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Effect of forest conversion to oil palm plantations on carbon dioxide balance in tropical peatlands

（熱帯泥炭林のオイルパームプランテーションへの土地利用変化が二酸化炭素収支に与える影響）

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THESIS ABSTRACT

1. Introductions

In recent decades, Malaysian tropical peatlands have been developed for agricultural purposes due to its high accessibility, as the distribution of mineral soil for agricultural use becoming scarcer. Even though it is once considered as less valuable for agricultural development, the advancement in scientific and technological knowledge made agricultural activities on tropical peatlands possible. In Malaysia, oil palm is regarded as the most important strategic crops, which made the country the second largest producer of palm oil in the world after Indonesia. To date, large distribution of peat swamp forest (PSF) has been converted into large scale oil palm plantation in those countries. Indonesia and Malaysia hold about 63% of the total distribution of peatlands in the tropic. This accounted for about 66.4 Gt carbon or 97% of the total of 68.5 Gt carbon all over southeast Asia.

Due to the large C stock, reclamation of PSF often triggered environmental issues associated with C emission to the atmosphere in the form of carbon dioxide (CO_2) and methane (CH_4). Preceding PSF reclamation, GWL lowering through drainage are crucial to aerate the crop root zone followed by mechanical compaction of the peat soil to increase the peat soil bulk density, soil surface loadbearing capacity and water-filled pore space (Melling et al., 2005a, 2005b, 2008). However, GWL lowering has been reported to cause peatlands to shift from C sinks to C sources, thus increasing CO_2 deposition to the atmosphere, while reducing CH_4 emissions (Furukawa et al., 2005; van Huissteden et al., 2006; Couwenberg, 2011). This is associated with enhanced microbial degradation of organic matter in soil that increased decomposition rate of peat as observed in boreal and temperate peatlands. However, the differences in peat soil properties, environmental factors, microbial community, vegetation cover and management practices could possibly alter the ecosystem CO_2 dynamic. To date, published data on ecosystem scale CO_2 fluxes following PSF conversion to oil palm plantation (OPP) are nonexistence. By using the CO_2 fluxes measured at a PSF and an OPP, this study will assess the changes in the CO_2 balance after conversion by comparing 1) CO_2 fluxes seasonality, 2) environmental controls, and 3) annual CO_2 balance.

2. Materials and methods

2.1. Study site

The study sites were located at the state of Sarawak, Malaysia, in the Island of Borneo, separated about 100 km away from each other. The PSF is located at Betong division and the OPP in Sibu division of Sarawak, Malaysia. Two eddy covariance towers with the height of 40 m was constructed at the PSF (1°23’59.42” N, 111°24'6.69"E) and the OPP (02º11’12” N, 111°50’35.7”E) sites in 2010. The terrains are almost flat at both sites. Peat thickness was 10 m at PSF and 8-11 m at OPP (Sangok et al., 2017). The surrounding area of the forest was converted into oil palm plantations in 1990s. Originally, the forest was dominated by *Litsea* spp., but has been outgrew by native trees species known as *Shorea albida*. The OPP was planted with *Elaeis guineensis* with the planting density of 153 trees ha^{-1} in 2004. During the beginning of flux measurement in 2010 the canopy height was about 25 m and 8 m respectively at PSF and OPP. Plant area index (PAI) were 7.9 m^2 m^{-2} and 3.73 m^2 m^{-2} at PSF and OPP respectively.

2.2. Flux and meteorological measurement

Flux and meteorological data measured from 2011 to 2014 were used for analysis. CO_2 and energy fluxes were measured using the conventional eddy covariance method. Flux measurement heights were 41 m and 21 m respectively at PSF and OPP. Half-hourly mean CO_2 flux (F_C) was calculated using Flux Calculator software (Ueyama et al., 2012) from raw eddy data. Procedures like spike removal (Vickers and Mahrt, 1997), planar fit rotation (Wilczak et al., 2001), frequency response correction (Massman, 2000) and air density fluctuation correction (Webb et al., 1980) were applied during calculation. Meteorological measurements include global and reflected solar radiations, long-wave radiations (upward and downward), downward and upward photosynthetic photon flux densities (PPFD), wind speed, air temperature (T_a), and relative humidity (RH), ground water level (GWL), volumetric soil water content (VWC), and precipitation (PT). All data were averaged and recorded half-hourly using a datalogger (CR3000, Campbell Scientific Inc.).

