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Influence of Monsoon Regime and Microclimate On Soil Respiration In The Tropical Forests

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Abstract: *The consequence of precipitation and how environmental factors influence soil respiration remain poorly understood in the tropical forest ecosystems under a monsoon climate in Malaysia. This study was conducted in a recovering tropical lowland Dipterocarpus forest in Peninsular Malaysia, and its monthly variations were examined in association with changing precipitation. Soil respiration was measured using a continuous open flow chamber system connected to a multi gas-handling unit and an infrared gas analyser. The aim of this study was to determine the effects of the monsoon period and microclimate of the tropical region on soil respiration. The average monthly soil respiration rates were 152.79 to 528.67, 120.97 to 500.73, 106.77 to 472.89, 122.89 to 453.89 and 120.33 to 434.89 mg m^{-2} h^{-1} in the respective months from September to January. The emission rate varied across the days and months, with the highest value recorded between September and October, and then gradually decreasing from November to January. Soil temperature explained more than 90% of the soil respiration rate whereas precipitation had a major effect during the monsoon regime. Soil organic carbon (SOC), total organic carbon (TOC), soil organic carbon stock (SOCstock), forest biomass, carbon to nitrogen ratio (C/N) and soil pH were found to vary in considerable amounts, provide nutrients and the environment favourable for microorganism activities, leading to emission of soil CO_2. The low values of soil respiration rate between November and January were due not only on the amount of soil moisture and water potential but also on the intensity and frequency of precipitation. Therefore, these results indicate that the monsoon regime can significantly alter the emission of soil CO_2 and influence the microclimatic conditions and other environmental factors.*

Keywords: *Bulk density- Environmental factors- Forest biomass- Precipitation - Soil organic carbon- Soil respiration.*

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I. Introduction

Respiration from forest ecosystems is an important aspect of the global carbon cycle. The spatial and temporal variations in soil respiration could be the dominant factors controlling ~~of~~ inter-annual variations in the net carbon budget [1, 2]. Various factors are responsible for emission of soil CO_2 in entire ecosystems which increase the concentration of CO_2 in the atmosphere. Cox *et al.* [3] also reported that any increase in terrestrial respiration, associated with future global warming, could cause a significant release of carbon dioxide through positive feedback, thereby accounting for the total greenhouse effect [4]. Ascertaining the microclimatic conditions (precipitation, moisture, water potential and temperature) is crucial for evaluating their effects on soil respiration in the tropics.

Several factors such as soil moisture, soil temperature, soil organic matter and nutrients, microbial activity, soil diffusivity and soil tillage practices are recognised as having an influence on soil CO_2 production and efflux rate [5, 6]. An increase in soil moisture and temperature generally accelerates organic matter decomposition, mineralization processes, microbial activity and oxidation [7]. Microclimatic conditions in relation to soil temperature have been reported to be the major as well as the leading controlling factor of soil respiration rate, and this is the result of the influence of soil temperature on the kinetics of plant respiration and microbial decomposition [8, 9]. Soil moisture content (SMC) can also be a good predictor [10, 11]; higher soil moisture content (in the absence of water-logging) has been reported to provide better conditions for increasing microbial oxygen consumption and microbial activity, as well as soil carbon dioxide production and emission rate [12]. In spite of recent studies that have been carried out on the response of soil respiration rate to precipitation events, there are conflicting views and results, while the association is not clearly understood in the tropical climate. The possible explanations and rational mechanism through which precipitation affects soil respiration include: (i) increased activities of micro-organisms and root respiration with the supplementation of water from rainfall [13, 14, 15, 16]; (ii) carbon dioxide diffusivity decreases with an increase in water-filled soil pores [17, 18]; (iii) dissolution of carbon dioxide in soil pore spaces [5]; and (iv) anaerobic conditions increase as the number of soil pores decreases [19]. Furthermore, the relationship and effects of soil moisture content have been explained using quadratic, linear parabolic and logarithmic models [20]. In addition, several studies have likewise demonstrated that soil moisture content plays an important role in soil CO_2 efflux [20, 21]. It has also been reported that increasing water content increases the rate of soil CO_2 efflux in both grassland, forests and deforested soil [20], and an empirical regression equation has shown that soil CO_2 efflux is a function of the soil matrix potential. Kieft *et al.* [22] were of the opinion that high soil CO_2 efflux rates may be a function of soil-wetting– effects, which have been observed to produce pulses of microbial activity and CO_2 production, likewise, with higher soil temperature. Considering the pattern of precipitation and the microclimate of Southeast Asia, a clear understanding of soil respiration under these environmental factors is essential. The main objective of this study is to determine the effects of the monsoon period and the microclimate of the tropical region on soil respiration.

