COMPARISON OF SOIL CO_2 EFFLUX IN TROPICAL FORESTS OF DIFFERENT AGES, PENINSULAR MALAYSIA

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ABSTRACT

The forest age, environmental abiotic and biotic factors are important in controlling soil CO_2 efflux in forest ecosystems, as they play an important role in soil respiration. The aim of this study was to determine the environmental factors associated with each forest age and their impact on the soil CO_2 efflux rate. This study was conducted in 10-, 30-, 50- and 70-year-old recovering tropical lowland forests in Peninsular Malaysia, measuring soil CO_2 efflux using the continuous open flow chamber technique connected to a multi gas-handling unit and infrared gas analyser. The forest biomass and soil properties were quantified using the Kjeldahl method and Walkley-black wet oxidation technique. The results show that soil CO_2 efflux was higher in the 10-year-old forest than the older forests and lowest in the 70-year-old forest. Soil CO_2 efflux ranged from 92.09 to 634.78, and 106.77 to 536.00 mg m^{-2} h^{-1} between February and June, and September and December for all forests. The higher soil CO_2 efflux in the 10-year-old forest was significantly positively correlated with high soil temperature (R=0.96) compared to the spatial and temporal variation in the 30-, 50- and 70-year-old forests. The entire spatial and temporal variation in soil CO_2 efflux can be largely accounted for by the soil properties, forest carbon input and environmental factors. In conclusion, soil CO_2 efflux, soil properties, microclimate condition and forest biomass varies significantly with forest age. Soil CO_2 efflux decreases with forest age, and increases the carbon use efficiency. The environmental factors, dominated by soil temperature, affect soil CO_2 efflux substantially.

Key words: Biomass, Forest Ecosystem, Stand Density, Soil Carbon, Soil CO_2 Efflux, Soil Temperature

Introduction

Soil CO_2 efflux in the forest is an important process that is responsible for the carbon loss from the terrestrial ecosystem because it accounts for 67-76% of the total ecosystems respiration (Law et al. 1999; Janssens et al. 2001; Raich et al. 2002). Soil CO_2 efflux is a major component for assessing the capacity of the forest ecosystems as part of the global carbon budget and for predicting its change to climate change (Wang et al. 2006). Likewise the forests play a major role in the global terrestrial carbon balance as they determine the net ecosystem carbon exchange (Valentini et al. 2000); therefore, estimating the soil CO_2 efflux from forests of different ages and their contributions to the atmospheric carbon balance is a crucial challenge in climate change and carbon cycle research.

The tropical forests are acknowledged to contain approximately 37% of the global terrestrial carbon pool within the soil and vegetation (Dixon et al. 1994), and any change in the tropical forests CO_2 fluxes can have a negative effect on the carbon budget because of its dominant role in the global terrestrial carbon cycle (Bae et al. 2012). Despite the vital role of the tropical forest systems, deforestation and land conversion are at high rates resulting in a release of soil CO_2 (Murphy et al. 2008). For example, recovering forests vary with age resulting from deforestation, logging and land conversion, and account for much of the soil CO_2 efflux, which has been estimated to be 75% in tropical Asia (Houghton and Hackler 1999). The contribution of roots and microbial respiration to the total soil CO_2 efflux ranges from 10 to 90%, depending on the forest age, vegetation type and season (Boone et al. 1998; Hanson et al. 2000; Frey et al. 2006). The respiration associated with microbial activities varies among forests of different ages, as it involves the contribution and decomposition of litter and the mineralization of soil organic matter, as they are affected by many biotic and abiotic factors, such as litter biomass, vegetation, substrate supply, soil temperature, soil moisture, microbial biomass, carbon to nitrogen ratio, soil pH and carbon content (Kang et al. 2003; Scott-Denton et al. 2003; Dilustro et al. 2005; Li et al. 2008). As a result of the spatial and temporal changes resulting from these aforementioned factors, soil CO_2 efflux also varies among forests of different ages, at both the small and large scale (Fang et al. 1998). It is vital to estimate soil CO_2 efflux in the recovering forests of different ages while taking cognisance of the associated environmental factors for a better understanding of the rational involved.

