Chapter 44

Soil CO_2 Fluxes from Different Ages of Oil Palm in Tropical Peatland of Sarawak, Malaysia

Lulie Melling, Kah Joo Goh, Auldry Chaddy, and Ryusuke Hatano

Abstract Conversion of tropical peatland into oil palm plantation in Southeast Asia has been alleged to have increased the decomposition process via peat oxidation due to drainage and water management, raising the emission of soil CO_2. This is postulated to increase with age of oil palm cultivation. However, management also plays a role in soil CO_2 emissions from oil palm plantations. The objective of this study was to determine the controlling factors influencing soil CO_2 fluxes in different ages of oil palm on tropical peatland. The soil CO_2 fluxes were measured for 24 months from three palm ages (1, 5 and 7 years palm; S1, S2, S3) in tropical peatland of Sarawak, Malaysia using a closed-chamber method. The highest mean soil CO_2 flux was recorded in S3 (221 mg C m^{-2} h^{-1}) followed by S2 (195 mg C m^{-2} h^{-1}) and S1 (178 mg C m^{-2} h^{-1}) palms. The cumulative soil CO_2 fluxes for S1, S2 and S3 were 14.7, 16.4 and 18.5 t C ha^{-1} $year^{-1}$, respectively. Water table was found to have no correlation with soil CO_2 fluxes but water-filled pores space (WFPS) correlated negatively with soil CO_2 fluxes in all three different ages of oil palm. The increase in soil CO_2 flux with palm age was consistent with higher root biomass, suggesting that root respiration and microbial activity were associated with root exudates as major component of soil respiration in tropical peatland under oil palm.

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Keywords Water-filled pore space (WFPS) • Root biomass • Oil palm • Tropical peat

Introduction

The oil palm (*Elaeis guineensis* Jacq.) is currently the most productive oil crop in the world. Given that less suitable mineral soils are now available for development due to difficult terrain, and poor accessibility from the land to the ports due to a lack of infrastructure, the expansion of oil palm cultivation into vast unutilized peat soil areas is deemed necessary to drive development in Sarawak, provide job opportunity and eradicate rural poverty. Under natural condition of tropical peatland, the water saturated peat may impede root penetration and respiration which present a challenge for any agriculture development. This could be resolved through drainage, mechanical compaction and water management by maintaining the water table at 50–70 cm, which corresponds to the oil palm deep rooting system where the majority of roots are found in the upper 50 cm of the soil profile (Henson and Chai 1997). Drainage created an aerobic zone for better plant root respiration while compaction increases soil bulk density and reduces leaning problem due to poor root anchorage while at the same time increases moisture holding capacity via better capillary rise. However, lowering the water table in tropical peatland has been claimed to increase oxygen diffusion, promote higher microbial activity and accelerate peat oxidation causing higher soil carbon dioxide (CO_2) flux to the atmosphere (Nykanen et al. 1998; Jaenicke et al. 2010; Page et al. 2011).

Soil respiration comprises two components: microbial and root respiration (Moore and Dalva 1993; Tang et al. 2005). Plants may play an important role in soil respiration through their influence on root biomass. Soil CO_2 flux increased with root biomass (Wang et al. 2005; Luo and Zhou 2006) which agrees with the findings of Melling et al. (2013) for oil palms in peat soils. Similar results were also obtained for other plants where the contributions of root respiration to total soil respiration ranged from 40 to 70 % (Ohashi et al. 2000; Wang et al. 2006). In addition to root biomass, temperature, soil moisture and nutrient status are also key factors responsible for the variation in soil respiration through their influences on microbial and root activities (Davidson et al. 1998; Adachi et al. 2006). Microbial activity and root respiration have been found to increase with temperature (Wang et al. 2006) but decrease with soil moisture more than 60 % (Linn and Doran 1984).

Despite many studies on soil respiration rates, little work has been done on cultivated tropical peatland. Understanding on the factors responsible for soil CO_2 flux is crucial to explain the variations caused by land use change in tropical peatland. Hence, the objective of this study was to determine the controlling factors on soil CO_2 fluxes in different ages of oil palm on tropical peatland.