II. Materials And Methods

2.1 Study Area

The study plot of 50 x 50 m with two replicates was carved out of 117.64 hectares of a recovering forest dominated by the *Dipterocarpus* tree species in lowland Peninsular Malaysia ($27^0 50'95''$N, $43^0 76'90''$E). The study was conducted from September, 2013 to January, 2014, representing the period from the tail end of the Southwest monsoon (late May to September) to the middle of the Northeast monsoon (November to March). In general, the forest experiences equatorial climatic conditions with a mean temperature range of 23.7–32^0C and relative humidity of 59–96%. The wet and humid tropical climate experiences a monsoon period with a monthly rainfall of 200 mm between November and January [43] (Suhaila and Jemain, 2008a), while the average solar radiation is 17.00 MJm^{-2} and the daily evaporation rate is 3.1 mm day^{-1} [24]. The soil in the study plot is classified as the Serdang-Kedah series developed over mixed sedimentary rocks with a combination of local alluvium colluvium resulting from metamorphic rock [25, 26]. In the FAO/UNESCO Soil Map of the World – Revised Legend [27] the Serdang series is classified as Haplic Nitisols.

2.2 Microclimate Monitoring

To monitor and quantify the tropical microclimate conditions and environmental factors, the following procedures were adopted: Soil temperature was measured using the Watchdog data logger model 125 spectrum technology. Soil moisture was determined by using the TDR Trime FM and water potential by using the Delmorst model KS-D1. All these variables were measured at 5 cm soil depth, while ambient air temperature was recorded at 50 cm above the ground. All the measurements were conducted concurrently with the measurements on soil respiration on a daily basis from 0800 to 1700 hours.

2.3 Measurement of Soil CO_2 Efflux

We measured soil CO_2 efflux with two constructed continuous open flow chambers connected to a multi gas-handler (WA 161 model), which provided a channel to regulate the flow of CO_2 from the various chambers to a flow meter connected to a CO_2/H_2O gas analyser as described by Mande *et al.* [28]. Thirty sampling points were established and soil collars were inserted 3 cm into the soil for 24 hours to reach an equilibrium stage before the chambers were placed on them, with a 3 cm thick closed foam gasket to prevent leakage from the chamber base. Soil respiration was measured continuously on a daily basis from 0800 to 1700 hours. Efflux was recorded every 5 sec over a period of 5 min in each chamber, from which an average was calculated to estimate the CO_2 concentration over 5 min for each chamber. Measurements were taken in the centre of the plot to avoid border effects. The coefficient of determination (R^2) from a simple linear regression was typically better than 0.99.

2.3 Soil Sampling and Forest Biomass

Soil samples were collected randomly at three different sampling points from the topsoil between 0 and 100 cm depth; soil cores of 10 cm diameter and 10 cm height were extracted with a metal core sampler. The samples were placed in sterile plastic bags, sealed and returned to the laboratory, and were later oven-dried at 105°C for 48 hours to determine the soil water content (mass basis) [29]. The standard methods were used to determine soil organic carbon (SOC), soil moisture content (SMC), bulk density, electrical conductivity (EC) and cation exchange capacity (CEC). Soil pH was measured in water (1:2.5 w/v) [30], while the Walkley Black wet oxidation technique was used to determine total organic carbon (TOC), [31]. Soil organic carbon stock (SOCstock) was estimated using the model of Eleanor [32] within a given depth of top soil ranging from 0 to 100 cm.

Determination of the forest site characteristics was confined also to the central area of the plot to reduce border effects. The parameters determined were: canopy stand densities and light intensity distribution based on leaf area index (LAI) using an Asunfleck ceptometer (AccuPAR model sf-80, Decagon, Pullman, WA). LAI was calculated from an instant measurement by positioning the ceptometer horizontally at 1 m above the ground level, and 6 readings were taken in the four cardinal directions within the stand density [33]. Over 193 trees were measured in the study plot. To ascertain carbon to nitrogen ratio, leaf litter were collected from ten litter trap nets of 1 x 1 m^2 with 1 mm^2 mesh which were placed at 1 m above the forest floor. Collections were made at 14-day intervals over the period of the study to avoid decomposition. The leaf litter were weighed and air-dried in the laboratory and then oven-dried at 70^0C for at least 48 hours, before reweighing and separating them into leaves, twigs, fruits and miscellaneous components. The leaf component was later blended, and used to determine carbon and nitrogen ratio (C/N) using the TruMac CNS Macro Analyser (LecoCorp), while the mass loss rates in the litter were estimated using the litterbag technique [34]. To establish a linear relationship between soil CO_2 efflux in the monsoon period and carbon input, we estimated forest biomass using allometric relationships obtained in the forest according to the International Biological Programme [35]. The total above-ground biomass (TAGB) was determined using the diameter at breast height (DBH) of about 193 trees in the 50 x 50 m plot [36]; all the trees > 5 cm in DBH were identified, mapped and tagged, and their DBH were measured. If a tree had a large buttress, its DBH was measured just above the buttress [37]. DBH was measured on each tree using ~~the~~ a DBH tape, at 1.3 m above the forest floor and TAGB was estimated using the model of Kato *et al.* [38], while below-ground carbon biomass was calculated using the model of Ogawa *et al.* [39]. The first model estimates the tree trunk, branches and leaf biomass. These components form (TAGB) based on simple regression lines fitted for DBH and tree height.

