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Soil CO_2 Efflux of Oil Palm and Rubber Plantation in 6-Year-Old and 22-Year-Old Chronosequence

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ABSTRACT

Soil CO_2 efflux, in relation with chronosequence at oil palm and rubber plantations, was measured monthly, each with both 6- and 22-year-old stands. Other environmental factors such as soil temperature and relative humidity (RH), as well as soil properties, were also measured at 0–30 cm depth. Soil CO_2 efflux was found to be highly affected by forest types and chronosequence factor. The 22-year-old age stand ($M = 0.91$; $SD = 0.17$ g CO_2 m^{-2} h^{-1}) had significantly higher soil CO_2 efflux than the 6-year-old stand ($M = 0.54$; $SD = 0.18$ g CO_2 m^{-2} h^{-1}). Soil RH plays a significant role controlling soil CO_2 efflux compared with soil temperature, especially at younger stands of tropical oil palm and rubber plantations spatially. Lower Q_{10} values were found to be caused by higher temperature that had reduced enzymatic and substrates activities for soil respiration. Non-discernible trends of temporal soil CO_2 efflux, soil temperature, and RH indicated that other significant factors could be the catalyst, and thus further research is required to explain the relations between soil CO_2 efflux and environmental factors. Research findings indicated that older stand age of oil palm and rubber plantations in Malaysia released higher soil CO_2 efflux, but with no degrading effects towards the environment.

Keywords: Chronosequence, environment, land use, oil palm, plantation, rubber, soil respiration, tropical

INTRODUCTION

Globally, net carbon (C) emission from land use is approximately 1.0 ± 0.8 pg C yr^{-1} (Le Quéré et al., 2015). Therefore, the slightest alteration of the terrestrial ecosystems may lead to a considerable change of the atmospheric CO_2 concentration (Arevalo, Bhatti, Chang, Jassal, & Sidders, 2010;

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Schlesinger & Andrews, 2000). The role of land use, or terrestrial ecosystems, is critical in the global C cycle as it releases CO_2 into the atmosphere, which accounts for 90% of the total ecosystem respiration that is predominantly facilitated by soil CO_2 efflux (Hanson, Edwards, Garten, & Andrews, 2000). Soil CO_2 efflux refers to the instantaneous CO_2 transports via soil ground surface into the atmosphere, and *vice versa*, which includes rhizosphere, microbes, and soil fauna respiration (Raich & Schlesinger, 1992; Maher, Asbjornsen, Kolka, Cambardella, & Raich, 2010). Besides that, soil CO_2 efflux varies significantly among plant biomes, indicating environmental changes in vegetation via land use conversion which potentially alters the soil CO_2 emissions into the atmosphere, and *vice versa* (Raich & Tufekcioglu, 2000). However, the impacts of anthropogenic activities on soil CO_2 efflux from land use modification differ from one site to another, and are still poorly documented (Nazaries et al., 2015; Raich & Schlesinger, 1992; Veldkamp, Purbopuspito, Corre, Brumme, & Murdiyarso, 2008).

Studies on soil CO_2 efflux in Malaysia have been conducted and quantified to improve the understanding of soil CO_2 efflux at various levels. However, these studies focused on tropical forests (Mande, Abdullah, Aris, & Nuruddin, 2014a; Mande, Abdullah, Zaharin, & Ainuddin, 2014b), peat soils (Choo, Nuriati, & Ahmed, 2014), and single plantation species (Firdaus & Husni, 2011; Choo et al., 2014). In addition, soil CO_2 efflux studies in Malaysia generally explored a single ecosystem age (Mande et al., 2014a). Thus, little to no information is available on the chronosequence associations, which also remain unclear. Therefore, there is a knowledge gap on soil CO_2 efflux dynamics with the association of chronosequence between different ecosystem types despite the acknowledgement of the importance of soil CO_2 efflux in terrestrial-atmosphere balance, especially in Malaysia. A comprehensive understanding of soil CO_2 efflux, particularly on its impact on environmental factors from the types of forest management, is important as it will enhance our knowledge of the fundamental ecological processes controlling soil CO_2 efflux (Fan, Yang, & Han, 2015; Liu et al., 2016). Therefore, the present study was undertaken to explore the association of oil palm and rubber plantations at different ecosystem age stands and its influence on soil CO_2 efflux.