The natural forest of Malaysia has suffered greatly from deforestation, logging and land conversion, so afforestation is of increasing importance, particularly, as *Dipterocarps* are not a fast growing species but yield significant biomass production. The recovering forests of the tropical climatic zone have proven to be an interesting research subject because of their fast responses to environmental changes and the need for the management of the forests in the global carbon balance (Gielen and Ceulemans 2001). The response of the tropical forest ecosystems to the rise in atmospheric CO_2 will likewise have implications for future forest management, and, hence, having detailed information on soil CO_2 efflux from the recovering forests of different ages and the control factors to guide future management decisions is critical for managing carbon budgets in the tropical forest ecosystems.

The scope of this study involves the investigation of soil CO_2 efflux in forests of different ages and the associated environmental factors, such as forest biomass carbon input, total above ground biomass, below ground biomass, forest carbon stock, soil organic carbon, soil organic carbon stock, soil temperature, soil moisture, water potential, carbon to nitrogen ratio and soil pH. The main objectives were (1) to investigate the spatial and temporal variation of soil CO_2 efflux in a recovering forest and the impact of forest age on soil CO_2 efflux, and (2) to determine the environmental factors associated with each forest age and the rate of influence on soil CO_2 efflux.

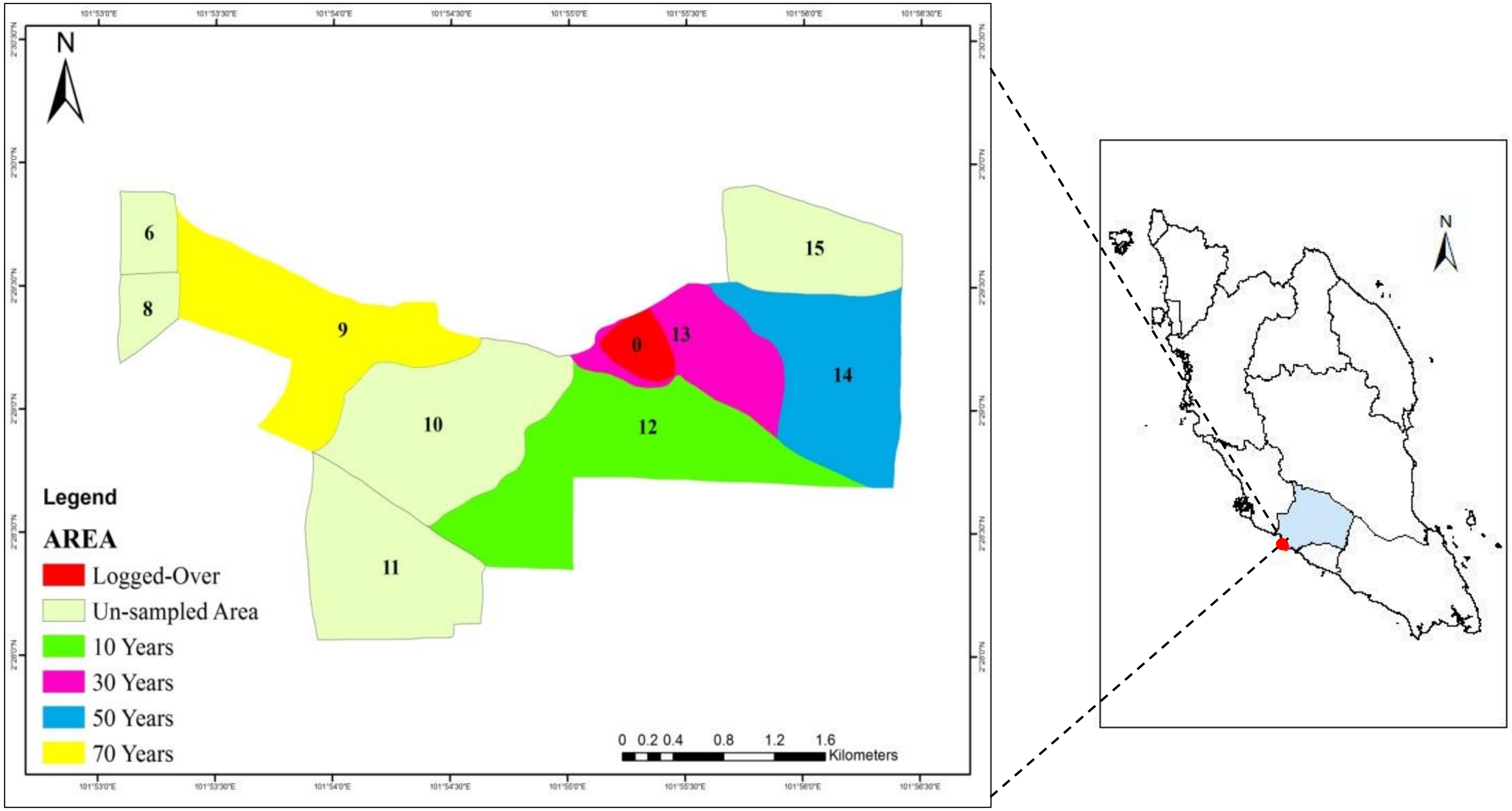
Materials and methods

Study site

The study was conducted in Sungai Menyala forest reserve, Port Dickson, Negeri Sembilan, Malaysia, located at $27^0 50'95''$N, $43^0 64'99''$E (Fig. 1). The forest reserve is a research, recreational and extension forest for Negeri Sembilan, Malaysia. The study area is approximately 93.1 km from Kuala Lumpur, the federal capital of Malaysia. The forest reserve has fifteen forest compartments of various trees species and ages, and a logged-over area with a total land mass of 1,273.43 hectares, located 500 m above sea level with a slope slant of 10-20% in the multimedia and super corridor area. Four forest compartments of 1500 m to 3 km apart, comprising various trees species and different tree ages were selected for this research. The four compartments comprised 10-, 30-, 50- and 70-year recovering forests that included the following trees species – *Dipterocarpus baudii, Dipterocarpus verruscosus, Shorea pauciflora, Shorea bracteolata, Shorea spp, Shorea acuminata, Shorea parvifolia, Shorea macroptera, Shorea leprosula* and *Kopmpassia malaccensis* (Fig. 1). An extensive field research was performed on a daily basis