2.3. Quality control, gap filling and partitioning of NEE

Prior to gapfilling, NEE data were screened by the mean absolute deviation (MAD) spike detection method (Papale et al., 2006) and the deviation of each half-hourly NEE from mean diurnal variation (MDV). NEE was removed if it exceeds 3 standard deviation ± MDV. Friction velocity (u*) filtering was applied to the nighttime NEE (PPFD $\leq$ 10 μmol m^{-2} s^{-1}). Then the missing data were filled using the marginal distribution sampling (MDS) method (Reichstein et al., 2005). For partitioning, daytime ecosystem respiration (RE) was extrapolated from filled nighttime NEE using the same algorithm for gapfilling (MDS). Finally, the gross primary production (GPP) was calculated as the difference between NEE and RE (NEE = RE – GPP). During the nighttime, GPP was set to zero.

3. Results

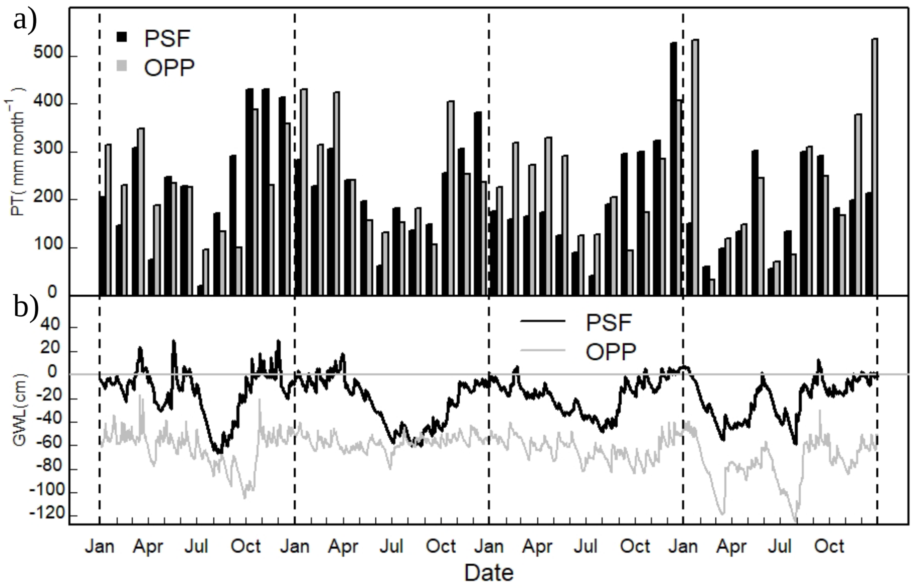

Figure 1 Seasonal variation of monthly PTs and daily GWL at PSF and OPP from 2011 to 2014.

Mean annual precipitations from 2011 to 2014 were 2517 ± 397 and 2903 ± 88 gC m^{-2} year^{-1} respectively in the PSF and OPP. In general, relatively low monthly PTs occurred between April to September (Figure 1a). However, this seasonal variation was obscure in 2014. In PSF, the monthly mean of daily GWL showed similar seasonal variation with monthly PT (Figure 1b). Daily GWL in PSF fluctuated between -66.8 and 29.5 cm with significant seasonal variation. On the other hand, the GWL significantly lower than that of PSF with no clear seasonal variation due to water management in the plantation. The GWL was maintained at approximately -60 cm, but in 2014 the seasonal variation followed that of monthly PT.

Figure 2 showed the seasonal variation of monthly NEE, RE, and GPP. The mean of daily NEE was higher or more positive in OPP (2.7 ± 2.8 g C m^{-2} day^{-1}) compared to the -0.4 ± 1.8 g C m^{-2} day^{-1} in PSF. Daily RE was also higher in OPP (9.7 ± 2.6 g C m^{-2} day^{-1}) as compared to 8.9 ± 2.5 g C m^{-2} day^{-1} at PSF. However, daily GPP was lower in OPP than PSF (7.0 ± 1.5 vs. 9.4 ± 2.1 g C m^{-2} day^{-1}). The seasonal variation of NEE, RE, and GPP were generally obscure at both sites.

Nighttime NEE or RE showed significant relationship ($p < 0.05$) with GWL at both sites (Figure 3). At PSF, RE decreased by -0.2 µmol m^{-2} s^{-1} with every 10 cm increase in GWL (r^2 = 0.41). On the contrary, the RE at OPP showed a positive relationship with GWL (slope = 0.03, r^2 = 0.22).

The PSF act as a net CO_2 sink CO_2 (-136 ± 51 gC m^{-2} year^{-1}) but the OPP was a net source of CO_2 (995±181 gC m^{-2} year^{-1}) from 2011 to 2014 (Figure 4). Annual REs were 3546 ± 149 and 3663±182 gC m^{-2} year^{-1} respectively at the PSF and OPP. Annual GPP in the PSF was larger than that of OPP (3682 ± 149 vs. 2552±135 gC m^{-2} year^{-1}).