MATERIALS AND METHODS

Study Site

The study was conducted at 6- and 22-year-old oil palm (*Elaeis guineensis*) and rubber (*Hevea brasiliensis*) plantations at Universiti Putra Malaysia, Serdang, Selangor, from April to June, 2016. The experimental plots are located at about 2°59′ N, 101°43 ′E, with the mean annual temperature and mean annual rainfall of 27°C and 2,215.7 mm, respectively. One month (March 2016) prior to commencement of the study, rainfall was 89.5 mm and the area received 134.6, 355.2, and 218.4 mm during the study months of April, May, and June, respectively. The soil series is classified as Haplic Nitisols. Important physical and edaphic characteristics of the stand ages are presented in Table 1.

Table 1
Site characteristics of oil palm and rubber plantation trees on sample plots, each with 6- and 22-year-old ecosystem ages

		Physical attributes		Soil characteristics				
Species	Age	Diameter (cm diameter at breast height)	Height (m)	C (%) (*N* = 3)	N (%) (*N* = 3)	Soil organic content (kg C m^{-2}) (*N* = 3)	pH (*N* = 3)	Bulk density (g cm^{-3}) (*N* = 3)
Oil palm	6	45.21 ± 0.21 (*N* = 36)	2.47 ± 0.11 (*N* = 36)	2.26 ± 0.09	0.16 ± 0.01	7.57 ± 0.13	3.39 ± 0.07	1.31 ± 0.12
	22	58.12 ± 0.43 (*N* = 32)	9.5 ± 0.31 (*N* = 32)	1.93 ± 0.06	0.26 ± 0.06	7.80 ± 0.13	3.38 ± 0.06	1.3 ±0.11
Rubber	6	14.12 ± 0.70 (*N* = 95)	17.32 ± 0.56 (*N* = 95)	2.21 ± 0.07	0.28 ± 0.03	7.55 ± 0.14	3.43 ± 0.08	1.34 ± 0.10
	22	33.76 ± 1.38 (*s* = 70)	23.23 ± 1.43 (*N* = 70)	2.18 ± 0.06	0.24 ± 0.05	6.49 ± 0.12	3.30 ± 0.07	1.35 ± 0.09

The data are mean ± SE

For oil palm maintenance, the fertilizer types used were Blue NPK (13:2:14) and organic, which were applied at the recommended amounts of 6.0 and 10.0 kg per tree per year, respectively, in three split applications per year. Meanwhile, the fertilizers for the rubber plantation were MPOB F1 (10:5.4:16.2), Blue NPK, and organic, which were applied at 8.0, 6.0, and 10.0 kg per tree per year, respectively, in three split applications per year. Oil palm stands were typically established on 8.8 m × 8.8 m × 8.8 m spacing and rubber stands on 7 m × 3.5 m, and averaging approximately 150 and 408 trees per hectare, respectively. The chronosequence technique in the present study presents an integration of a forest type with different ages as a unit, replacing space for time (Wellock, Rafique, LaPerle, Peichl, & Kiely, 2014). The condition of sites is approximately identical so as to reduce variability besides the age stand features. There was no fertilization and maintenance executed on the stands during the research.

Experimental Design

The experiment was done in the field for three consecutive months by using random sampling method. Forest types (oil palm and rubber) and age stand (6- and 22-year-old) were used as factors influencing soil CO_2 efflux. Three replications for each stand age, measuring 50 × 50 m plots for oil palm and 25 × 50 m plots for rubber plantations, were randomly selected for soil CO_2 efflux measurements. The replications represented by 12 stands were distributed across four geographical blocks. Subplots were established in selected plots, each measuring 25 × 25 m for the oil palm plantation, and 25 × 50 m for the rubber plantation. The chosen subplots were then specified to 1 m^2 plot grids through random number generator for the soil collar installation to account for within-stand variability.

Measurements of Soil CO_2 Efflux and Environmental Factors

Soil CO_2 efflux (g CO_2 m^{-2} h^{-1}) was measured using a portable LI-8100A Automated Soil CO_2 Flux System (Li-Cor Inc., Lincoln, NE) with a 20-cm-sized chamber connected to an infrared gas analyzer (IRGA, LI-8100A, Li-Cor Inc., Lincoln, NE). Soil collars (measuring 100 mm high and 200 mm diameter) were installed approximately at 80 mm soil surface depth 2 weeks prior to soil respiration measurements to avoid biases due to soil disturbance during collar installation. Litterfall of approximately 1 m radius, around and within the soil collar, was manually removed from the soil surface. Soil CO_2 effluxes were measured hourly at intervals of 2 min from 0900-1700 h. Soil CO_2 efflux measurements were taken on a bi-monthly basis for 3 months from April to July at each forest type. LI-8100A instrument software program was used to analyze the primary data of soil CO_2 efflux measurements.