III. Statistical Analysis

Data on soil respiration, TOC, SOC, TAGB, BGB, SOCstock and microclimatic conditions were analysed using one-way analysis of variance (ANOVA), followed by a post hoc Dunn's test and Turkey multiple comparison test [28, 40]. ANOVA was used to test the difference of standard deviations and means for soil respiration, soil temperature, soil moisture and water potential in different months. Descriptive statistics were established to calculate and explain the normality of data distribution and also to quantify the correlations among soil respiration, TAGB, BGB, SOCs, changes in soil properties as well as microclimatic conditions. Exponential regression and the multiple linear regression models were employed to ascertain any significant effect from microclimate, forest biomass input and soil properties, as well as their interactions with carbon-nitrogen ratio (decomposition) and soil microorganisms in emitting soil CO_2 efflux in the study area. Likewise, the Pearson correlation was calculated to show the correlation of CO_2 efflux variation with the environmental factors and changes in soil properties. Before analysis, all data were tested for the assumption of ANOVA. If data were heterogeneous, they were ln-transformed before analysis. All the statistical tests were performed using SPSS version 21 software (SPSS Inc., Chicago, Illinois, USA). The techniques used were for both predictive and explanatory purposes within the experimental and non-experimental designs.

IV. Results

4.1 Air and Soil Temperatures, Soil Moisture and Water Potential

Temperature is an important factor that regulates several physiological processes, and during the whole study period, the various months showed differences in the entire microclimatic conditions. Temperatures showed large diurnal fluctuations, as ambient air temperature range from 25.45 to 26.79^0C and soil temperature was between 24.56 and 26.59^0C. During this period, the site had high precipitation (20.0 to 28.0 mm/month) between November and January. This rainfall caused rapid increases of soil moisture content and water potential, ranging from 24.58 to 30.98% and 97.33 to 98.89%, respectively. Ambient air and soil temperatures were maximum between September and October, and decreased gradually from November to January. The changes in ambient temperature is responsible for the increasing soil temperature, while the soil temperature is one of the major variables controlling soil biological activity such as soil processes and microorganism activity. Huge soil moisture content and water potential values occurred during the Northeast monsoon period, starting low at the beginning of the measurements, and increasing rapidly from November to their peak in January as result of the heavy monsoon rains. The soil water content is an expression of the mass or volume of water in the soil, while the soil water potential is an expression of the soil water energy status. The availability of water moisture content increase microbial activity by increasing substrate supply and thus increase hydration and activity of enzymes. Whereas soil water potential which describes the energy status of the soil water and was responsible for water transport and water storage. There were significant differences in microclimatic conditions among the months (one-way ANOVA, $p<0.05$). The multiple regression model was used to present soil respiration rate and its variation with respect to soil temperature, soil moisture content and water potential because the model provided a better fit of R^2. The coefficient of the model of the microclimate and environmental factors *vs.* soil temperate was higher for September and October than for soil moisture and water potential (Tables 1 and 2). This indicates that soil temperature had a more significant effect on soil respiration than soil moisture and water potential ($p<0.01$). A decrease in soil respiration can also be in response to an increase in soil moisture and water potential as it was observed that in the month of November. The higher coefficients for soil moisture content and water potential and the lower one for soil temperature (Table 3), suggest more significant impacts ($p<0.01$) from soil moisture content and water potential on soil respiration. For December, the beta coefficient suggests that rainfall had a stronger effect on soil respiration than soil temperature (Table 4), and this may be due to changes in the weather. The month of January shows stronger beta coefficients for soil moisture content and water potential with soil respiration, than soil temperature (Table 5). In other words, soil moisture content and water potential had a greater influence on the decline in soil respiration. The correlation analysis showed a strong relationship between soil respiration and microclimatic conditions. However, soil temperature was found to be the dominant controlling factor only between September and October, while soil moisture content and water potential were found to be dominant controlling factors between November and January, implying that climatic conditions influenced soil respiration. Consequently, the combined effects of environmental factors proved to be the overriding factor that accounted for the variation in soil respiration rate across the seasons, covering the intermonsoon and monsoon periods, in the recovering forest.

To further clarify the contribution of the entire set of environmental factors measured to the observed changes in soil respiration rate, we performed a Pearson correlation analysis. Each environmental factor was a controlling variable at a particular season, as each of their correlation coefficients with soil respiration was significant ($p<0.001$) and positive (0.47).

Table: 1 Parameters of multiple regression model for September

Model		Unstandardized Coefficients		Standardized Coefficients	T	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	11539.24	4053.87		2.85	.01		
	SeptTMP	15.65	20.69	.79	.76	.01	.22	4.49
	SepMST	-1835.86	112.50	-1.29	-16.32	.01	.45	2.23
	SeptWP	325.26	56.41	.09	5.77	.01	.15	6.48

a. Dependent Variable: SeptCO_2. TMP= soil temperature, MST= soil moisture, WP= water potential.