Table 44.1 Environmental characteristics and soil properties for oil palm plantation

Age of palm	S1 (1 year palm)	S2 (5 years palm)	S3 (7 years palm)
Peat thickness (cm)	520	475	375
Relative humidity (%)	67.6 ± 1.8	74.9 ± 1.9	78.0 ± 2.0
Air temperature (°C)	33.8 ± 0.5	31.7 ± 0.5	30.6 ± 0.4
Soil temperature at 5 cm (°C)	27.9 ± 0.2	26.8 ± 0.2	26.6 ± 0.2
Soil temperature at 10 cm (°C)	27.5 ± 0.2	26.7 ± 0.2	26.5 ± 0.2
Annual rainfall (mm)	3,493	4,058	3,447
Water table (cm)	−56.4 ± 2.5	−66.6 ± 3.7	−55.6 ± 3.4
Water-filled pore space (%)	74.2 ± 1.3	81.2 ± 1.3	78.5 ± 1.5
Bulk density (g cm^{-3})	0.23 ± 0.004	0.21 ± 0.002	0.22 ± 0.003
Soil pH	3.6 ± 0.02	3.8 ± 0.04	3.9 ± 0.03
Loss of ignition (%)	94.4 ± 1.0	93.9 ± 1.1	94.2 ± 0.9
Total C (%)	55.6 ± 0.6	55.0 ± 0.8	56.1 ± 0.5
Total N (%)	2.1 ± 0.1	1.9 ± 0.1	1.9 ± 0.1
Base saturation (%)	40.7 ± 1.5	60.4 ± 2.4	61.8 ± 3.0

Values are mean monthly ± SE

Materials and Methods

The study was conducted at an oil palm plantation in Mukah, Sarawak, Malaysia (2° 51′ N, 112° 13′ E) on three sites, namely S1, S2 and S3, with oil palms of 1, 5 and 7 years, respectively. Further environmental and soil characteristics of each site are shown in Table 44.1.

Monthly measurements of soil CO_2 flux were carried out using a closed-chamber method for 24 months (July 2006–June 2008) (Crill 1991). Simultaneously all the environmental variables and soil samples were collected both during and after sampling as described in Melling et al. (2005).

Root dry weight estimation was done based on the Henson and Chai (1997) method. The standing root biomass was estimated from a linear regression of root on shoot biomass derived from intensive measurements of the palms.

Pearson correlation was used to determine if there is a correlation among variables and soil CO_2 fluxes. Simple linear regression analysis was used to determine the relationship between root dry weight and soil CO_2 fluxes. All statistical analysis was performed using the SAS version 9.2.

Results and Discussion

As shown in Fig. 44.1a, the monthly air temperature pattern was inversely related to the relative humidity (RH). Soil temperatures at 5 and 10 cm were relatively constant for all sites (Fig. 44.1b). In this study, the RH did not correlate with the soil CO_2

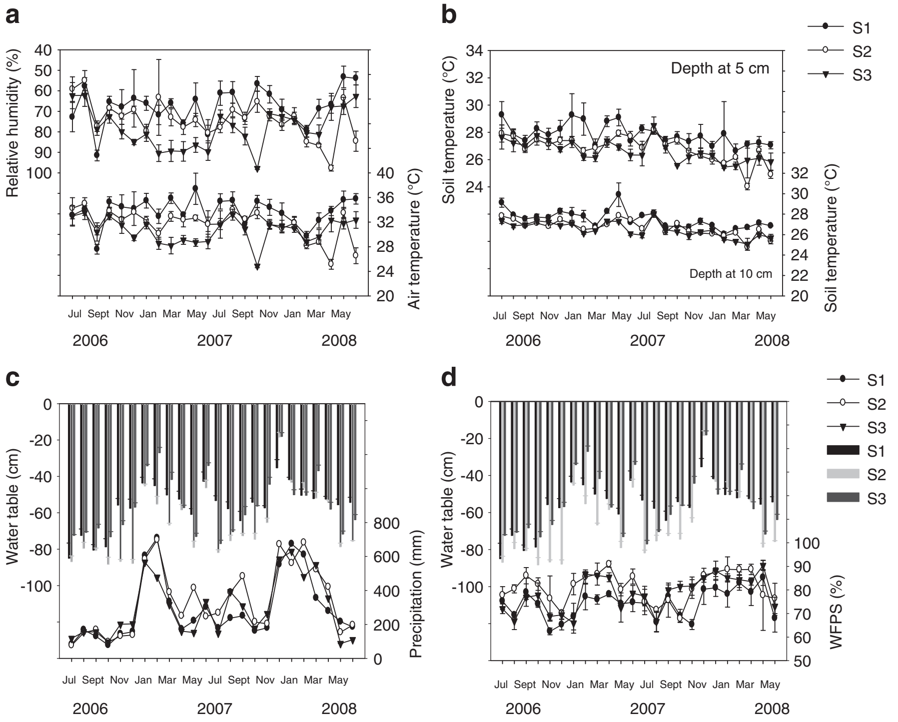

Fig. 44.1 Monthly mean for (**a**) relative humidity and air temperature, (**b**) soil temperature at 5 and 10 cm depth, (**c**) precipitation and water table and (**d**) precipitation and WFPS for different age of oil palm. Data represents means ± SE (n = 3)

fluxes but negatively correlated with the air and soil temperatures at 5 cm depth. As shown in Table 44.1, the RH increase with increasing palm age which might be attributed to the increase in palm canopy density. As the palm grows the size of its canopy increases and eventually closes (usually 4 years after planting). Open canopy in younger palms might cause the soil temperature to increase which will reduce microbial activity (Jauhiainen et al. 2008) thus lower soil CO_2 flux in the youngest palm.

