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Original Research

A Comparison of Soil CO_2 Efflux Rate in Young Rubber Plantation, Oil Palm Plantation, Recovering and Primary Forest Ecosystems of Malaysia

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Abstract

Tropical deforestation and land conversion has been an environmental challenge over time and this is likely to have wide-reaching consequences for soil CO_2 efflux. Such soil-carbon dynamic disturbances are critical in light of climate change, as tropical forests store almost 30% of global forest carbon. Soil CO_2 efflux and environmental factors were determined in four different forest ecosystems of primary *Dipterocarp* forest, a 50-year-old recovering *Dipterocarp* forest, and a 5-year-old rubber and oil palm plantation using an automated soil CO_2 chamber technique (Li-Cor 8100) with an in-built infrared gas analyzer. The forest sections are located within 1,800 m of each other while the plantation is 1,500 m away in the tropical lowland forest of Pasoh, Peninsular Malaysia. The aim was to determine the influence of environmental factors influencing soil CO_2 efflux in relation to different forest ages and stand densities as a result of forest disturbance. Multiple regression analysis has been conducted on the relationship between soil CO_2 and environmental factors. Soil CO_2 efflux rate was found to range from 1.47-13.22 $\mu molCO_2\ m^{-2}{\cdot}s^{-1}$ (5.37 $\mu molCO_2\ m^{-2}{\cdot}s^{-1}$), 1.18-10 $\mu molCO_2\ m^{-2}{\cdot}s^{-1}$ (5.107 $\mu molCO_2\ m^{-2}{\cdot}s^{-1}$), 0.88-12.07 $\mu molCO_2\ m^{-2}{\cdot}s^{-1}$ (3.260 $\mu molCO_2\ m^{-2}{\cdot}s^{-1}$), and 2.33-7.89 $\mu molCO_2\ m^{-2}{\cdot}s^{-1}$ (4.678 $\mu molCO_2\ m^{-2}{\cdot}s^{-1}$) in the 50-year-old recovering forest, primary forest, oil palm plantation, and rubber plantation, respectively. Likewise, the highest forest biomass occurred in the primary forest and was followed by the 50-year-old recovering forest, rubber and oil palm plantation. Although the mean soil CO_2 efflux rate did not differ significantly, differences were evident in the environmental factors such as soil temperature and moisture occurring at a range of 23 to 32°C and 15 to 35.56%, respectively, to influence soil CO_2 efflux. The highest CO_2 efflux rate was recorded in the 50-year-old recovering forest and followed by the primary forest, and rubber and oil palm plantation. The finding revealed a significant and strong correlation

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between soil CO_2 efflux and soil temperature, moisture, and forest carbon input. Furthermore, the spatial variation in soil CO_2 efflux was attributed to total above-ground biomass, below ground biomass, and forest carbon stock. We can conclude that the spatial variation in Soil CO_2 efflux across the four different forest ecosystems is as a result of forest disturbance and land conversion triggering changes in environmental factors as well as forest carbon, thereby increasing microbial activity to emit soil CO_2.

Keywords: forest ecosystem, recovering forest, plantation, primary forest, soil CO_2 efflux, soil temperature

Introduction

Knowledge of soil CO_2 efflux from different forest ecosystems, forest disturbances, and land conversion is important in estimating future atmospheric CO_2 contributions from the tropical forest, as climate change may trigger feedback between the atmosphere and forest ecosystems due to forest disturbance effects on soil CO_2 efflux, plant respiration, and changes in soil properties [1, 2]. A good determination of soil CO_2 efflux from various ecosystems will play a significant role in understanding the global carbon cycle and ecosystem [3]. Soil CO_2 efflux in the terrestrial ecosystems has been estimated to be 55-85% [4, 5], while the tropical forest annual net primary productivity is estimated to be 32% [6]. A large amount of carbon has been found in the tropical soil and forest equivalent to 37% of global forest carbon pool [7], and the carbon sink of the tropical forest is estimated at 1-3 Pg·C·y^{-1} (1 Pg =10^{15}) [8]. Therefore, understanding the rationale and dynamics of soil CO_2 efflux in various forest ecosystems, forest disturbance, and land conversion is of importance in completing the jigsaw puzzle of global carbon cycles and climate change issues. Tropical forests in Asia are rapidly being converted to secondary forests, oil palm, rubber plantation, and logging activity for timber wood and deforestation to permanent croplands. These scenario account for an estimated 75% of total CO_2 efflux from the tropical forest [9]. Annual carbon flux due to changes in forests disturbance and land conversion from the tropical forests of Asia was estimated at 0.88 Pg·C·y^{-1} in the 1980s and 1.09 Pg·C·y^{-1} in the 1990s, and this was attributed to deforestation and land conversion, [10].