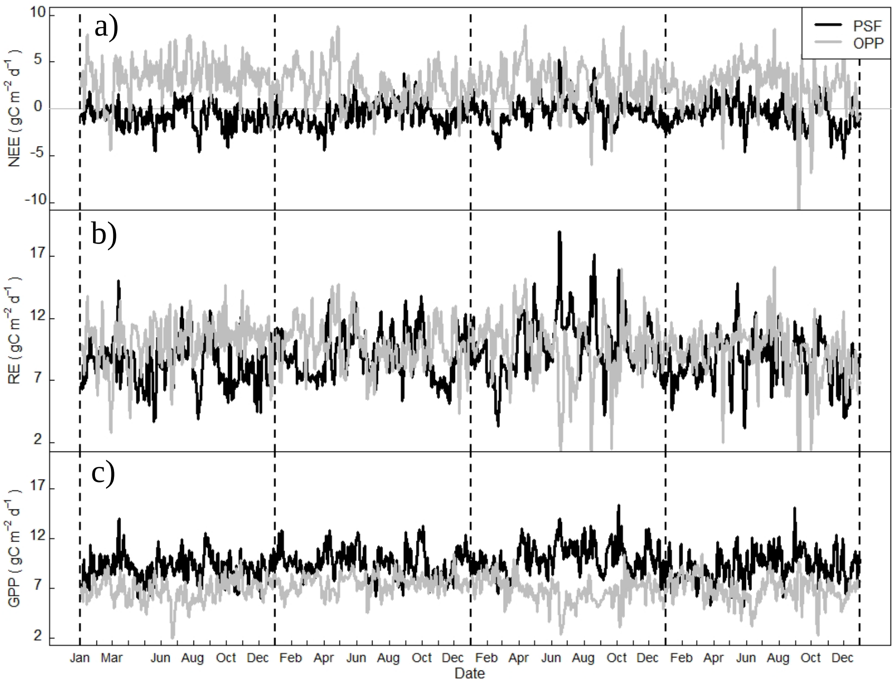

Figure 2 Seasonal variation of monthly NEE, RE, GPP from 2011 to 2014 at PSF (grey lines) and OPP (black lines).

4. Discussion

The large CO_2 source at the OPP was mainly due to the lower GPP and higher RE as compared to the forest site. The NEE values were 16 to 20% larger than the mean of tropical humid evergreen forests reported by Luyssaert et al. (2007) (3061 ± 162 g C m^{-2} year^{-1}). In similar ecosystem but drier environment in Central Kalimantan, Hirano et al. (2012) reported similar large annual RE (3642 ± 115 and 3519 ± 132 g C m^{-2} year^{-1}). Annual GPP of 3682 ± 149 g C m^{-2} year^{-1} in PSF was slightly larger than that of tropical humid evergreen forests (3551±160 g C m^{-2} year^{-}

^{1}) and undrained PSF in Kalimantan (3468 ± 118 g C m^{-2} year^{-1}). The large GPP was the attributable to the dense canopy at PSF (LAI of 8.20 m^{2}m^{-2}). In addition, PSF used in this study are a regenerated forest with rapidly growing trees. RE in most PSF are generally larger than other types of tropical forest. Therefore, its net sink of CO_2 is highly dependent on the magnitude of GPP, induced by the vegetation cover.

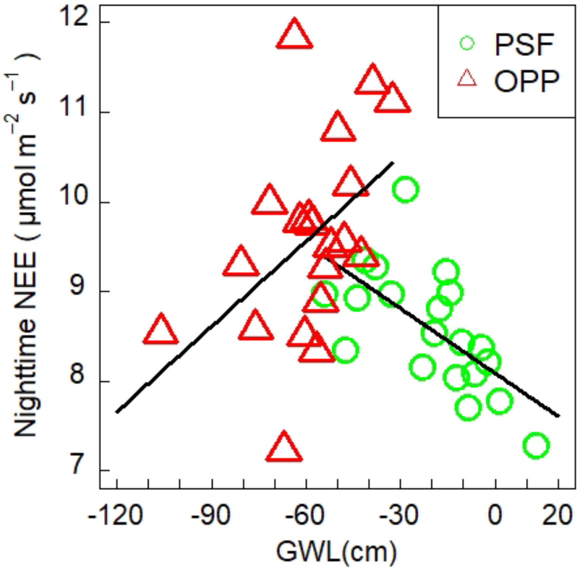

Figure 3 Relationship between measured nighttime NEE and groundwater level (GWL) at PSF and OPP. Half-hourly NEE data were sorted according to GWL and bin-averaged for 20 classes in the same size. Lines were drawn for significant relationship ($p < 0.05$)