Soil temperature and soil relative humidity (RH) were simultaneously measured using two probes connected to the LI-8100A gas analyzer recorder at approximately 80 mm soil depth. Air temperature and RH were recorded hourly throughout the study period using a data logger weather station (WatchDog Model 2475 Plant Growth Station, Spectrum Technologies) placed within 50 m of the study sites. All the measurements were taken in triplicates. Soil sampling was conducted to determine soil pH, bulk density (BD), soil organic content (SOC), carbon (C), and nitrogen (N). Using a soil auger, three samples were collected randomly from each plot to yield composite samples of soil at 0–30 cm depths. The soil samples were air dried for 3 days, ground, sieved through a 2-mm sieve, and stored in sealed plastic bags before further laboratory analysis. SOM was determined using a conversion factor of 1.72, where organic matter was assumed to contain 58% organic carbon using equation:

$$\text{Organic matter (\%)} = \\ = \text{Total organic carbon (\%)} \times 1.72 \quad (1)$$

Total C and N concentration were measured using the CN-element analyzer (PE 2400 II CHN elemental analyzer; Perkin-Elmer, Boston, MA). Soil pH was determined in salt solution 1:2.5 dilution of potassium chloride (KCl). BD was determined using the soil analysis standard method (Blake, 1965).

Statistical Analysis

All the statistical analyses were conducted using SPSS software 23 (SPSS Inc., Chicago, IL, USA). Normality and homoscedasticity data were tested with the Kolmogorov–Smirnov and Levene's tests, respectively, and no significant deviations from normality or homoscedasticity were found. A two-way analysis of variance (ANOVA) and Tukey's honestly significant (HSD) tests were used to examine the effects of land use types and chronosequence on soil CO_2 efflux. Meanwhile, one-way ANOVA and Tukey's HSD tests were used to examine the effects of temporal variations and plot on soil CO_2 efflux, with $P < 0.05$ being at significant level. In order to examine soil CO_2 efflux–soil temperature relations, regression analysis was conducted using a classic parametric exponential model (Lloyd & Taylor, 1994):

$$\text{Soil } CO_2 \text{ efflux} = \alpha e^{\beta T} \tag{2}$$

where T = soil temperature (°C) at 80 mm depth, α and β = regression coefficients.

The temperature sensitivity of soil respiration on soil temperature, expressed by Q_{10} which is the difference in respiration rates over a 10°C interval, was calculated using the equation (Boone, Nadelhoffer, Canary, & Kaye, 1998):

$$Q_{10} = e^{10\beta} \tag{3}$$

A linear function model (Han, Huang, Liu, Zhou, & Xiao, 2015) was used to describe the relationship between soil CO_2 efflux and soil RH:

$$\text{Soil } CO_2 \text{ efflux} = \alpha_1 \text{RH} + \beta_1 \tag{4}$$

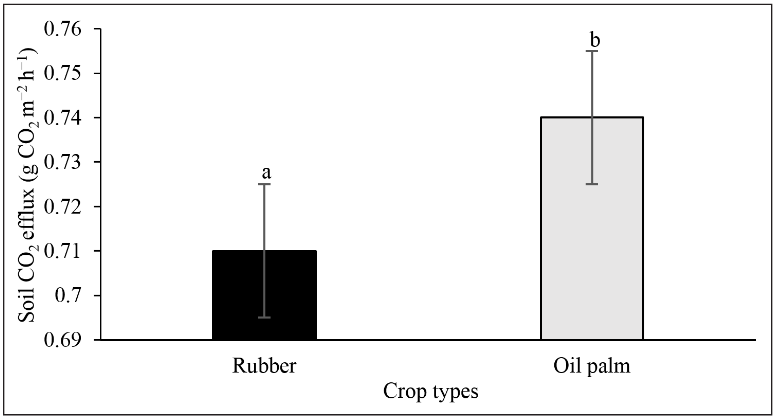
where RH = soil RH, and α_1 and β_1 are the fitted parameters.