Table 2. Parameters of multiple regression model for October

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	157548.22	17629.07		8.94	.01		
	OctTMP	88.31	16.04	.77	5.51	.01	.22	4.54
	OctMST	-5.30	212.71	-.00	-.03	.01	.18	5.62
	OctWP	-1636.24	139.96	-.06	-11.69	.01	.60	1.68

a. Dependent Variable: OctCO_2. TMP= soil temperature, MST= soil moisture, WP= water potential

Table 3. Parameters of multiple regression model for November

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	261404.88	25869.29		10.11	.01		
	NovTMP	-174.47	257.52	-0.068	-.68	.01	.26	3.84
	NovMST	-356.91	115.66	0.64	-3.09	.01	.243	4.12
	NovWP	-2544.45	248.12	0.71	-10.26	.01	.546	1.83

a. Dependent Variable: NovCO_2. TMP= soil temperature, MST= soil moisture, WP= water potential

Table 4. Parameters of multiple regression model for December

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	-12631.30	13751.57		-0.92	.01		
	DecTMP	404.16	236.61	0.025	1.71	.01	.18	5.72
	DecMST	1261.21	317.60	0.78	3.97	.01	.18	5.56
	DecWP	-292.10	22.11	0.90	-13.21	.01	.83	1.20

a. Dependent Variable: DecCO_2. TMP= soil temperature, MST= soil moisture, WP= water potential

Table 5. Parameters of multiple regression model for January

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	95015.64	11059.96		8.59	.01		
	JanTMP	-1391.985	210.78	-0.89	-6.60	.01	.15	6.60
	JanMST	-1269.296	237.95	-0.72	-5.33	.01	.15	6.61
	JanWP	-288.616	18.41	-0.90	-15.68	.01	.83	1.21

a. Dependent Variable: JanuaryCO_2. TMP= soil temperature, MST= soil moisture, WP= water potential

4.2 Variation in Soil CO_2 Efflux

The measured rates of soil respiration showed strong daytime patterns during those periods which had no rain and low occurrences during the peak level of the rain. The daytime pattern of change in soil respiration was strongly correlated with changes in microclimate conditions, and results from ANOVA indicated that the precipitation significantly affected soil respiration. There were also significant differences among the months of measurement (P<0.05) (Table 6). Spatial variation in soil respiration, as quantified by the coefficient of variation, was on average 26.2% and 18.8% at the end of the Southwest monsoon and during the Northeast monsoon, respectively. At peak respiration effluxes, higher respiration rates were observed in the months of September and October compared with in the months of November to January (Table 6) (Fig 1). This suggests that our sampling months was adequate for characterizing the variation in soil respiration observed at the end of the Southwest monsoon, inter-monsoon and Northeast monsoon and its controlling environmental factors.

Soil respiration responded to changes in the microclimate conditions. In September and October, soil respiration responded to the increases in soil and air temperatures and to the decreases in soil moisture and water potential. However, between November and January, the relationship between respiration and soil temperature declined as soil moisture and water potential increased through the rising amounts of rainfall. This explains the influence of the Northeast monsoon and the environmental factors on soil respiration because a lower respiration rate was observed during the rainy season due to the much lower daytime variation in soil temperature, increased soil moisture and water potential, consequently resulting in a lower variation in soil respiration rate (Table 6). Correlation analysis showed that soil respiration rate was more closely associated with microclimate conditions and environmental factors with most of R^2 more than 0.9 at p<0.01. This indicates that microclimate and environmental factors influenced the spatial and temporal variations in soil respiration. Microclimate conditions and environmental properties seemed to move in parallel with soil respiration rate due to variations in time and period in relation to season because the one-way ANOVA shows significant variations between the months. Furthermore, the multiple regression model employed illustrated that rainfall had significant influence on soil respiration efflux rate (p<0.01). In addition, the multiple regression models indicated strong correlations at R^2 between 0.86 and 0.96 (Table 7) for September, October, November, December and January, respectively. The analysis shows an existence of microclimate condition relationship at different months and relevance increased obviously between September and October and decreased between November and January.

Table 6. Descriptive statistics of soil CO_2 efflux (mg m^{-2} h^{-1})

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Sept CO_2 efflux	72	373.11	111.15	13.10	346.10	399.23	152.79	528.67
Oct CO_2 efflux	72	288.18	122.89	14.48	259.30	317.06	120.97	500.73
Nov CO_2 efflux	72	256.69	109.53	12.91	230.95	282.43	106.77	472.89
Dec CO_2 efflux	72	314.51	90.68	10.69	293.20	335.81	122.89	453.89
January CO_2 efflux	72	282.71	89.69	10.57	261.64	303.79	120.33	434.89
Total	360	303.04	112.20	5.91	291.41	314.67	106.77	528.67

Table 7. Multiple-regression models

Model	R Square	Adj- R^2	Std Error of estimation	F	Sig
Sept	.90	.81	49.68	95.83	<0.001
Oct	.91	.82	52.97	107.71	<0.001
Nov	.91	.82	47.38	103.80	<0.001
Dec	.86	.74	47.52	63.51	<0.001
Jan	.90	.81	39.42	99.87	<0.001

a. Predictors: (Constant), Soil Temperature, Moisture, Water Potential
b. Dependent Variable: Soil CO_2

