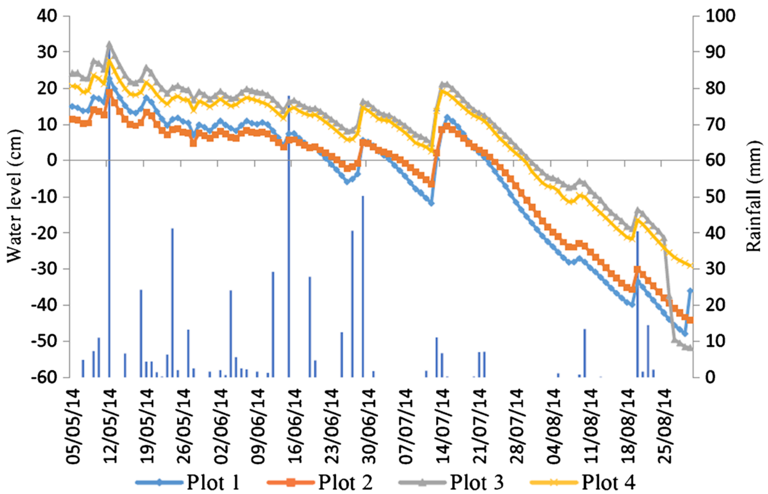

Fig. 8 Fluctuation of ground water levels in May–August 2014 at four sites representing shrubs and secondary peat swamp forests in Katingan Project area compared to the distribution of rainfall in the same period

water level was found to be more pronounced at sites closer to the main canal. The shrub areas were drained faster than secondary peat swamp forests.

The hydraulic conductivity (K) derived from two wells in the shrub sites and two wells in the secondary peat swamp forest sites was 4.2×10 and 6.4×10^{-7} ms^{-1}, respectively. These results are an order of magnitude lower than those found in temperate peat in Canada (Hogan et al. 2006) and tropical peat in Loagan Bunut National Park in Sarawak, Malaysia (Sayok et al. 2008). The low hydraulic conductivity in the Katingan Project area could be due to degradation processes followed by fires that deposit fine materials; these processes typically lower hydraulic conductivity in these areas.

Nine-day measurements in May 2014 and then in August 2014 in the shrub and secondary peat swamp forest sites showed contrasting fluxes of CO_2. In May 2014, most areas were flooded with a mean ground water level of 12.2 cm in the shrub sites and 21.0 cm in the secondary peat swamp forest sites. Such anoxic environments suppressed a maximum CO_2 flux of $38.7 + 6.3$ Mg ha^{-1} $year^{-1}$ to a minimum of $29.4 + 10.8$ Mg ha^{-1} $year^{-1}$ in the secondary peat swamp forests. When the ground water levels were lowered to − 32 cm in the shrub sites and − 17 cm in the secondary peat swamp forest sites, the flux of CO_2 substantially increased to $67.5 + 5.4$ Mg ha^{-1} $year^{-1}$ in the shrub sites and $41.4 + 1.8$ Mg ha^{-1} $year^{-1}$ in the secondary peat swamp forest sites. These results suggest that lowering ground water levels up to 40 cm caused CO_2 fluxes to increase 40–75%.

4 Concluding remarks

The restoration of peat swamp forests by rewetting shrubs and secondary peat swamp forests could lower total CO_2 fluxes in these areas by up to 75%. In the secondary peat swamp forest sites, heterotrophic and autotrophic respiration contributed almost equally to the total fluxes. Further restoration by introducing vegetation could potentially improve the source of input of organic materials. They could also improve rhizospheres and hydraulic conductivity, which both affect the lateral flow of water.

Fluxes of non CO_2 gases (CH_4 and N_2O) were found to be relatively small and highly variable. However, their large global warming potential suggests that further studies are needed on these gases, especially when agricultural inputs in restored or managed peatlands are involved. Among other methods recommended is eddy covariance, where spatial and temporal variability of the fluxes may be integrated over a large and stabilized boundary layer and in relatively short intervals.