between the months of February and June, and September and December 2013, representing the post monsoon, pre-monsoon and monsoon period. The experiment was carried out in 50 x 50 m plots with two replicates in each forest ecosystem. The *Dipterocarpus* forest had been regenerated and the stand density was naturally maintained without any artificial management such as thinning. There was little ground vegetation and its contribution to below ground biomass to total above ground biomass was negligible. The soil was classified as the Serdang-Kedah series developed over mixed sedimentary rocks with a combination of local alluvium colluvium resulting from metamorphic rock (Paramananthan 1998; Paramananthan 2012). In the FAO/UNESCO Soil Map of the World – Revised Legend (FAO 1990), the Serdang series is classified as Haplic Nitisols, with a mean temperature range of 23.7-32^{0}C, relative humidity of 59-96%, and a monthly rainfall of 200 mm (Suhaila and Jemain, 2008), while the average solar radiation was 17.00 MJm^{-2} and the daily evaporation rate was 3.1 mm day^{-1} (MMD 2013).

We selected four *Dipterocarpus* forests of different ages located within 1500 m, 1800 m and 3 km of each other with similar environmental conditions and management histories. Table 1 summarizes the site characteristics of the forests.

Figure 1: Map of Sungai Menyala Forest Reserved showing various forest compartments.



Source: Negeri Sembilan Forest Dept. 2013.

Table 1: Sites characteristic of the four forests ecosystems

Site	Stand age(yr)	Area of Forest (hac)	Average diameter at Breast height (DBH,cm)	Average trees height (m)	Leaf Area Indx (LAI)
1	10	242.91	92	20.78	2.94
2	30	117.64	103.9	30.11	2.97
3	50	173.63	123.6	39.89	5.69
4	70	202.67	165	50.01	6.0

Measurement of soil respiration

Soil respiration was measured using two constructed continuous open flow chambers connected to a multi gas-handler (WA 161 model), which provide 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. (2013). Thirty sampling points were established in each of the forest ecosystems and soil collars were inserted 3 cm into the soil for 24 hours to create 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 CO_2 efflux was measured continuously on a daily basis from 0800 hours to 1700 hours from February to June 2013 and September to December 2014. 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.

Measurement of environmental factors and Soil sampling

Soil temperature, soil moisture and water potential at depth of 5 cm near the soil collars were measured concurrently on a daily basis from 8:00 to 17:00 hours using the soil temperature probes, moisture probes and Trime-FM TDR (Watchdog data logger model 125 spectrum technology, Delmorst model KS-D1 and Trime-Fm TDR), respectively.