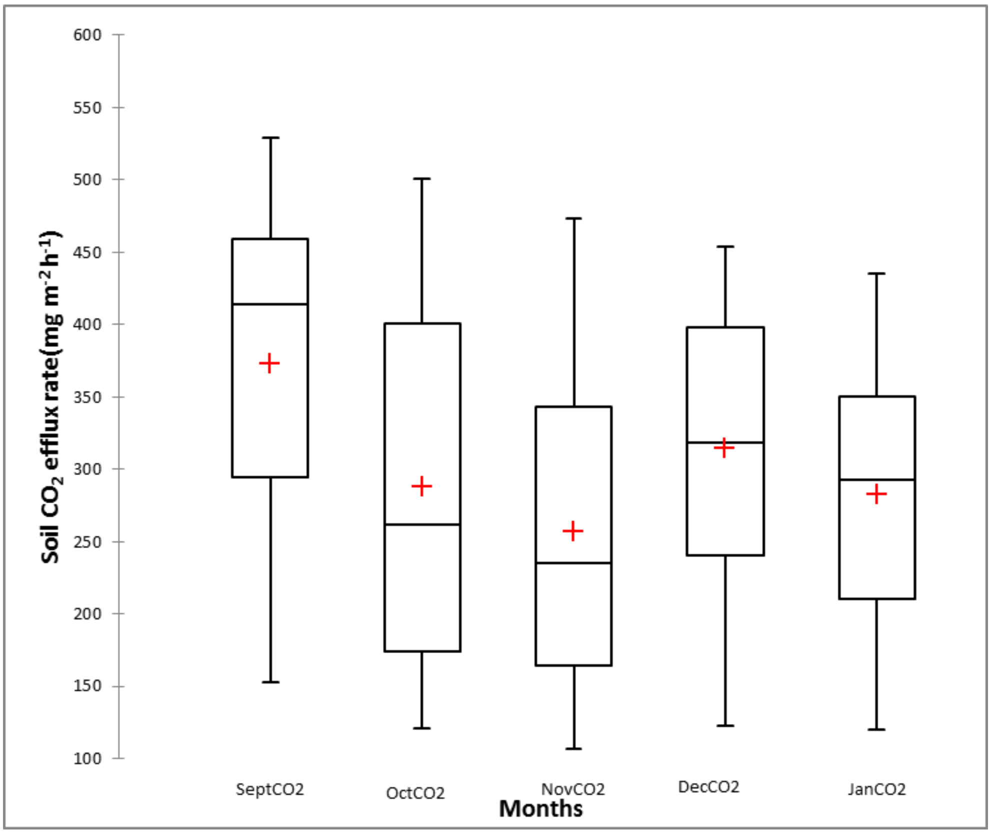

Figure 1. Variation in Soil Respiration

4.3 Soil Properties and Forest Biomass

To understand the effects of soil properties and forest biomass on soil respiration, we determined total organic carbon (TOC), soil organic carbon (SOC), soil pH and carbon and nitrogen inputs. There were considerable amounts of total organic carbon (TOC) and soil organic carbon (SOC), ranging from 2.4 to 1.7% and from 4.96% to 4.53%, respectively. There was high carbon concentration at the top of the soil profile (10 cm), which dropped at 100 cm depth (Table 8), Soil moisture content was 17.5% with a correction factor of 1.18 (Table 8). All these parameter play a part in soil nutrient content. The findings show that bulk density increased with soil depth between 10 and 100 cm (Fig. 2) given the good porosity for soil water movement and cation exchange capacity to hold the nutrients necessary for microbial activity. Soil properties were influenced by forest biomass in the presence of microclimate conditions and environmental factors, being positively and strongly related to soil respiration (R^2=0.96 at p<0.01). Soil pH was found to be slightly acidic at 5.16 (Table 8). Consequently, the carbon-nitrogen ratio from litter fall amounted to 50.11-51.86% and 1.41-1.58%, respectively (Table 8). The C/N ratio influences the rate of decomposition of organic matter and this result in the release (mineralisation) or immobilization of soil nitrogen.

The recovering lowland forest hosted an estimated forest biomass of total aboveground biomass (TABG), below-ground biomass (BGB) and total forest carbon (SOCs) of 3.9 x 10^3 mg ha^{-1}, 2.9 x 10^3 mg ha^{-1} and 4.0 x 10^3 mg ha^{-1}, respectively (Table 8). Soil carbon stock in the soil profile was estimated at 69.44, 67.78 and 65.67 mg ha^{-1} at 10, 20 and 30 cm soil depths, respectively (Table 8). A higher percentage of carbon contents increases soil nutrients and energy for microbial activity with a corresponding effect of releasing more soil CO_2. The correlation coefficients for each variable reflected the relationships between the affirmative variables and soil respiration (R^2=0.94, p<0.01).