RESULTS AND DISCUSSION

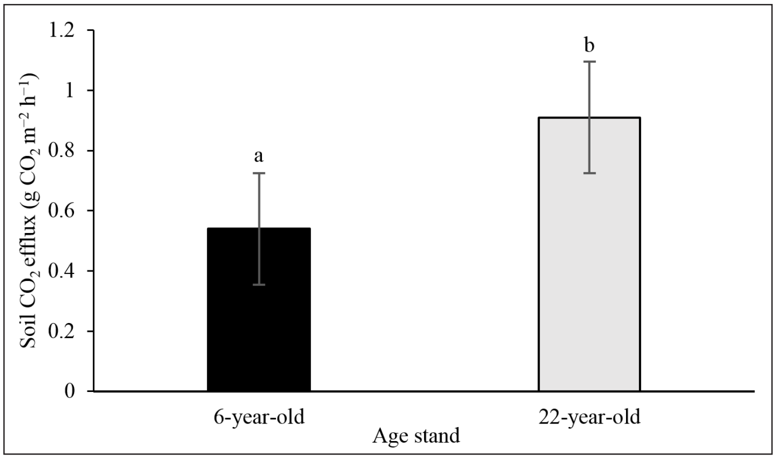
Soil CO_2 Efflux Spatial Variations

A two-way ANOVA assessed the effects of two land uses, which were oil palm plantation and rubber plantation at the age stands of 6 years and 22 years, respectively, on soil CO_2 efflux. There was a statistically significant interaction between the forest types and chronosequence on soil CO_2 efflux, $F(1, 104) = 241$, $P < 0.05$. It was found that forest types had a statistically significant result, indicating the differences in the mean values between oil palm (M = 0.74; SE = 0.01 g CO_2 m^{-2} h^{-1}) and rubber (M = 0.71; SE = 0.01 g CO_2 m^{-2} h^{-1}), $F(1, 104) = 4.15$, $P < 0.05$, which influenced soil CO_2 efflux. The age effect was also shown to be statistically significant on soil CO_2 efflux, $F(1, 104) = 364.09$, $P < 0.05$ (Figure 1a). The 22-year-old ecosystem age stand (M = 0.91; SE = 0.01 g CO_2 m^{-2} h^{-1}) had significantly higher soil CO_2 efflux than the 6-year-old ecosystem age stand (M = 0.54; SE = 0.01 g CO_2 m^{-2} h^{-1}), as shown in Figure 1(b).

The present study contradicts with that of Zhao et al. (2016), where no significant effect of forest types on soil CO_2 efflux



(a)



(b)

Figure 1. Soil CO_2 efflux between: (a) crop types; and (b) age stand; means with different letters indicate significant differences ($P < 0.05$)

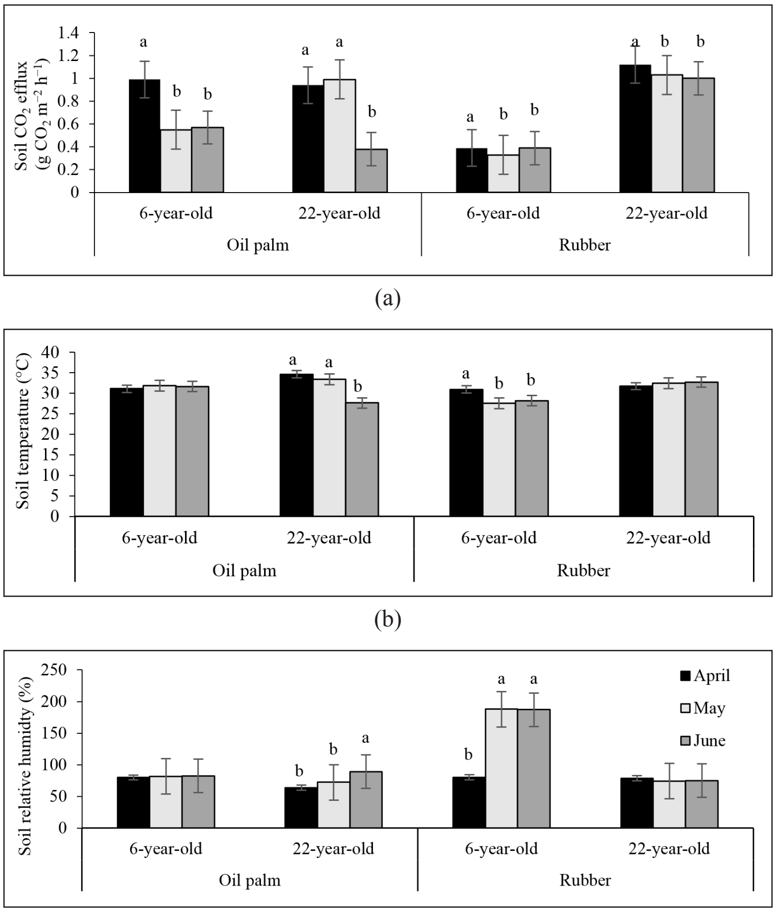
was found within a tropical region. The difference in the findings of soil CO_2 efflux is most likely caused by the tree species at different regions (Wang et al., 2016). Both oil palm and rubber plantations had a similar pattern, whereby soil CO_2 efflux increases with the age of stand. Older stands have higher soil CO_2 efflux compared with younger stands (Yan, Zhang, Zhou, & Liu, 2009). The increase of soil CO_2 efflux with age was associated with the differences in canopy density, fine root biomass, and soil substrates (Zhao et al., 2016). However, the present findings contradicted with other studies, where younger stands revealed higher soil CO_2 efflux due to the abundance of fine root biomass in younger stands, or forest carbon input, and canopy density (Mande et al., 2014a; Wang et al., 2017).