Soil CO_2 efflux from the soil of terrestrial ecosystems is a major factor responsible for the global carbon cycle. Soil CO_2 efflux has been determined in various terrestrial ecosystems in several locations in the world [11], such as cropland [12], tropical bare soil [13], boreal forest [14], temperate forest [15], semi-arid steppe [16], neotropical rain forest [17], subalpine forest [18], and plantations [19]. Likewise, various techniques were involved, such as the eddy covariance technique for aboveground measurement and closed portable chamber system for below-ground CO_2 efflux measurement, [20]. Furthermore, carbon stock measurements from the forest floor was also conducted by collecting soil samples in the field and analyzed in the laboratory using an elementary analyzer [21]. A Licor 6400 system was used in virgin beech forest stands on a silicate bed rock [22] and open flow chamber system (CFX-2PP) was used to established the diurnal pattern of soil efflux in a *pinus densifloral* forest ecosystem in central Korea [23].

The stated methods of soil CO_2 determination were done to understand the dynamics of the CO_2 efflux of various forest ecosystems, although many factors such as physical and biological processes regulate soil CO_2 efflux as it varies with time and space. The various studies have shown considerable soil CO_2 emissions in relation to soil temperature and moisture playing a dominant role, and soil carbon organic serving as predicting factors [10, 24]. However, there are knowledge gaps on the soil CO_2 efflux and environmental factors for forests of different ages and stand densities and tropical forest plantations [25]. Soil CO_2 efflux estimation from forests of different ages, plantations, and associated environmental factors using an automated soil CO_2 chamber to minimize error in an over or underestimation due to chamber effect [26-28], will be pivotal for developing a standard to determine carbon efflux in various forest ecosystems of the tropics [29, 30].

Understanding the factors responsible for soil CO_2 efflux is important for estimating and predicting changes in these parameters caused by changes in deforestation, logging, and land conversion. The objectives of this study were:

(1) To determine soil CO_2 efflux rates in different forest ecosystems resulting from forest disturbances and land conversion.

(2) To examine the factors responsible for soil CO_2 efflux rates in primary and recovering forests and rubber, and oil plantations.

Materials and Methods

Site Description

Four different ecosystems were selected (primary and 50-year-old recovering forest, oil and rubber plantations) to consider and compare the spatial variability of soil CO_2 efflux, and the effect of forest disturbance and land conversion on environmental factors. The entire study area is located within the same axis of the *Dipterocarp* forest reserve of Pasoh, Negeri Sembilan, 110 km southeast of Kuala Lumpur, Peninsular Malaysia. The succession 5-year-old rubber plantation is at latitude N03 00 19.8 and E102 14 17, and the 5-year-old oil palm plantation is at latitude N02 18 41.3 and E 102 17 11.3, located 1,500 m from each other. The 50 years recovering forest is at latitude Nº258 15·4 and E1º218 41·3 with the primary forest at latitude N02 58 18.6 and E102 17 59.6, located within 1,800 m apart. The four experimental plots are of 6 m × 20 m sizes with 30 sampling points in each. The climatic condition is equatorial, characterized by high even temperature and heavy rainfall with no distinctive season. The average rainfall is 2,000 mm with a range of 1700-3200 mm [31] and the average daily temperature is 38ºC. The soil is classified as ultisol [32] while the species of trees in both the primary and the recovering forest are *dipterocarpa-ceae* and *leguminosae* (*malaccensis cornutus* and *koompassia*) with an extended height of about 50 m, and over 800 species are spatially spread in the forest [31, 33].

The primary and recovering forests are of closed canopy density, heavily shaded, damp, and highly humid. Thick roots were observed but thicker in the primary forest, while the rubber and oil palm plantations have relatively wide open canopy densities. Soil CO_2 efflux and environmental conditions were measured to cover the entire seasons.