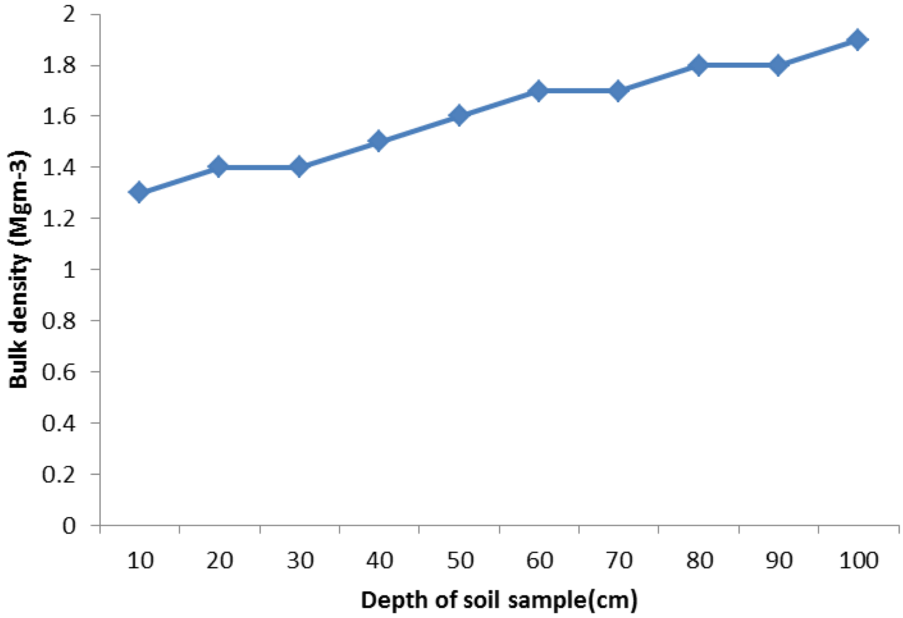

Figure 2. Bulk Density increases with Soil Depth.

Table 8. Analyses of soil samples, litter fall, total aboveground biomass, below-ground biomass, soil organic carbon stock and total organic carbon

ECOSYSTEM	SOC %	TOC %	pH	Soil Moisture Content %	Moisture Correction factor	Litter fall Carbon % Nitrogen %	SOCstock mg ha^{-1}	TAGB mg ha^{-1}	BGB mg ha^{-1}	SOCs mg ha^{-1}
Forest	4.96(10 cm) & 4.53(100 cm)	2.4(10 cm) & 1.7(100 cm)	5.16	17.5	1.18	50.11 to 51.86 1.41 to 1.58	69.44 (10cm) 67.78 (20cm) 65.67 (30cm)	3.8 x 10^3	2.9 x 10^ 3	4.0 x 10^3

SOCstock=Soil organic carbon stock, TOC= Total Organic Carbon, TAGB=Total Above Ground Biomass, BGB=Total Below Ground Biomass, SOCs=Total Forest Carbon Stock

V. Discussion

Soil respiration at the end of the Southwest monsoon was significantly higher than during the Northeast monsoon, with the rate decreasing as rainfall increased (Fig. 3). The magnitude of the fluctuations in soil respiration in response to changes in microclimatic conditions and environmental factors also changed with season. The trend of decreasing soil respiration with increasing precipitation was previously reported in a temperate forest subjected to an East Asia monsoon climate [41], a cool-temperature forest in central Korea [18], and in the context of global climate [42]. In the tropical climate of our study, there was a significant difference in soil respiration between the periods September and October and November and January (Northeast monsoon). High soil respiration rates in the months of September and October may have resulted from high temperature and associated physiological activity of microbes. With the occurrence of increasing precipitation between November and January, soil respiration by micro-organisms and roots decreased gradually and then tended to stabilize. As a result, the lower soil respiration during the Northeast monsoon could be said to improve the efficiency of carbon sequestration [29].