Younger oil palms in the present study (0.70 g CO_2 m^{-2} h^{-1}) had an approximately similar range of soil CO_2 efflux to that of Mande et al. (2014a) with 0.52 g CO_2 m^{-2} h^{-1} recorded at Pasoh Reserve Forest. Meanwhile, the soil CO_2 efflux of the 22-year-old stand (0.77 g CO_2 m^{-2} h^{-1}) at the oil palm plantation was only slightly higher than the younger stand in the present study. Adachi, Bekku, Rashidah, Okuda and Koizumi (2006) reported a higher soil CO_2 efflux with 0.97 g CO_2 m^{-2} h^{-1} at the 28-year-old oil palm plantation, which was also recorded at Pasoh Forest Reserve. As for the rubber plantation, the present study recorded lower soil CO_2 efflux (0.35 g CO_2 m^{-2} h^{-1}) compared with readings from other locations reported by Mande et al. (2014a) with 0.74 g CO_2 m^{-2} h^{-1}. Another reason for the lower and variation in soil CO_2 emissions from the younger stand was the accumulation of recalcitrant C in the soil (Table 1) as a result of higher stability in soil mineral particles (Zhao et al., 2016). Besides, forests at different developmental stages have varied changes in terms of the aboveground and belowground quantity and quality of litterfall affecting soil CO_2 efflux (Tedeschi et al., 2006).

In the present study, the values of soil CO_2 efflux recorded were <1, which are similar to the primary and secondary tropical forest types. The highest soil CO_2 efflux recorded in the 22-year-old rubber plantation was 1.05 g CO_2 m^{-2} h^{-1}. Soil CO_2 efflux is one of the fundamental terrestrial C cycling components that is controlled by various environmental factors, and varies spatially that sometimes result in contradictory findings due to the complex interactions between factors (Martin & Bolstad, 2009). One of the main reasons is the difference between the morphological structure of oil palm and rubber trees. Oil palms are single stemmed with pinnate leaves, while rubber trees are tall several-stemmed deciduous trees with three leaflets and spirally arranged leaves with inflorescences. Younger stands had less soil CO_2 efflux caused by the canopy photosynthesis reduction from less litter inputs which eventually reduce C substrates supply to microbes (Gong et al., 2014). Gong et al. (2014) explained that litter quality modifies utilization pattern of soil microbes affecting the soil characteristics such as the BD. The morphological difference and low-density influence root biomass, soil microbial biomass, and belowground C inputs such as roots, exudates, and also litter into the soil (Yan et al., 2009). Meanwhile, spatial and temporal variations of soil CO_2 efflux are attributed to the total aboveground and belowground biomass and forest carbon stock resulting from forest disturbance and land conversion (Mande et al., 2014a). Over time, changes take place in the species composition, soil functions, and processes such as biology, soil organic matter, and biogeochemical cycles (Yan et al., 2009). In the present study, mature stands had higher biomass from litterfall received from larger morphological characteristics (leaves, branches, stems, and roots) and subsequently triggered decomposition on the soil surface that increased microbial activity which eventually released soil CO_2 efflux. On the chronosequence, there was incremental growth in tree biomass that caused changes in the total ecosystem C (Wellock et al., 2014). The results indicated that the older the stand age, the higher the release of CO_2 from the soil into the atmosphere.