Soil CO_2 Efflux Measurement

The soil CO_2 efflux was measured using an automated soil CO_2 10 cm chamber (Li-Cor 8100) with an in-built infrared gas analyzer, an advanced model of chamber technique. The chamber is automatically calibrated and the pressures both inside and outside the chamber were kept in a dynamic equilibrium state with no internal fan that may create pressure fluctuations inside the chamber. Prior to the measurement, a PVC two open-ended was inserted 3 cm into the ground and gasket foam placed in-between the chamber base and the PVC to prevent leakage and left for 24 hrs to establish an equilibrium state before commencing measurement. 30 sampling points at a distance of 5 m were set out in 6 m × 20 m plots in each of the ecosystems. The Li-Cor 8100 automated closed soil CO_2 chamber system, as the name implies, opened and closed automatically and was calibrated to a CO_2 standard and zero prior to field measurement. The chamber is placed on the soil collar and it automatically stabilizes itself with ambient atmospheric air before flushing out the air and then closes firmly to the ground floor automatically for a few minutes to allow soil CO_2 to concentrate. When steady rises in CO_2 concentration are achieved, measurements are then recorded. This in turn flushes out the concentrating CO_2. Two readings are recorded in each sampling point automatically within 3 mins and an average is taken before relocating to the next sampling point. All data are recorded and analyzed in the analyzer instantly.

Soil Temperature, Soil Moisture, and Forest Biomass Measurements

Soil temperature and soil moisture were measured automatically at a depth of 5 cm concurrently with the soil CO_2 efflux measurement using a soil temperature sensor and moisture probe connected to the gas analyzer recorder. Diameter breast height (DBH) using DBH tape, 1.3 m above the forest floor of each tree, were measured to calculate total above-ground biomass (TAGB), below-ground biomass (BGB), and total forest carbon (SOCs).

Statistical Analysis

Statistical analyses were conducted using statistical packages, analysis of variance (ANOVA), version 21.0 of the SPSS software (SPSS Inc., Chicago, Illinois, USA). One-way ANOVA was used to present the means ± based on the least significant difference (LSD) method, standard deviation of [n] and descriptive statistics to explain the normality of data distribution and the relationship of soil CO_2 with environmental parameters. Correlation analysis and multiple linear regression models were implemented to ascertain the impact of the environmental variable to soil CO_2 efflux, which has an advantage over common classical multiple regressions [18, 34-37] with the non-linear relationship method [38].

Results

Soil CO_2 Efflux

Soil CO_2 efflux showed fluctuation in the pattern of emission across the four ecosystems. The average means of soil CO_2 efflux in the 5-year-old rubber plantation was 4.679 µmolCO_2 $m^{-2}\cdot s^{-1}$ and it rose from 2.33 µmolCO_2 $m^{-2}\cdot s^{-1}$ in the morning between 1100-1200 hours to 7.89 µmolCO_2 $m^{-2}\cdot s^{-1}$ (1300-1500 hours) as the soil temperature increases (Table 1).

The oil palm plantation soil CO_2 efflux also followed a similar trend (Table 1), efflux recorded in the morning at 1000 hours was 0.88 µmolCO_2 $m^{-2}\cdot s^{-1}$ and increases with time to 12.07 µmolCO_2 $m^{-2}\cdot s^{-1}$ (3.260). The recovering forest displayed soil CO_2 efflux of 1.47 µmolCO_2 $m^{-2}\cdot s^{-1}$ and increased to 13.22 µmolCO_2 $m^{-2}\cdot s^{-1}$ by 1300 hours, indicating an average of 5.37 µmolCO_2 $m^{-2}\cdot s^{-1}$. (Table1), while the primary forest having an average of soil CO_2 efflux of 5.11 µmolCO_2 $m^{-2}\cdot s^{-1}$ with minimum efflux of 1.18 µmolCO_2 $m^{-2}\cdot s^{-1}$ at 1000 hours and increases to 10.11 µmolCO_2 $m^{-2}\cdot s^{-1}$ by 1200 hours. The highest soil CO_2 efflux was recorded in the recovering forest at an average of 5.37 µmolCO_2 $m^{-2}\cdot s^{-1}$ (Table1) compared to efflux in the primary forest with 5.11 µmolCO_2 $m^{-2}\cdot s^{-1}$ at a significant difference of $p<0.05$ (Table 1). Moderate soil CO_2 efflux was observed in the rubber plantation and oil plantation at an average of 4.68 µmolCO_2 $m^{-2}\cdot s^{-1}$ and 3.26 µmolCO_2 $m^{-2}\cdot s^{-1}$, respectively (Table 1). Soil CO_2 efflux in the two forest ecosystems were slightly higher than those of the plantation sites.