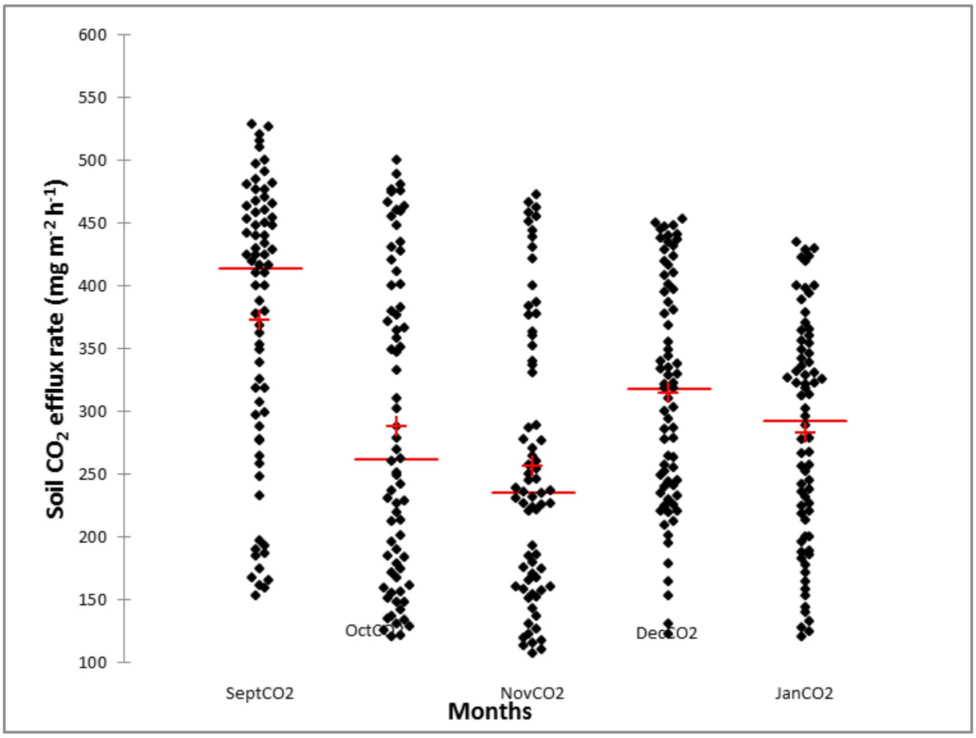

Figure 3. Soil Respiration Rate between Months

5.1 Effect of Climatic Conditions and Mechanism of Soil Respiration Reduction

Rainfall during the period of soil respiration measurements accounted for 85 to 90% of the total annual rainfall [43] and this constrained soil respiration by 30 to 50%. Considering the potential effect of a changing pattern of precipitation, including soil moisture and water potential during the Northeast monsoon, it was clear that increases in these parameters resulted in a decline in soil respiration compared to the end of the Southwest monsoon period. Consecutive, intense rainfall would fill soil pores, disturb CO_2 diffusion, and thus hamper the activity of microorganisms as well as the dissolution of CO_2 with reduced oxygen supply, causing a reduction in soil respiration. This suggested mechanism is further supported by forest canopy cover, fallen leaves and litter layers. A high forest leaf area index would significantly intercept rainfall and provide slow but steady water infiltration into the soil without soil evaporation or rapid run-off, and would enhance anaerobic conditions in the soil, resulting in a slowdown in the rate of decomposition. Especially, very wet layer of fallen leaves and litter would in turn obstruct gaseous exchange between the soil and atmosphere [41]. Hence, the occurrence of rainfall in the study area could result in significant suppression of soil carbon dioxide emission from the forest floor. Lee *et al.* [18] reported a similar scenario at the Gwangneung forest in summer, and suggested the possibility that suppression of soil carbon dioxide was due to saturation of the soil pore spaces. In addition, the effects of rainfall intensity, duration, and frequency of drying and wetting on carbon in a terrestrial soil was studied by Borken and Matznen [44]; they suggested that hydrophobicity of the organic surface is an important mechanism that reduces carbon in top soils after precipitation. Recently, Chae [41] studied the variation in soil respiration and precipitation in the east Asia monsoon climate, and suggested that the precipitation pattern had a major effect on soil respiration.

5.2 Relationship between Soil Respiration and other Environmental Factors

Soil respiration is also controlled by biotic and abiotic factors, such as soil temperature, moisture, water potential, forest biomass, soil microbial biomass, photosynthetic characteristics of the vegetation, vegetation type and organic carbon content [42, 45, 46]. Generally, soil temperature and soil moisture are the key factors that affect variations in soil respiration [47]. In this study, we found similar correlations, as soil respiration was significantly and positively correlated with soil temperature, soil moisture and water potential, which agree with the results of previous studies [48].

The one-way ANOVA employed in analysis of the soil respiration data showed a significant difference at $p<0.001$ and a distribution aligned along a straight line without any outliers, giving good skewness (Fig. 4). Application of the enter method for the multiple linear regression model, having performing diagnostic collinearity with the model dimensions, displayed a conditional index within the acceptable threshold of 30.0 with a no tolerance value below 0.10, indicating that no multicollinearity problem among the environmental variables in the model were encountered given that the equality of variance, linearity and normality classical assumptions were met. Based on that, it is conclusive that the estimated multiple linear regression models can be used to explain the impact of the environmental factors on soil respiration, namely, soil respiration was positively correlated with soil temperature, soil moisture and water potential ($p<0.001$). Similarly, soil respiration was linearly correlated with aboveground biomass and soil properties ($p<0.01$). All significant continuous variables (soil temperature, soil moisture, water potential, forest biomass and soil properties) could as a whole explain more than 90% of the variation in soil respiration. The increased variation in soil respiration was attributed to the change in soil temperature between the months, which was observed to be one of the important controlling factors [42,49]. The availability of soil water moisture content and the energy status of the soil water transport were found to be higher in certain months signifying a positive correlation with the spatial and temporal variations in soil respiration ($p<0.01$). Furthermore, the forest biomass (TAGB, BGB and SOCs at 3.9 x 10^3 mg ha^{-1}, 2.9 x 10^3 mg ha^{-1} and 4.0 x 10^3 mg ha^{-1}, respectively) similar to the study by Green *et al.* [50] was found to increase the availability of food and energy for microbial activities, which includes respiration during the process of decomposition of soil organic matter, thus serving as a prime factor in emitting a considerable amount of soil respiration [45]. Litter fall increased TOC and SOC of 1.7 to 2.4% and 4.53 to 4.96%, and SOCstock 69.44, 67.78, 65.67 mg ha^{-1} in a slightly acidic soil (5.16), as was also reported by [51]. This influence and change in soil carbon stock could make more substrates available for decomposition [52, 53, 54]. Soil bulk density was found to increase with depth indicating the role that pore spaces plays in water movement, electric conductivity and microbial activity. Subsequent litter deposition and carbon-nitrogen ratio could supply more soil nutrients to microorganism for decomposition, in the process of which soil CO_2 is released. The Pearson correlation analysis indicated that the strength of association between soil temperature, soil moisture and water potential and soil respiration was very high, significant and positive, ($p<0.01$, R^2= 0.85 - 0.96), suggesting that the contribution of microclimate and environmental factors to soil CO_2 efflux was strong and played a dominant role. Therefore, these results suggest that the monsoon regime was a major influencing factor in soil respiration.