The current study was designed in the context of the rewetting and abandonment of shrubs and secondary peat swamp forests. The re-vegetation of abandoned peatlands could help secure land tenure to support further restoration. Based on the above results, further studies on restored sites should broaden the context. Specifically, the study should include rewetting and re-vegetating areas, that would eventually revitalize livelihoods where interactions with human activities are found. In addition to carbon benefits, other non-carbon ecosystem services should also be explored. These forest management practices could help contribute to conservation and sequestration of carbon in the terrestrial biosphere, reducing GHG emissions to the atmosphere.

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References

Abrams JF, Hohn S, Rixen T, Baum A, Merico A (2016) The impact of Indonesian peatland degradation on downstream marine ecosystems and the global carbon cycle. Glob Chang Biol 22(1):325–337. https://doi.org/10.1111/gcb.13108

Baral KJ, Arthur E, Olesen JE, Petersen SO (2016) Predicting nitrous oxide emissions from manure properties and soil moisture: an incubation experiment. Soil Biol Biochem 97:112–120. https://doi.org/10.1016/j.soilbio.2016.03.005.

Bouwer H, Rice RC (1976) A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. Water Resour Res 12(3):423–428. https://doi.org/10.1029/WR012i003p00423

Carlson KM, Goodman LK, May-Tobin CC (2015) Modeling relationships between water table depth and peat soil carbon loss in Southeast Asian plantations. Environ Res Lett 10(7):074006. https://doi.org/10.1088/1748-9326/10/7/074006.

Chimner RA (2004) Soil respiration rates of tropical peatlands in Micronesia and Hawaii. Wetlands 24(1):51–56. https://doi.org/10.1672/0277-5212(2004)024[0051:SRROTP]2.0.CO;2

Comeau L-P, Hergoualc'h K, Smith JU, Verchot L (2013) Conversion of intact peat swamp forest to oil palm plantation: effects on soil CO_2 fluxes in Jambi, Sumatra. Center for International Forestry Research (CIFOR), Bogor

Dariah A, Marwanto S, Agus F (2014) Root- and peat-based CO_2 emissions from oil palm plantations. Mitig Adapt Strateg Glob Chang 19(6):831–843. https://doi.org/10.1007/s11027-013-9515-6

Dommain R, Couwenberg J, Joosten H (2011) Development and carbon sequestration of tropical peat domes in south-east Asia: links to post-glacial sea-level changes and Holocene climate variability. Quat Sci Rev 30(7-8):999–1010. https://doi.org/10.1016/j.quascirev.2011.01.018.

Gumbricht T, Roman-Cuesta RM, Verchot L, Herold M, Wittmann F, Householder E, Herold N, Murdiyarso D (2017) An expert system model for mapping tropical wetlands and peatlands reveals South America as the largest contributor. Glob Chang Biol. 23(9):3581–3599. https://doi.org/10.1111/gcb.13689

Hiraishi T, Krug T, Tanabe K, Srivastava N, Baasansuren J, Fukuda M, Troxler TG (eds) (2014) 2013 supplement to the 2006 IPCC guidelines for National Greenhouse Gas Inventories: wetlands. IPCC, Switzerland

Hogan JM, van der Kamp G, Barbour SL, Schmidt R (2006) Field methods for measuring hydraulic properties of peat deposits. Hydrol Process 20(17):3635–3649. https://doi.org/10.1002/hyp.6379

IPCC (2014) 2013 Supplement to the 2006 IPCC Guidelenes for National Greenhouse Gas Inventories: Wetlands. In: Hirashi T, Krug T, Tanabe K, Srivastava N, Baasunsuren J, Fukuda M, and Troxler TG (eds) IPCC, Switzerland

Jauhiainen J, Hooijer A, Page SE (2012) Carbon dioxide emissions from an Acacia plantation on peatland in Sumatra, Indonesia. Biogeosciences 9(2):617–630. https://doi.org/10.5194/bg-9-617-2012