Soil samples were collected randomly from three different sampling points from 0-100 cm depth using the soil core with a metal core sampler of 10 cm in diameter and 10 cm in height. The samples were placed in sterile plastic bags, sealed and returned to the laboratory and later oven-dried at 105°C for 48 hours to determine the soil water content (mass basis) (Gong et al. 2012). Soil samples were analysed for Soil Organic Carbon (SOC), Bulk Density, Electric Conductivity (EC) and Cation Exchange Capacity (CEC), and the soil moisture contents (SMC) and soil pH were measured in water (1:2.5 w/v) according to the Kjeldahl method (Bremner 1960) while the Walkley-black wet oxidation technique was used to determine the total organic carbon (TOC) (Sollins et al. 1999). The soil organic carbon stock (SOCstock) was estimated using the model of Eleanor (2008) within a given depth of top soil ranging from 0 to 100 cm.

Forest biomass, Litter fall input and leaf area index (LAI)

The estimation of forest biomass was carried out using the allometric relationships obtained in the forest according to the International Biological Programme (Kira 1978). To estimate the carbon input from the forest biomass, the tree height and diameter breast height (DBH) of about 3,168 trees in four main different plots of 50 x 50 m were measured. All the trees > 5 cm in *DBH* were identified, mapped and tagged, and their *DBH* were measured. If a tree had large buttresses, its *DBH* was measured just above the buttresses (Niiyama et al. 1999). The DBH was measured using a DBH tape, 1.3 m above the forest floor for each tree (Manokaran et al. 1990) and the Total Above Ground Biomass (TAGB), Below Ground Biomass (BGB) were estimated using the model of Kato et al. (1978), while the Total Forest Carbon (SOCs) was based on the model of Ogawa et al. (1963). The model estimates the tree stem, branch and leaf biomass. These components form the total above ground biomass (TAGB) based on simple regression lines fitted for DBH and tree height. To estimate the carbon to nitrogen ratio (C:N) and litter productivity, ten litter traps were installed at 1 m above the forest floor, and the litter was collected at two week intervals throughout the study period. The litter from each trap was transported to a laboratory and oven-dried at 75°C for 48 hr. All dried samples were separated into broad-leaves, needles, bark, cones branches and miscellaneous components, oven-dried at 75^0C and weighed. The C/N ratio concentration was determined using a TruMac CNS macro elemental analyser (vario MACRO CN, Elementar Analysensysteme GmbH, Germany), while the mass loss rates in the needle litter were estimated using the litterbag technique (Kim 2007). The leaf area index (LAI) was determined on a monthly basis during the period of study using a Sunfleck Ceptometer (AccuPAR model SF-80, Decagon, Pullman, WA). The Sunfleck Ceptometer considers the canopy leaf distribution in which the LAI was calculated at an instant measurement by positioning the ceptometer horizontally 1 m above ground level, and 6 readings taken in the four cardinal directions within the stand density (Bolstad and Gower 1990).

Statistical analysis

The soil CO_2 efflux, TAGB, BGB, SOCstock, soil temperature, soil moisture and water potential of each forest stand were subjected to one way analysis of variance (ANOVA), followed by a post hoc Dunn's test and Tukey's multiple comparison test (Mande et al. 2013; Müller et al. 2011) using version 21.0 of SPSS software (SPSS Inc., Chicago, Illinois, USA. The analysis of variance (ANOVA) was used to test the difference in the standard deviation and mean soil CO_2 efflux, soil temperature, soil moisture and water potential for different months based on the least significant difference (LSD) method, and the significance of each forest stand on soil CO_2 efflux, at a significance level of $P<0.05$. The descriptive statistics were established to calculate and explain the normality of the data distribution and also to quantify the correlations between soil CO_2, *TAGB*, changes in soil properties as well as environmental factors. Exponential regression and the multiple linear regression models were employed to ascertain the significant effect of the environmental properties on soil CO_2 efflux in the study area, likewise Pearson's correlation was calculated to show the correlation of CO_2 efflux variation with the environmental factors and changes in soil properties.