Our field measurement from study showed that large reduction in GPP occurred following PSF conversion to OPP. The low PAI as compared to forest is the main reason for such reduction. In addition, dead palm trees also abundance in the OPP site. Even though annual GPP was lower in OPP, the AGB increment was 57.4% larger than that of PSF (459 vs. 292 g C m^{-2} year^{-1}), indicating rapid growth of the oil palm trees as compared to forests. On the other hand, only slight increase in RE was observed after conversion. Enhanced peat oxidation is normally expected following peatlands conversion due to GWL lowering (Furukawa et al., 2005; Couwenberg, 2011). However, this study illustrates no significant increase in RE after conversion. In fact, soil respiration (RS) from manual and automated chamber showed lower RS in OPP compared to forest (Ishikura et al., 2018). The low RS despite lower GWL could be associated with the low gas diffusiveness due to high bulk density. High bulk density resulted in compaction and the consolidation of the soil. Moreover, the positive correlation between RE and GWL in this study also could be a good indicator of unalignment between RS and RE. Therefore, this study suggests the contribution of other emission source of CO_2 to the total RE after conversion. Accumulation of litter and plant debris from former forest are abundance in OPP. This could be the main emission source after conversion. However, there is still no published study conducted in OPP on peat that considering such respiration components. Most current studies in OPP on peat focussed on the changes in RS following GWL lowering. This could be an opportunity for future study to have better understanding of the ecosystem scale CO_2 dynamic. Understanding such process(es) is crucial for future mitigation strategy for sustainable development of PSF especially in developing countries.

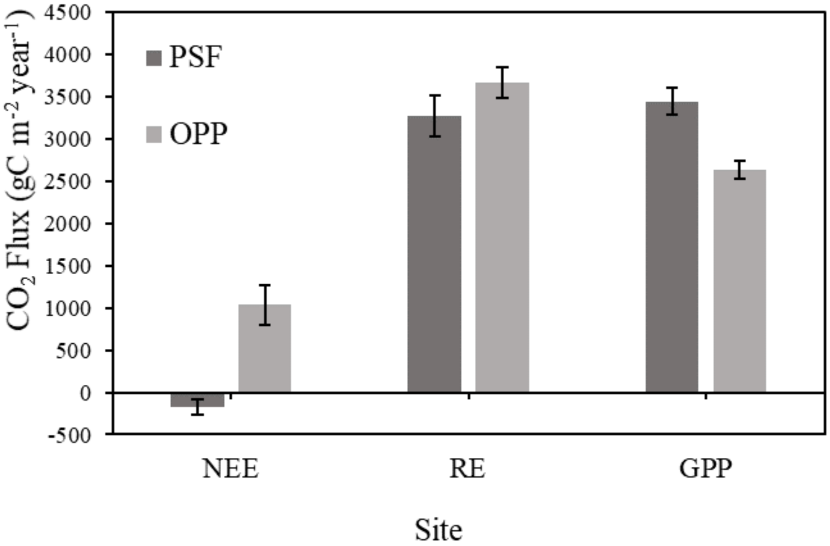

Figure 4 Mean of annual NEE, RE, and GPP from 2011 to 2014 at the PSF and OPP.

5. Conclusion

This study is the first study to successfully quantify CO_2 balance of tropical peatlands after conversion. NEE was measured during a 4 years period from 2011 to 2014 in an OPP and a PSF. Each ecosystem was used to represent the condition before and after land conversion. The PSF was a modest CO_2 sink, whereas OPP was a large CO_2 source. The large source was mainly caused by reduction in GPP and increased in RE after conversion. Seasonal variation of RE greatly influenced the variation of NEE in the PSF. RE was sensitive to GWL similar to the previous studies. Similarly, in OPP, variation in NEE was mainly governed by variation in RE. However, inverse relationship was found between RE and GWL.

The large source following conversion was partly due to the low GPP in OPP. This was induced by the high mortality and relatively low density of the palm trees. On the other hand, the respiration components were a little complicated. Soil chamber measurement indicates reduced RS despite the lower GWL after conversion. This suggests that CO_2 emitted from leaf litter and plant debris might be the dominant source after conversion. Removing huge tree stumps and debris before planting can be a good strategy to reduce emissions. This could be a valuable insight for reducing CO_2 emission in OPP on peat. However, further studies that include all respiration components in OPP are necessary to support such a hypothesis.

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