Effect of Soil Temperature and Moisture on Soil CO_2 Efflux

Soil temperature and soil moisture variation are similar in both forest ecosystems. The recovering forest was 24ºC (900 hrs-1000 hrs), increasing to 26ºC and 30ºC (1400 hrs

Table 1. Descriptive statistics of CO_2 efflux under study in μmolCO_2 $m^{-2}\cdot s^{-1}$ (CO_2).

	N	Mean	Std. Deviation	Std. Error	95% Confidence interval for mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Rubber Plantation	30	4.6788	1.73715	0.31716	4.0302	5.3275	2.33	7.89
Oil Plantation	30	3.2598	2.24357	0.40962	2.4221	4.0976	0.88	12.07
Secondary Forest	30	5.3708	2.76528	0.50487	4.3383	6.4034	1.47	13.22
Primary Forest	30	5.1073	2.35540	0.43004	4.2278	5.9869	1.18	10.11
Total	120	4.6042	2.41798	0.22073	4.1671	5.0413	0.88	13.22

to 1500 hrs) with soil moisture ranging from 17 to 26% and 30.9% (1400-1500 hrs). Similarly, such a trend was recorded in the primary forest with 25-28ºC from 900 hrs to 1500 hrs while soil moisture increased from 24 to 35.56% (900 hrs-1500 hrs). Soil temperature and moisture range varies in time in both rubber and oil palm plantation. Soil temperature increases with time from 25ºC (10.00 hrs) to 28.02ºC (1400-1500 hrs) and 23ºC (10.00 hrs) to 32ºC (1400-1500 hrs) for the rubber and oil plantation, respectively. Soil moisture was recorded at 15-24% and 15-23% in rubber and oil plantation, respectively (Fig. 1). Environmental parameters slightly vary across the four different sites, with forest ecosystems greater than the plantation.

Soil temperature and moisture correlate positively with the spatial variation in soil CO_2 efflux rate because they were both at parallel and increased with time. But the forest ecosystems showed higher efflux rates and environmental parameters compare to those of the plantations.

Total Above-Ground Biomass (TAGB), Below-Ground Biomass (BGB), and Forest Carbon Stock (SOCs)

Forest biomass input was estimated to ascertain total above-ground biomass (TAGB), below-ground biomass (BGB), and forest carbon stock (SOCs) in both forest and plantation. Their occurrence has a significant effect in contributing to carbon input for microbial activities to emit soil CO_2 efflux during breakdown of food. The forest hosts an estimated forest biomass of 4.8×10^6, 3.1×10^6, 2.6×10^6, and 2.5×10^6 of TAGB for primary forest, the recovering forest, rubber and oil plantation, respectively, while BGB was 8.9×10^6, 2.8×10^6, 2.2×10^6, and 2.0×10^6 in the primary forest, the recovering forest, rubber and oil plantation, respectively, and SOCs were found to be 10.6×10^6, 5.4×10^6, 4.1×10^6, and 3.9×10^6 for primary forest, the recovering forest, and rubber and oil plantation, respectively (Table 2). The enormous abundance of this forest biomass increases the soil nutrients and serves as a major source of food and energy for microorganisms to emit CO_2.

Discussion

Soil CO_2 Efflux

Field measurements of soil CO_2 efflux in the study area are insufficient to estimate an average annual soil CO_2 efflux. However, the effects of environmental variables and their impact on soil CO_2 efflux under different ecosystems,