Results

Soil CO_2 efflux pattern for different forest ages

The total soil CO_2 efflux clearly varied among the four forest ecosystems at different forest ages. Analysis of variance indicated that the forest age significantly affected soil CO_2 efflux. There were significant differences among the 10-, 30-, 50- and 70-year-old forests ($P<0.05$) (Fig. 1). In the 10-year-old forest, soil CO_2 efflux ranged from 100.22 to 553.40 mg m^{-2} h^{-1} between February and June, and 115.33 to 536.00 mg m^{-2} h^{-1} between September and December; versus from 99.23 to 520.58, and 180.96 to 500.22 mg m^{-2} h^{-1} between February and June, and September and December, respectively, in the 30-year-old forest; 100.13 to 634.78 and 141.44 to 424.89 mg m^{-2} h^{-1}, February and June, and September and December, respectively, in the 50-year-old forest; and 92.09 to 619.67, and 106.77 to 528.67 mg m^{-2} h^{-1}, February and June, and September and December, respectively, in the 70-year-old forest. On average, soil CO_2 efflux in the 10-year-old forest was significantly ($P<0.05$) higher than in the older forests, but the 50-year-old forest had significantly higher soil CO_2 efflux than the 30- and 70-year-old forest between February and June. Likewise, from September to December, the soil CO_2 efflux for the 10-year-old forest was significantly ($P<0.05$) higher than for the older forests.

Soil CO_2 efflux showed a similar single-peak pattern in all four forests from February to December. The mean daily soil CO_2 efflux rates for all the forest ecosystems increased from February attaining their peak in June except for the 50- and 70-year-old forests, for which the efflux peaked in May and February, respectively, which is attributed to the fluctuations in environmental factors. Soil CO_2 efflux subsequently decreased in September and December. Soil CO_2 efflux increased sharply with increasing soil temperature and decreasing soil moisture and water potential and decreased with an increase in soil moisture, water potential and decreasing soil temperature. The efflux rate increased in the morning at 0800 hours and peaked in the afternoon between 1300 hours and 1400 hours before declining as the sun set. The magnitude of fluctuation in the soil CO_2 efflux rate was greatest in the 10-year-old forest, followed by the 30- and 50-year-old forests, with the 70-year-old forest showing the lowest fluctuations.

Figure 2: Variation in soil CO_2 efflux for the four forests Ecosystem. The variation differed significantly ($P<0.005$) among the forest ages.

Effect of abiotic and biotic factors on soil CO_2 efflux

The multiple regression model was used to present the study in terms of the spatial and temporal variation of soil CO_2 efflux with respect to soil temperature, moisture and water potential since it provided a better fit of R^2 ($P<0.05$). The correlation analysis showed that soil CO_2 efflux was more strongly significant and positively correlated between soil temperature and soil moisture in the 10-year-old forest (R=0.65 to 0.96; $P<0.05$) (Tables 2 & 3). We also found a strongly significant positive correlation among soil temperature, soil moisture and water potential for the 30-, 50- and 70-year-old forests (R= 0.74 to 0.96, $P<0.05$, Tables 4 & 5; R=0.65 to 0.96, $P<0.05$, Tables 6 & 7; R=0.55 to 91, $P<0.05$, Tables 8 & 9) respectively. The relationship was generally equally good at the four ages and the relevance clearly increased with increasing forest age.