Kauffman JB, Arifanti VB, Basuki I, Kurnianto S, Novita N, Murdiyarso D, Donato DC, Warren MW (2016) Protocols for the measurement, monitoring, and reporting of structure, biomass, carbon stocks and greenhouse gas emissions in tropical peat swamp forests. Center for International Forestry Research (CIFOR), Bogor

Kim DJ, Chung SG, Lee SH, Choi JW (2012) Relation of microbial biomass to counting units for *Pseudomonas aeruginosa*. Afr J Microbiol Res 6(21):4620–4622. https://doi.org/10.5897/AJMR10.902.

Lähteenoja O, Ruokolainen K, Schulman L, Alvarez J (2009) Amazonian floodplains harbor minerotrophic and ombrotrophic peatlands. Catena 79(2):140–145. https://doi.org/10.1016/j.catena.2009.06.006

Lähteenoja O, Reategui YR, Rasanen M, Del Castillo Torres D, Oinonen M, Page S (2011) The large Amazonian peatland carbon sink in the subsiding Pastaza-Maranon foreland basin, Peru. Glob Chang Biol 18(1):164–178. https://doi.org/10.1111/j.1365-2486.2011.02504.x

Linn DM, Doran JW (1984) Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. Soil Sci Soc Am J 48(6):1267–1272. https://doi.org/10.2136/sssaj1984.03615995004800060013x

Manuri S, Brack C, Nugroho NP, Hergoualc'h K, Novita N, Dotzauer H, Verchot L, Putra CAS, Widyasari E (2014) Tree biomass equations for tropical peat swamp forest ecosystems in Indonesia. For Ecol Manag 334: 241–253. https://doi.org/10.1016/j.foreco.2014.08.031

Meurer KHE, Franko U, Stange CF, Rosa JD, Madari BE, Jungkunst HF (2016) Direct nitrous oxide (N_2O) fluxes from soils under different land use in Brazil—a critical review. Environ Res Lett 11(2):023001. https://doi.org/10.1088/1748-9326/11/2/023001

Miettinen J, Shi C, Liew SC (2012) Two decades of destruction in Southeast Asia's peat swamp forests. Front Ecol Environ 10(3):124–128. https://doi.org/10.1890/100236

Miettinen J, Hooijer A, Vernimmen R, Liew SC, Page SE (2017) From carbon sink to carbon source: extensive peat oxidation in insular Southeast Asia since 1990. Environ Res Lett 12:024014. https://doi.org/10.1088/1748-9326/115b6f

Murdiyarso D, Hergoualc'h K, Verchot LV (2010) Opportunities for reducing greenhouse gas emissions in tropical peatlands. PNAS 107(46):19655–19660. https://doi.org/10.1073/pnas.0911966107

Novita N (2016) Carbon stocks and soil greenhouse gas emissions associated with forest conversion to oil palm plantations in Tanjung Puting tropical peatlands, Indonesia. Dissertation, Oregon State University

Sayok AK, Nik AR, Melling L, Samad RA, Efransyah E (2008) Some characteristics of peat in Loagan Bunut National Park, Sarawak, Malaysia. Proceedings of the International Symposium, Workshop and Seminar on Tropical Peatland, Yogyakarta, pp 27–31. http://www.geog.le.ac.uk/carbopeat/yogyaproc.html. Accessed 25 Aug 2017

Skopp J, Jawson MD, Doran JW (1990) Steady-state aerobic microbial activity as a function of soil water content. Soil Sci Soc Am J 54(6):1619–1625. https://doi.org/10.2136/sssaj1990.03615995005400060018x.

Warren M, Hergoualc'h K, Kauffman JB, Murdiyarso D, Kolka R (2017) An appraisal of Indonesia's immense peat carbon stock using national peatland maps: uncertainties and potential losses from conversion. Carbon Balance Manag 12(1):12. https://doi.org/10.1186/s13021-017-0080-2