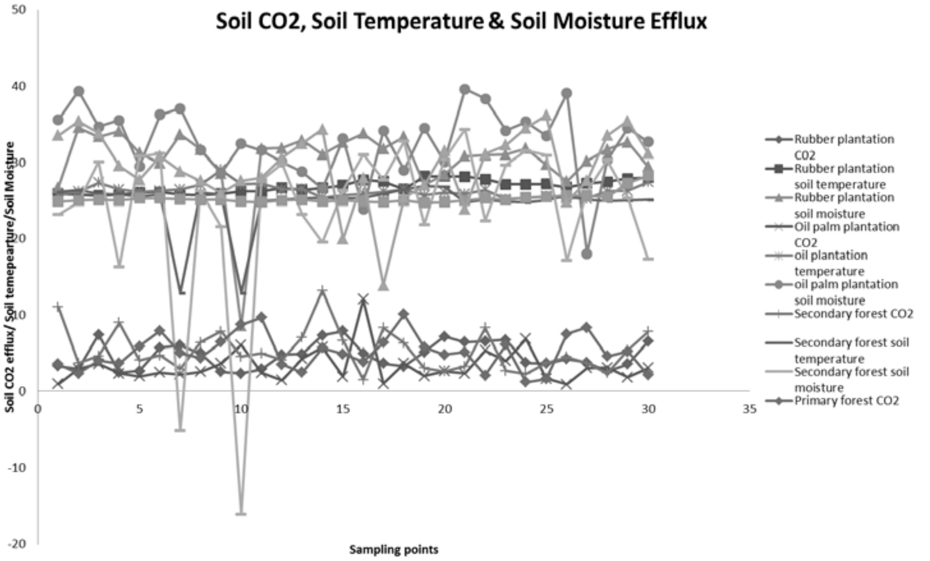

Fig. 1. Soil CO_2 efflux rate and influence of coil temperature and soil moisture at 5 cm.

Table 2. Biomass carbon input.

Ecosystem	TAGB	BGB	SOCs
Primary	4.8×10^6	8.9×10^6	10.6×10^6
50-year-old recovering forest	2.1×10^6	2.8×10^6	$5.\ 4\times10^6$
Rubber plantation	2.6×10^6	2.2×10^6	4.1×10^6
Oil plantation	2.5×10^6	2.0×10^6	3.9×10^6

TAGB – total above ground biomass, BGB – below ground biomass, SOCs – forest carbon stock

forest age, and plantation resulting from disturbances and land conversion can be determined. The measurement and estimation covered a considerable period of time while representing the various climatic seasons. The descriptive statistics of the environmental parameters from the study (Table 1) gave a summary of the mean, standard deviation and the range of measured parameters, with the 50-year-old forest taking the lead and followed by the primary forest and rubber and oil plantations, respectively.

The soil CO$_2$ efflux found in the primary forest ranged between 1.18-10.11 μmolCO$_2$ m^{-2}·s^{-1} as reported by Matjaz in a virgin beech forest of Slovenia using Li-Cor 6400-09, having soil CO$_2$ efflux of 2.9-11.8 μmolCO$_2$ m^{-2}·s^{-1} [22] and also similar to soil CO$_2$ efflux of 0.5- 6 μmolCO$_2$ m^{-2}·s^{-1} of an old unmanaged deciduous forest in central Germany [20]. The similarity in soil CO$_2$ efflux may have been that both ecosystems are primary forests under similar environmental factors and forest carbon input. The 50-year-old recovering forest displayed a soil CO$_2$ range of 1.47-13.22 μmolCO$_2$ m^{-2}·s^{-1} compared to those observed in a 70-year-old *pinus densifloral* forest in central Korea [23], and a loblolly pine forest plantation of the virgin Piedmont and South Carolina [39] ranging from 1.1-8.5 μmolCO$_2$ m^{-2}·s^{-1}. Previous studies reported that such spatial variation in soil CO$_2$ efflux could be influenced by soil physiological activities, soil temperature, and moisture, with predictor factors such as microbial respiration, root growth, and litter fall carbon input [40, 41]. Moderate soil CO$_2$ efflux recorded in the rubber plantation having a mean of soil CO$_2$ efflux of about 4.68 μmolCO$_2$ m^{-2}·s^{-1} similar to the pine plantation ecosystem 4.78 μmolCO$_2$ m^{-2}·s^{-1} in southeastern China [42], and the temperate deciduous forest of 4.12 μmolCO$_2$ m^{-2}·s^{-1} and 4.11 μmolCO$_2$ m^{-2}·s^{-1} using a portable infrared chamber system [43]. While efflux rates observed in the oil palm plantation ranges between 0.88- 12.07 μmol CO$_2$ m^{-2}·s^{-1} correlates to a similar reading with that of the daily reading of Florida slash pine plantation 0.238 μmolCO$_2$ m^{-2}·s^{-1} and 0.105 μmolCO$_2$ m^{-2}·s^{-1} [44]. The variation and increase in soil CO$_2$ efflux from the four ecosystems were attributed to forest carbon input and canopy density to accelerate microbial activity and root respirations as the predictor factors vary with time and season.