In order to establish the impact of soil temperature, soil moisture and water potential on the spatial and temporal variation of soil CO_2 efflux from February to December. In the 10-year-old forest, the month of February showed a beta coefficient of 0.71 and -1.10 for soil temperature and moisture, while, in March, the impact of soil temperature and moisture was recorded as 0.88 and -1.01. This indicated that soil temperature accounted for a significant effect in soil CO_2 efflux compared to soil moisture. Soil CO_2 efflux responded to an increase in soil temperature, as observed in the month of April to display a beta coefficient of soil temperature and moisture impact on soil CO_2 efflux at 0.388 and -0.61, respectively. The March beta coefficient of soil temperature and moisture were recorded at 0.70 and 0.56, respectively, suggesting a significant impact from soil temperature as the soil moisture was at constant level. The month of June beta coefficient was attributed to the effect of soil temperature on CO_2 efflux compared to the soil moisture at 0.86 and -0.69, respectively. The influence of soil temperature and moisture was observed to occur each month, indicating a significant impact on the variation of soil CO_2 efflux. The coefficient of the model of environmental properties for the months of September to December (Pre-monsoon and monsoon regime), were shown to occur at 0.92, 0.32 and -0.79 of soil temperature, moisture and water potential for the month of September; and 0.81, 0.47 and -0.14 for soil temperature, moisture and water potential for October. This indicated that the soil temperature and soil moisture had a major effect on soil CO_2 efflux compared to water potential. The exponential impact was observed from the soil temperature, moisture and water potential on soil CO_2 efflux at 0.48, 0.31 and 0.30 beta coefficient, respectively, for November, while, for December, the beta coefficients were 0.51, -0.05 and 0.37 for soil temperature, moisture and water potential, which is attributed to the effect of soil temperature and water potential on soil CO_2 efflux compared to the soil potential. These occurrences signified the potential impact of the environmental factor on soil CO_2 efflux as the precipitation increased during the measurement period, which increased the nutrients and water movement for the benefit of microbial activities. The relationship is equally good for the 30-, 50- and 70-year-old forests and the relevance clearly increased with the change in the season and forest age. The effects of soil temperature, soil moisture and water potential are therefore confounded. To clarify the contribution of these environmental factors to the observed changes in the soil CO_2 efflux rate, Pearson's correlation analysis was performed. With soil temperature as the control variable, the correlation between soil moisture and soil CO_2 efflux was significant ($p<0.001$) and positive (0.57), while the water potential and soil CO_2 efflux was also significant ($p<0.001$) and positive (0.53). When soil moisture was the control variable, the correlation between the soil temperature and soil CO_2 efflux was significant ($p<0.001$) and positive (0.68), and the water potential was significant ($p<0.001$) and positive (0.55). When water potential was the control variable, the correlation between the soil temperature and soil CO_2 efflux was significant ($p<0.001$) and positive (0.68), and the soil moisture was significant ($p<0.001$) and positive (0.55). During the entire period of measurement, soil temperature was shown to exert a stronger control then the other environmental properties on soil CO_2 efflux.

Table 2: Ten-year-old Forest Best Single and Multiple-Regression Models were generated using Enter Independent Variable Selection from Feb-June

Model	R Square	Adj- R^2	Std Error of estimation	F	Sig
February	.79	.62	43.08	58.75	<0.001
March	.66	.42	65.92	26.92	<0.001
April	.65	.42	72.10	24.69	<0.001
May	.74	.53	49.38	40.77	<0.001
June	.81	.64	84.98	63.49	<0.001

Table 3: Ten-year-old Best Single and Multiple-Regression Models were generated using Enter Variable Selection from Sept- Dec

Model	R square	Adj-R^2	Std Error of estimation	F	Sig
September	.87	.75	45.86	70.92	0.001
October	.92	.84	38.87	128.20	0.001
November	.96	.92	28.52	287.19	0.001
December	.81	.64	44.90	43.14	0.001

Table 4: Thirty-year-old Forest Best Single and Multiple-Regression Models were generated using Enter Independent Variable Selection for Feb-June

Model	R Square	Adj- R^2	Std Error of estimation	F	Sig
February	.96	.92	41.04	244.29	<0.001
March	.93	.85	38.49	186.42	<0.001
April	.92	.77	31.64	125.86	<0.001
May	.94	.90	52.19	218.84	<0.001
June	.91	.75	29.96	102.06	<0.001

Table 5: Thirty-year-old Best Single and Multiple-Regression Models were generated using Enter Independent Variable Selection for Sept-Dec

Model	R Square	Adj- R^2	Std Error of estimation	F	Sig
September	.95	.89	31.56	201.62	<0.001
October	.88	.77	36.91	75.43	<0.001
November	.90	.80	35.19	97.91	<0.001
December	.74	.53	42.057	27.84	<0.001

Table 6: Fifty-year-old Best Single and Multiple-Regression Models were generated Using Enter Independent Variable Selection from Feb- June

Model	R Square	Adj- R^2	Std Error of estimation	F	Sig
February	.65	.42	68.45	16.47	<0.001
March	.78	.61	96.01	35.49	<0.001
April	.93	.86	54.73	139.98	<0.001
May	.68	.44	93.75	19.76	<0.001
June	.86	.73	51.36	63.59	<0.001

Table 7: Fifty-year-old Best Single and Multiple Regression Models were generated using Enter Independent Variation Selection from Sept-Dec

Model	Rsquare	Adj-R^2	Std Error of estimation	F	Sig
September	.92	.83	23.49	118.52	0.001
October	.96	.91	18.50	253.11	0.001
November	.87	.75	25.10	73.01	0.001
December	.89	.78	29.09	83.28	0.001