Temporal Variability of Soil CO_2 Efflux and Environmental Factors

Temporal variations of soil CO_2 efflux revealed a significant effect ($P < 0.05$) at both oil palm and rubber plantations throughout the investigation. During the period from April to June 2016, soil CO_2 efflux was the highest in April (0.33–1.12 g CO_2 m^{-2} h^{-1}) for all stand ages, except in June for the 22-year-old oil palm, as illustrated in Figure 2(a). Meanwhile, significant temporal variations were also recorded between the monthly variations of soil temperature and soil RH in older oil palm stand and younger rubber plantation, as shown in Figures 2(b) and 2(c). Soil temperature and soil RH



(a)

(b)

(c)

Figure 2. Mean monthly values (±SE) of (a) soil CO_2 efflux in relation to (b) soil temperature, and (c) soil RH, for four study plots; different letters indicate significant differences between months across oil palm and rubber plantation at both 6- and 22-year-old ($P < 0.05$)

had contradictory patterns every month. Meanwhile, air temperature and air RH were not significant throughout the months. Soil temperatures were the highest during April and the lowest during June, ranging from 25-35°C, whereas soil RH produced the opposite results from 50-190%. The overall temporal parameters also did not portray any association and no discernible trends with each other throughout the investigation.

These findings are in contradiction with the previous results reported by Wellock et al. (2016) who found a similar pattern of soil CO_2 efflux changes between 1–2 years old, 4–6 years old, 8–12 years old, and 20–25 years old of *Pinus taeda* (loblolly pine) throughout the year. This rather contradictory result might be due to the differences in soil characteristics and climatic factors on seasonal changes between two different regions leading to soil CO_2 efflux variation. A number of studies on soil CO_2 efflux have documented a distinct temporal dependency governed by abiotic factors such as soil temperature and soil water content (Davidson, Verchot, Cattânio, Ackerman, & Carvalho, 2000; Wang et al., 2016). Hourly observation was also done on the trends in soil CO_2 efflux from 0900 h until 1700 h at all stand ages (2°59′ N, 101°43′ E). Soil CO_2 efflux pattern was similar for all the plots, whereby from 0900 h, the efflux was found to be consistent until it reached the peak at 1300 h and fluctuated until 1400 h, after which the effluxes remained consistent. The 22-year-old rubber plantation had significantly higher rates of soil CO_2 efflux compared to other stands (Figure 3).

The rubber stands also portrayed slightly higher soil CO_2 efflux emission than oil palm stands. Rubber and oil palm possess similar growth requirements such as deep soils, high and stable temperature, as well as constant moisture (Verheye, 2010). The higher soil CO_2 efflux in rubber are most

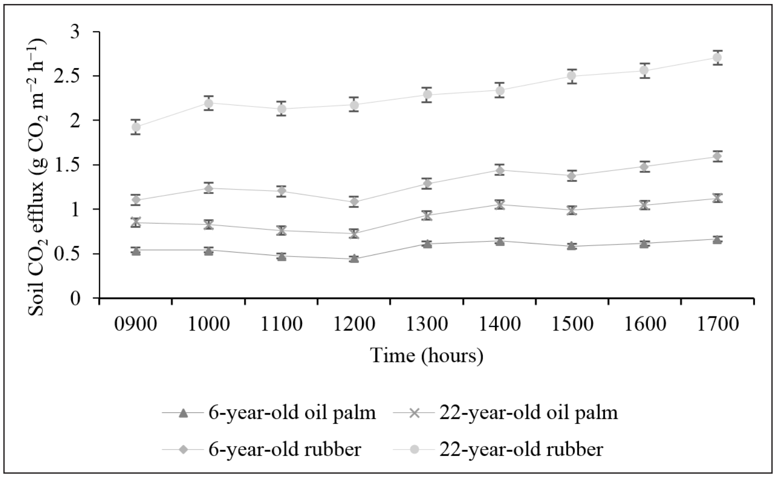


Figure 3. Soil CO_2 efflux trends during the measurement period of study (mean ± SE)

likely caused by the presence of flowers, fruits, and seeds that fall off after certain period of time. Thus, resulting in better quality and quantity of litterfall for vigorous microbial decomposition. The gradual increase of soil CO_2 efflux from morning to afternoon (at 1400 h) was due to the rise in soil temperature when photosynthesis and other plant metabolic activities started to take place. The physiological and metabolic processes reached the optimum state at 1400 h, and then slowed down, indicating the decrease of soil CO_2 efflux. Temporally, soil temperature and soil RH were the main factors controlling the variation in soil CO_2 efflux, suggesting the marginal impact differences in mature oil palm and younger rubber plantations in the present study. Meanwhile, Figure 4 shows a more detailed trend of soil CO_2 efflux every month at each plantation (bi-monthly soil CO_2 efflux measurements). There is an inconsistent variation in the temporal pattern of soil CO_2 efflux reflecting the nature of the field phenomena. Therefore, other factors that could be affecting the temporal trends of soil CO_2 efflux need to be studied, preferably on a longer period.