Temporal Variation in Soil CO$_2$ Efflux Relationship, Effluence, and Impact by Soil Temperature and Moisture

Partial correlation analysis (Guilford's rule of thumb) indicated a moderate to strong relationship between soil CO$_2$ efflux and environmental factors, meaning that any increase in soil temperature will increase the rate of soil CO$_2$ efflux. Application of entry method for multiple linear regression model with performing diagnostic collinearity with the model dimensions, displayed a conditional index within the acceptable threshold of 30.0 with no tolerance value below 0.10, indicating that no multicollinearity problem among the environmental variables in the model were encountered given that equality of variance, linearity, and

Table 3. Rubber plantation estimates of coefficient of the model of environmental parameters.

Model		Unstandardized Coefficients		Standardized Coefficients Beta	T	Sig.	Collinearity Statistics	
		B	Std. Error				Tolerance	VIF
1	(Constant)	-14.982	9.950		-1.506	0.144		
	RubberSoilTempt	0.643	0.362	0.316	1.776	0.087	1.000	1.000
	RubberSoilMoist	0.079	0.067	0.209	1.176	0.250	1.000	1.000

Table 4. Oil Palm plantation estimates of coefficient of the model of environmental parameters.

Model		Unstandardized Coefficients		Standardized Coefficients Beta	t	Sig.	Collinearity Statistics	
		B	Std. Error				Tolerance	VIF
1	(Constant)	10.236	13.346		0.767	0.450		
	OilplantationSoilTempt	-0.049	0.493	-0.018	-0.099	0.922	0.999	1.001
	OilplantationSoilMoist	-0.175	0.085	-0.367	-2.047	0.050	0.999	1.001

Table 5. Secondary forest estimates of coefficient of the model of environmental parameters.

Model		Unstandardized Coefficients		Standardized Coefficients Beta	t	Sig.	Collinearity Statistics	
		B	Std. Error				Tolerance	VIF
1	(Constant)	-10.916	4.775		-2.286	0.030		
	SecondaryFSoilTempt	0.931	0.252	1.100	3.687	0.001	0.271	3.688
	SecondaryFSoilMoist	-0.280	0.077	-1.082	-3.627	0.001	0.271	3.688

Table 6. Primary forest estimates of coefficient of the model of environmental parameters.

Model		Unstandardized Coefficients		Standardized Coefficients Beta	T	Sig.	Collinearity Statistics	
		B	Std. Error				Tolerance	VIF
1	(Constant)	19.639	13.650		1.439	0.162		
	PrimaryFSoilTempt	-0.324	0.556	-0.102	-0.583	0.565	0.934	1.071
	PrimaryFSoilMoist	-0.215	0.084	-0.445	-2.549	0.017	0.934	1.071

Table 7. Correlation statistics of environmental parameters under study (soil temperature and soil moisture).