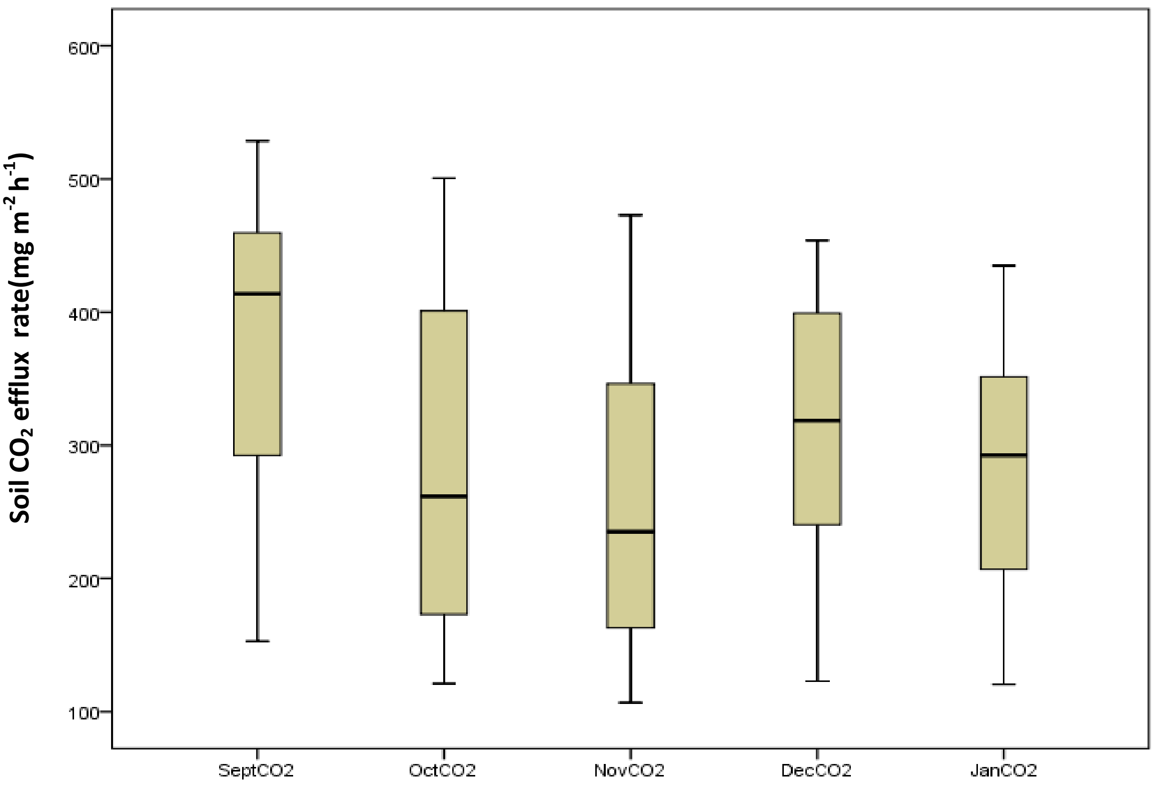

Figure 4. Box and Whisker Plot of Soil Respiration

VI. Conclusions

The overall results from these studies indicate that precipitation and environmental factors can decrease soil respiration. The soil respiration estimates for the entire period of measurement varied significantly, being relatively high between September and October and decreasing between November and January. Soil respiration was a function of precipitation which affects the magnitude, frequency and efflux rate depending on the duration of rain, in relation to soil temperature, soil moisture and water potential. During the first two months of measurement, soil temperature was the predominant factor, explaining >90% of soil respiration rate due to the lowest amount of precipitation recorded at this time. During the months of November to January, however, soil respiration rate could not be explained by soil temperature, implying the potential effect of soil moisture and water potential. This period was notable for its wet spells, which are the typical characteristics of the Peninsular Malaysia Northeast monsoon regime. This implied that rainfall had a significantly effect on soil respiration during this period. Our results indicate that precipitation is a dominant factor in reducing soil respiration in the presence of soil moisture, water potential and soil temperature. Under the varied monsoonal climate, understanding of characteristics of precipitation is required for a realistic assessment of carbon emission. Consequently, understanding of amount and pattern of precipitation and its relationship with soil moisture, water potential and soil temperature must precede accurate assessment of soil respiration. Subsequently, to clarify the role of the monsoon climate in soil respiration, the relationship between microorganisms and precipitation needs to be clearly understood by improving the observations on precipitation.

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