Table 8: Seventy-year-old Best Single and Multiple- Regression
Models were generated using Enter Independent Variable Selection from Feb-June

Model	R Square	Adj- R^2	Std Error of estimation	F	Sig
February	.89	.79	66.85	86.65	<0.001
March	.90	.81	44.76	93.77	<0.001
April	.88	.76	44.34	75.41	<0.001
May	.55	.31	90.33	10.06	<0.001
June	.88	.77	60.56	77.43	<0.001

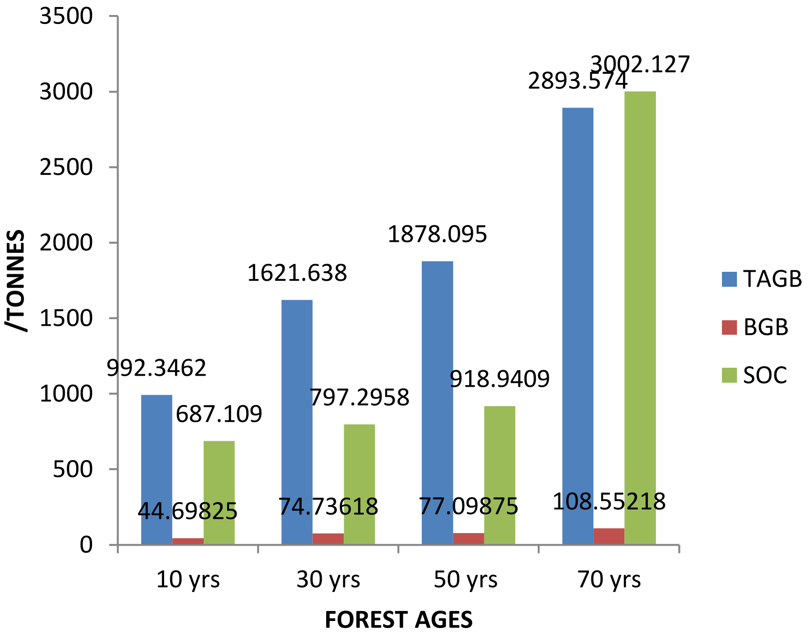
Table 9: Seventy-year-old Best Single and Multiple Regression Models
were generated using Independent Variable Selection from Sept-Dec

Model	R square	Adj-R^2	Std error of estimation	F	Sig
September	.80	.63	68.01	40.55	<0.001
October	.90	.80	54.70	96.80	<0.001
November	.84	.68	61.55	52.29	<0.001
December	.91	.83	37.81	113.45	<0.001

Forest Biomass at different age

The forest biomass – total aboveground biomass (TAGB), below ground biomass (BGB) and total forest carbon store (SOCs) – values showed significance among the different forest ages and stand densities ($p<0.001$). It increased from the 10-year-old forest and attained the maximum in the 70-year-old forest (Fig 3). The percentage of the forest biomass increased the total carbon stock, as soil nutrients would be utilised by microorganisms to emit soil CO_2.