	RCO2	OICO2	SCO2	PCO2	RST	OlST	SST	PST	RSM	OlSM	SSM	PSM
RCO2		0.092	0.046	-0.214	0.315	-0.200	0.069	0.045	0.208	0.112	0.123	0.006
		0.629	0.809	0.256	0.090	0.288	0.717	0.812	0.271	0.554	0.518	0.975
OlCO2	0.092		-0.153	-0.139	0.141	-0.005	-0.142	-0.111	-0.067	-0.366*	-0.058	0.177
	0.629		0.419	0.464	0.457	0.979	0.453	0.560	0.723	0.047	0.761	0.349
SCO2	0.046	-0.153		-0.035	-0.252	0.206	0.176	0.049	-0.004	-0.009	-0.143	-0.070
	0.809	0.419		0.856	0.179	0.275	0.352	0.798	0.985	0.962	0.451	0.712
PCO2	-0.214	-0.139	-0.035		-0.153	0.101	-0.169	-0.216	-0.316	-0.266	-0.153	-0.471**
	0.256	0.464	0.856		0.420	0.594	0.373	0.251	0.089	0.155	0.421	0.009
RST	0.315	0.141	-0.252	-0.153		-0.380*	0.224	0.321	-0.006	-0.067	0.278	-0.102
	0.090	0.457	0.179	0.420		0.038	0.233	0.084	0.977	0.726	0.137	0.591
OlST	-0.200	-0.005	0.206	0.101	-0.380*		-0.152	0.128	-0.144	-0.035	-0.250	-0.087
	0.288	0.979	0.275	0.594	0.038		0.421	0.500	0.448	0.855	0.182	0.648
SST	0.069	-0.142	0.176	-0.169	0.224	-0.152		0.023	0.522**	-0.109	0.854**	0.040
	0.717	0.453	0.352	0.373	0.233	0.421		0.904	0.003	0.567	0.000	0.835
PST	0.045	-0.111	0.049	-0.216	0.321	0.128	0.023		0.050	0.041	-0.051	0.258
	0.812	0.560	0.798	0.251	0.084	0.500	0.904		0.792	0.828	0.790	0.169
RSM	0.208	-0.067	-0.004	-0.316	-0.006	-0.144	0.522**	0.050		-0.010	0.628**	0.078
	0.271	0.723	0.985	0.089	0.977	0.448	0.003	0.792		0.957	0.000	0.682
OlSM	0.112	-0.366*	-0.009	-0.266	-0.067	-0.035	-0.109	0.041	-0.010		-0.139	0.040
	0.554	0.047	0.962	0.155	0.726	0.855	0.567	0.828	0.957		0.464	0.832
SSM	0.123	-0.058	-0.143	-0.153	0.278	-0.250	0.854**	-0.051	0.628**	-0.139		0.054
	0.518	0.761	0.451	0.421	0.137	0.182	0.000	0.790	0.000	0.464		0.775
PSM	0.006	0.177	-0.070	-0.471**	-0.102	-0.087	0.040	0.258	0.078	0.040	0.054	
	0.975	0.349	0.712	0.009	0.591	0.648	0.835	0.169	0.682	0.832	0.775	

*Correlation is significant at the 0.05 level (2-tailed).

**Correlation is significant at the 0.01 level (2-tailed).

normality classical assumption are met. Based on this it is conclusive that the estimated multiple linear regression models can be used to explain the impact of the environmental variables on soil CO_2 efflux.

The correlation showed a moderate to strong relationship between soil CO_2, soil temperature, and soil moisture with significance at $p<0.05$. Beta coefficient in rubber plantation indicated soil temperature and moisture at 0.0643 and 0.079, respectively, shows soil temperature and moisture having an impact on soil CO_2 efflux (Table 3). The oil palm soil temperature and moisture was analyzed to have a beta coefficient of -0.49 and -0.175, respectively, indicating environmental factors were at a constant as CO_2 was emitted, (Table 4). The beta coefficient in the recovering forest was analyzed to be 0.931 and -0.280 for soil temperature and moisture, respectively (Table 5), indicating soil temperature to have significant impact with soil moisture being at moderate level. Soil temperature and moisture in a primary forest occurred at -0.324 and -0.215 being at constant level as soil CO_2 efflux increases (Table 6). Likewise, correlation analysis for the four ecosystems confirmed a moderate to strong relationship between soil CO_2 efflux and environmental factors (Table 7).

Soil CO_2 efflux rates were positively correlated with soil temperature and moisture in the overall ecosystems and in certain cases where negative correlation exists. The major issue to be considered is the influence of soil temperature and moisture on belowground biotic activity and soil gas diffusion. It has been reported that aerobic microbial activity may play a major role at certain levels of soil temperature and moisture content occurrences [45]. Impact of soil temperature and moisture on soil CO_2 efflux is a result of seasonal and climate changes on environmental variables that play a key role [46]. Soil CO_2 efflux rates showed a significant positive correlation with TAGB, BGB, and SOCs in the whole ecosystem as it is responsible for soil nutrients as a source of food for microorganisms to release CO_2 [47]. However, the magnitude of contribution varies with the ecosystem, as the highest contribution was recorded in the primary forest and followed by recovering forest and rubber and oil plantations, respectively. The combined function of environmental factors and forest biomass on soil CO_2 efflux using excel stat (box plot) to compare efflux rate among the four ecosystems indicated higher soil CO_2 efflux in the recovering forest and followed by primary forest, oil palm, and rubber plantations, respectively (Fig. 2). For the normality of the distribution of data the Q-Q plot showed good normality distribution with no data deviating from normal distribution across the four-forest ecosystem (Fig. 3).