With a total rainfall of more than 3,000 mm per year, the seasonal rainfall has a direct effect on the seasonal change in the water table (Fig. 44.1c) but did not influence the monthly variations in water-filled pore space (WFPS) (Fig. 44.1d). For all sites, the monthly mean WFPS was between 62 and 91 %.

As shown in Table 44.2, there were positive correlations between air and both soil temperatures and soil CO_2 fluxes ($p < 0.05$) in S2. This relationship was enhanced when the water table was less than 75 cm (Fig. 44.3a). However, the above correlation was not obtained in S1 and S3. This shows that an increase in soil temperature with sufficient soil moisture would enhance soil organic matter decomposition, root-rhizosphere and microrhizal respiration (Fenn et al. 2010). Kuzyakov and Cheng (2001) and Tang et al. (2005) also found that soil temperature increases photosynthesis and root respiration leading to higher root exudation which serves as a C source for microbes and thus, enhances soil microbial activity, decomposition

Table 44.2 Correlation of soil CO_2 flux in different ages of oil palm with environmental variables

	Age of palm		
	S1	S2	S3
Variables	(n=72)	(n=72)	(n=72)
Air temperature (°C)	−0.09	0.27**	−0.11
Soil temperature at 5 cm (°C)	0.10	0.35**	−0.02
Soil temperature at 10 cm (°C)	−0.02	0.38**	−0.02
Water table (cm)	0.08	0.17	−0.09
Water-filled pore space (%)	−0.25**	−0.50**	−0.24*

Note: The top value in each parameter represents Pearson's correlation coefficient (r) with * and ** indicate with significance at $p<0.05$ and $p<0.01$, respectively

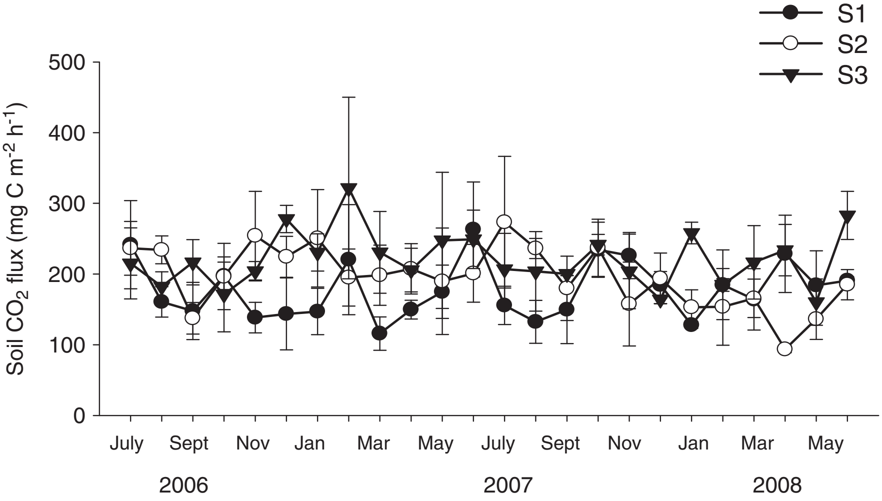

Fig. 44.2 Monthly means soil CO_2 flux for different age of oil palm. Data represents means ± SE (n=3)

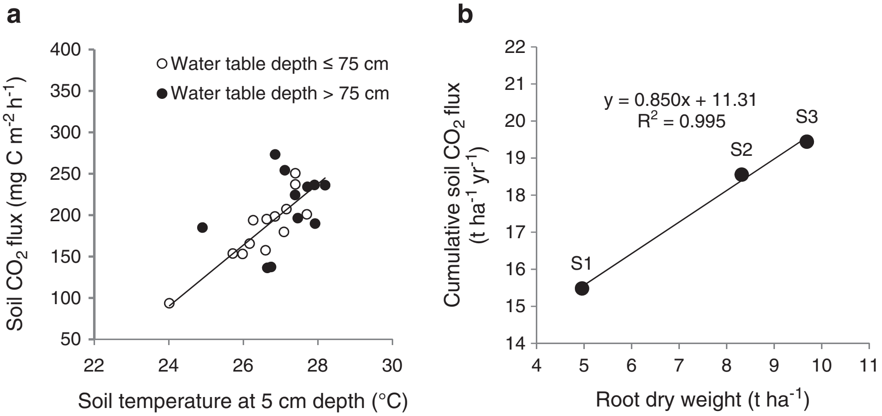

Fig. 44.3 (**a**) soil temp. at 5 cm depth and soil CO_2 fluxes S2 as influenced by depth of water table, (**b**) cumulative soil CO_2 flux and root dry weight in oil palm plantation ($p<0.05$)