Relationship between Soil CO_2 Efflux and Soil Temperature and Soil RH

Q_{10} is commonly applied to describe the dependence of soil CO_2 efflux with soil temperature as soil temperature is also accounted as one of the most important drivers of soil CO_2 efflux (Tang et al., 2015). Besides that, the relationship between soil CO_2 efflux and soil temperature is often described exponentially in many different types of forest (Wang et al., 2017). There are several studies investigating Q_{10} values at different soil depths and soil temperatures, with results ranging from 1 to 4 (Davidson & Janssens, 2006; Shi et al., 2014).

Even though Q_{10} indicates an important relationship portraying temperature sensitivity towards soil CO_2 efflux (Zhao et al., 2016), that is not the case in the present study. Soil temperature dependence at all sites had weak positive relationships with soil temperature and this is similar with other published findings (see Yi et al., 2007; Wang et al., 2016) in the tropical and subtropical forests compared to temperate forests (Davidson et al., 2000; Yi et al., 2007). In the present study, oil palm and rubber plantations at both young and mature stands had Q_{10} values in the range of 1 (less sensitive to temperature changes). Meanwhile, the Q_{10} values of soil CO_2 efflux in an oriental arborvitae forest and bare land were 1.97 and 1.43 at a semiarid ecosystem in China (Shi, Yan, Zhang, Guan, & Du, 2014), which were slightly higher than the present study conducted in a tropical ecosystem at 1.05–1.17. Q_{10} having the value of 1 indicates that soil temperature is less sensitive due to water stress that reduces the substrate supply from less organic matter decomposition process (Davidson & Janssens, 2006).

The main reason for the weak relationship was the temporal scale executed in the study. The soil CO_2 efflux measurements (3–5 months) may have confounded the relationship between soil