Our findings reveal that the canopy resulting from the age of the ecosystems significantly influences forest biomass input and environmental factors, as it explains the increase in net radiation and decrease in transpiration on the forest floor [48]. This situation results in an increase in microbial activity to release soil CO_2. Furthermore, forest disturbance and land conversion to plantations would influence environmental factors, thereby leading to soil CO_2 being emitted directly into the atmosphere. This result confirms the significant role played in a situation of forest disturbance and land conversion to trigger environmental factors to display soil CO_2 efflux.

Conclusion

The data indicated a high average soil CO_2 efflux of 5.371 µmolCO_2 $m^{-2}·s^{-1}$, 5.107 µmolCO_2, 4.679 µmolCO_2 $m^{-2}·s^{-1}$, and 3.260 µmolCO_2 $m^{-2}·s^{-1}$ in recovering forests, primary forest, and rubber and oil palm plantation ecosystems, respectively. The recovering forests having the highest and followed by primary forest and rubber, and oil plantations. The forest ecosystems are both older in age, of high stand and canopy density, and high relative humidity, and much litter falls on the forest floor compared to the plantation plots areas. These could increase forest biomass for soil

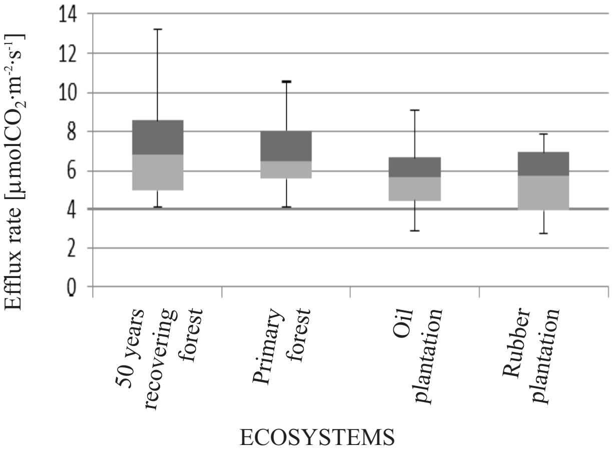

Fig. 2. Comparison of soil CO_2 efflux among ecosystems.

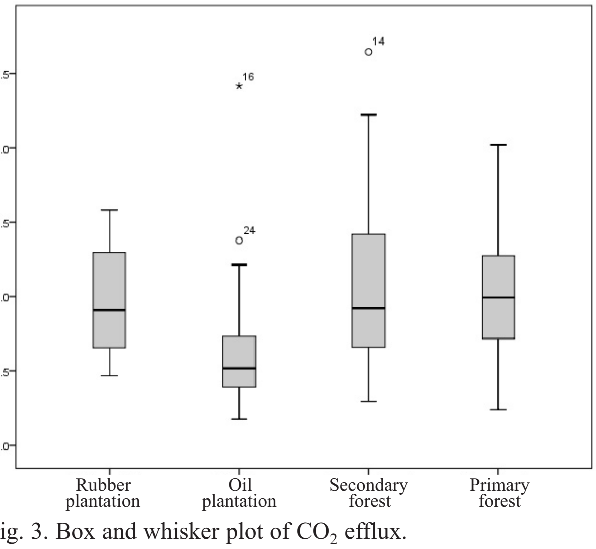

Fig. 3. Box and whisker plot of CO_2 efflux.

nutrients as the major energy source for microbial activity. Soil CO_2 efflux in the four ecosystems did not differ significantly; however, environmental factors influencing soil respiration could be different, such as land conversion (which always leads to differences in physical and chemical characteristics of soil, canopy cover, stand density, density in above and below ground biomass, and availability of resources for soil microbes). The scenario in the present study showed that soil CO_2 efflux in each of the sites are paramount when considering CO_2 efflux and carbon cycle. In addition, the interaction between soil CO_2 efflux, forest biomass, and environmental factors attributed to forest disturbance and land conversion are important when estimating a carbon cycle and its response to environmental changes resulting from human activity.

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