Table 44.3 Mean soil CO_2 flux and annual cumulative for oil palm plantation

Age of palm	Soil CO_2 flux (mg C m^{-2} h^{-1})	Annual cumulative soil CO_2 flux (t C ha^{-1} $year^{-1}$)
S1	178 ± 8	14.7
S2	195 ± 9	16.4
S3	221 ± 8	18.5

Values are mean monthly ± SE (n = 24)

process and soil CO_2 production (Yuste et al. 2007). As shown in Fig. 44.3a, S2 also has no significant correlation between soil temperature at 5 cm depth and soil CO_2 when its water table was more than 75 cm. But this relationship was not obtained in S1 and S3 indicating that the effect of soil temperature and water table on soil CO_2 fluxes was site specific.

As shown in Table 44.2, there was no correlation between soil CO_2 fluxes and water table. Thus, the lowering of water table in tropical peatland for agriculture purposes, which have always been claimed to be the main factor causing an increase in soil CO_2 flux (Hirano et al. 2007; Hooijer et al. 2010; Page et al. 2011) could be site-specific. This contention is further supported by some studies where no distinct variation in soil CO_2 flux with season or water table was found in tropical region (Melling et al. 2005, 2012; Inubushi et al. 2003; Watanabe et al. 2009). In a tropical peat swamp forest in Kalimantan, Jauhiainen et al. (2005) had also observed that water table has lower correlation with soil CO_2 flux. A similar relationship was also found by Parmentier et al. (2009) in the Netherlands. Berglund and Berglund (2011) had found higher soil CO_2 flux in higher water table of 40 cm compared with 80 cm depth because of sufficient amount of air and moisture for optimal microbial activity. At the lower water table, moisture became the rate limiting factor for microbial activity causing a reduction in soil CO_2 emission.

In all the study sites, WFPS was negatively correlated with soil CO_2 flux (Table 44.2). In the development of an oil palm plantation on tropical peatland, other than drainage and water management, mechanical compaction is a pre-requisite. Compaction increases the soil bulk density, while reducing soil porosity and enhancing root activity (Melling et al. 2013) and also reduces the incidence of leaning. Lower porosity increases the capillary rise and water retention capacity resulting in higher WFPS which plays an important role in controlling soil CO_2 flux (Linn and Doran 1984; Melling et al. 2005, 2012). Microbial population and respiration generally increases with WFPS but when it reaches more than 60 % (Linn and Doran 1984), respiration activity starts to decrease. Higher WFPS reduces the diffusion rates of O_2 into the soil, thus inhibiting the underground biotic activity such as the respiratory activity of plant roots (Adachi et al. 2006; Castellano et al. 2011) all leading to lower soil CO_2 flux.

Mean soil CO_2 flux and annual cumulative flux as shown in Table 44.3 increased with palm age. Soil CO_2 flux in S3 was significantly higher ($p<0.05$) than S1 and S2. The annual cumulative fluxes for the study sites were similar to the findings by Melling et al. (2005) and Adachi et al. (2006). There was also no distinct seasonal pattern for monthly soil CO_2 fluxes in all sites (Fig. 44.2). However, as shown in Fig. 44.3b, cumulative soil CO_2 flux increased linearly with root biomass ($R^2 = 0.995$), the latter due to increasing palm age are consistent with other studies (Ohashi et al. 2000; Adachi et al. 2006; Han et al. 2007). Oil palm root biomass is about 20–40 % of above ground biomass and it was found that total root respiration of 9 years old palm contributed 69 % of total soil respiration (Henson and Chai 1997). Melling et al. (2013) had also found that the contribution of root respiration to soil respiration is 62 %. Adachi et al. (2006) reported that soil respiration of oil palm plantation is mainly influenced by fine root biomass as 70 % of oil palm roots grow towards the soil surface (Reddy et al. 2002). This maybe the main reason for the older palm having higher soil CO_2 flux. Its larger root biomass would contribute more root residues and exudates as the C source for microbes and increase the microbial activity which in turn stimulates soil organic matter breakdown (Kuzyakov 2002). Figure 44.3b also shows that the heterotrophic respiration was similar for all three sites since they share a common intercept. This might be expected because microbial activity and decomposition are likely to be most active in the soil surface, which probably has similar properties in the three sites. Larger biomass is expected to have higher root respiration, root turnover and litter production (Pregitzer et al. 2008; Liu et al. 2009).

Conclusion

Soil CO_2 fluxes in oil palm plantation are not predominantly influenced by water table which had been alluded to by most studies but strongly influenced by soil WFPS and root biomass. Heterotrophic respiration was similar in the three sites with different palm ages and types of peat. Further studies should be conducted on the effect of root biomass on soil CO_2 fluxes in oil palm plantation on tropical peat soil.

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