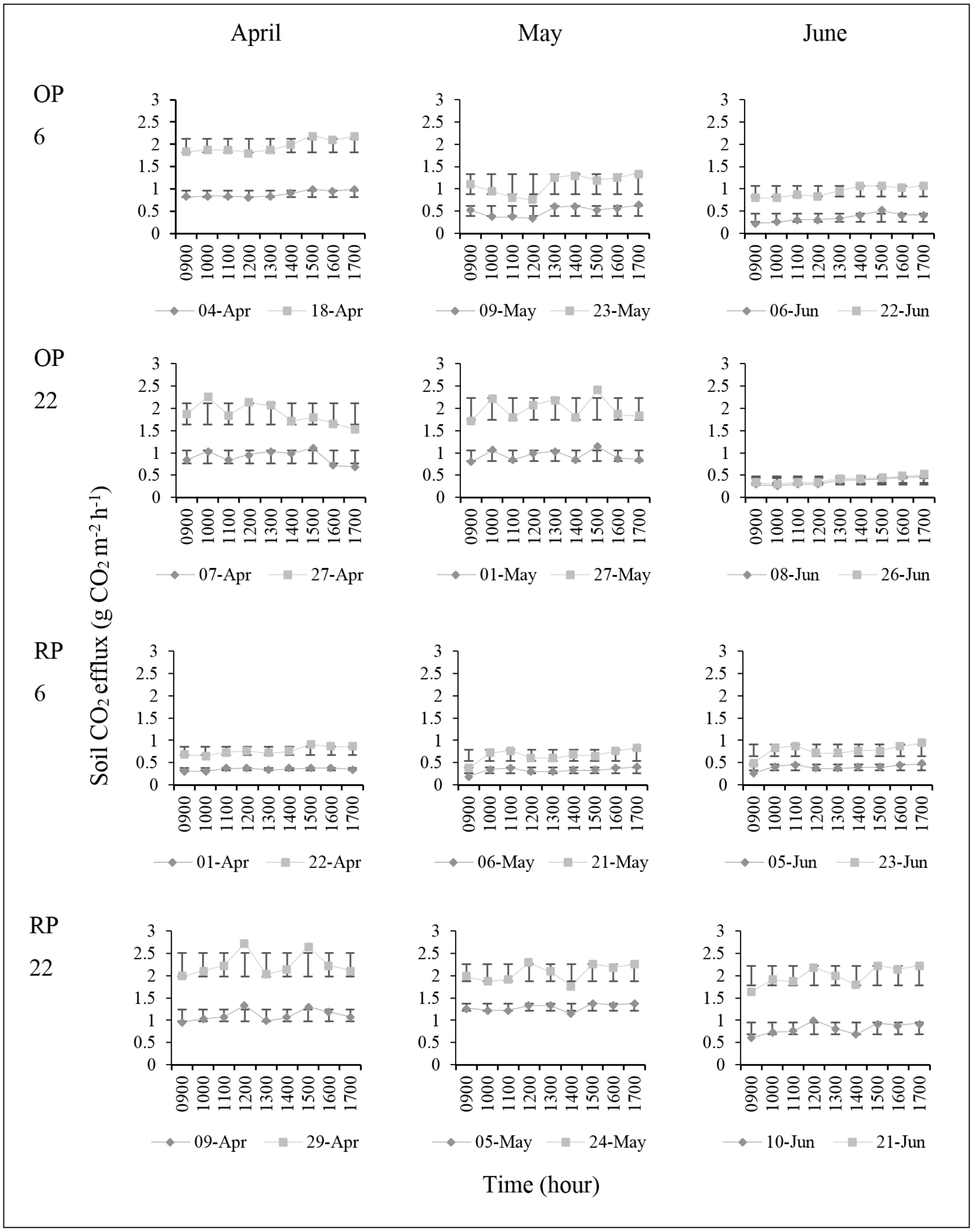


Figure 4. Soil CO_2 efflux trends during the measurement period of study per month at OP 6 (6-year-old oil palm), OP 22 (22-year-old oil palm), RP 6 (6-year-old rubber), and RP 22 (22-year-old rubber) plantation (mean ± SD)

CO_2 efflux and soil temperature such as root growth/mortality, seasonality, and litter inputs, resulting in Q_{10} not suitable for the measurement of temperature sensitivity (Adachi et al., 2006; Yuste, Janssens, Carrara, Meiresonne, & Ceulemans, 2003). Lower Q_{10} was caused by high temperatures that reduced the enzymatic and substrates activities for respiration (Zhao et al., 2016). Studies have shown that in humid and semi-humid regions, effects of soil RH on soil CO_2 efflux are weak due to sufficient water available in the soil pore spaces and microbial activities (Liu et al., 2006). The present findings showed soil temperature played non-significant role that affected soil CO_2 efflux compared with soil RH. Nonetheless, soil RH only significantly affected soil CO_2 efflux at younger stands spatially. The results in present study are similar to that reported by Gong et al. (2014), where soil RH is the primary constraint, and soil temperature plays a secondary role in influencing soil CO_2 efflux.

Nonetheless, the relationship between soil CO_2 efflux and soil RH is varied and complex, and often regulated by site specific. In fact, soil CO_2 efflux varies according to time and space where soil temperature and soil RH are the necessary environmental drivers for the variation (Adachi et al., 2006). The chronosequence studied in the present experiment should be expanded for the next few years, assessing for the repetition of younger sites or older ones for further insight on soil CO_2 efflux from forest establishment and management (Wellock et al., 2014).

CONCLUSION

The present study has shown that different types of land use had significant influence on soil CO_2 efflux. Age factor also played an important role in controlling soil CO_2 efflux, where older stands emit higher CO_2 efflux from soil. The significant differences on soil CO_2 efflux were associated with the changes in land structure leading to the evolution in soil CO_2 efflux variations, especially the morphological and physiological aspects which eventually contributed to the litterfall quantity and quality for decomposition and microbial biomass. Besides that, major environmental influences on soil CO_2 efflux were soil temperature and soil RH, which reacted differently in different forest types and age stand, as well either spatially or temporally. The non-discernible trends of temporal soil CO_2 efflux, soil temperature and RH indicated other significant factors could be the catalysts and thus, further research is required for justification.

However, no harm or degrading effects from soil CO_2 emissions resulted from the establishment of forest plantations recorded in the study. Proper decision making for an establishment of a large-scale plantation area is essential to reduce deteriorating impacts towards maintaining a sustainable ecosystem. The findings obtained from this study provide invaluable information to better understand the effects of human interferences, especially from the establishment of forest plantations on soil CO_2 efflux due to its close association with C cycle and climate change. Nonetheless, there is still a need for continuous and improved measurement of soil CO_2 efflux for future research.

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