Figure 3: Forest Biomass Carbon Input

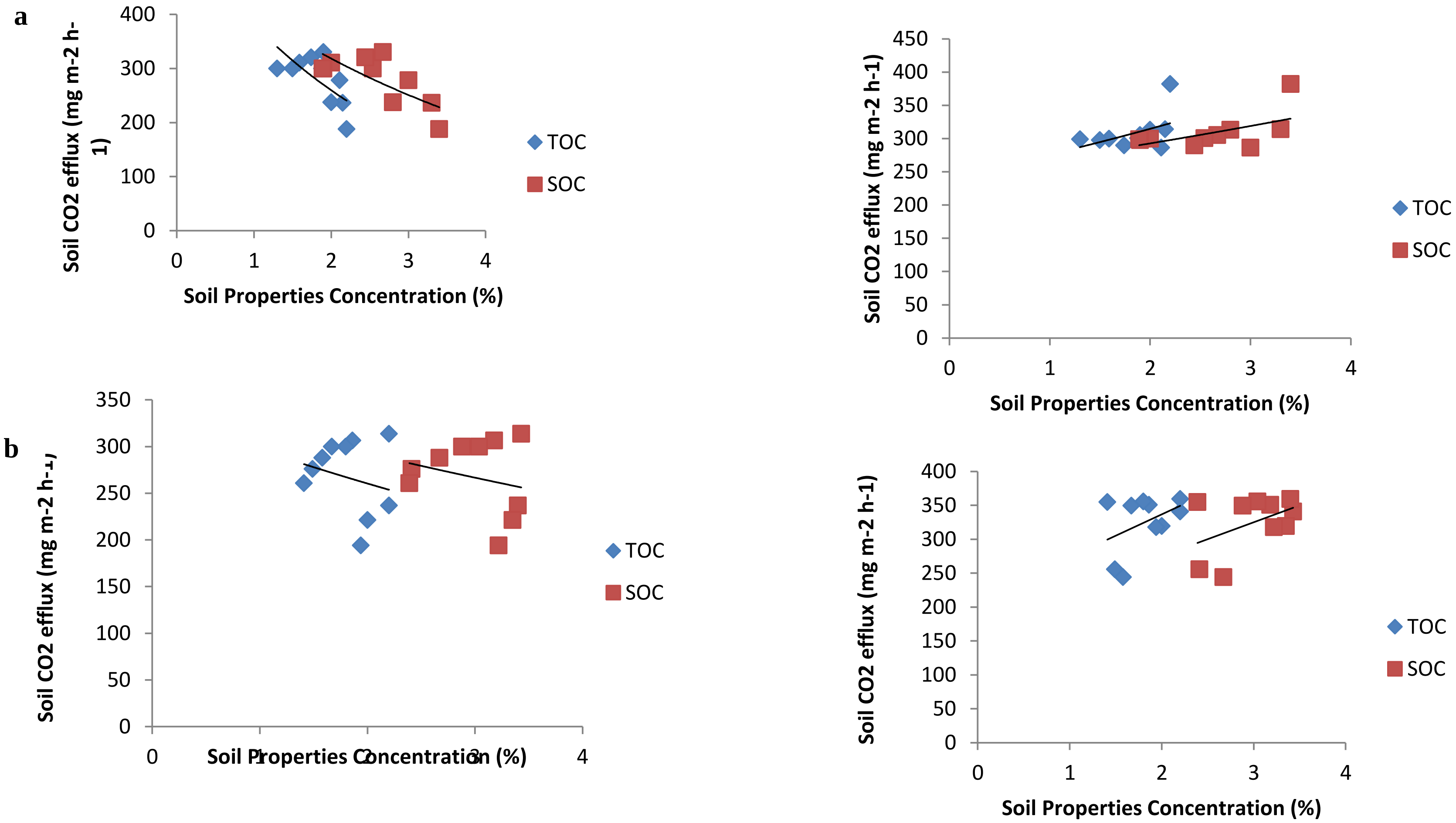


Litter fall (C/N) ratio
The percentage of C/N ratio present in the soil of the various forests indicated the decomposition rates of litter and its contribution to the increase in organic mineral, thereby contributing to the CO_2 emissions. The C/N ratio occurred at C= 45.92 to 50.85%, N=1.29 to 1.48%, C=47.99 to 50.89, N=1.32 to 1.49%, C=49.11 to 50.78%, N=1.33 to 1.48% and C=50.11 to 51.86, N=1.41 to 1.58% for 10-, 30-, 50- and 70-year-old forests respectively.

Soil Properties at different age
The estimated total organic carbon (TOC), soil organic carbon (SOC) and soil organic carbon stock (SOCstock) was significant ($p<0.001$) with soil CO_2 efflux, as they were recorded to occur in considerable quantities with a higher percentage between 0 and 30 cm soil depth and decreased between 10 and 100 cm soil depth. The multi-linear regression and Pearson's correlation was

further confirmed by indicating a significantly positive correlation between soil CO_2 efflux and TOC, SOC and SOCstock. Subsequently the spatial distribution of the soil CO_2 efflux rate between February and December was significantly and positively correlated with the soil properties (TOC and SOC), as the linear regressions for their relationships were relatively high in the upper layers and decreased with depth as the soil CO_2 efflux was also found to increase (Fig. 4). This suggested that the concentration of the soil properties influenced soil CO_2 efflux. There was also a significant relationship between the pH and soil CO_2 efflux in all sites. However, there was a weak correlation between the bulk density and soil CO_2 efflux in the different forest compartments.

Figure 4: The relationships between soil CO_2 efflux and TOC, SOC at **a** 10, **b** 30, **c** 50 and **d** 70-year-old forests



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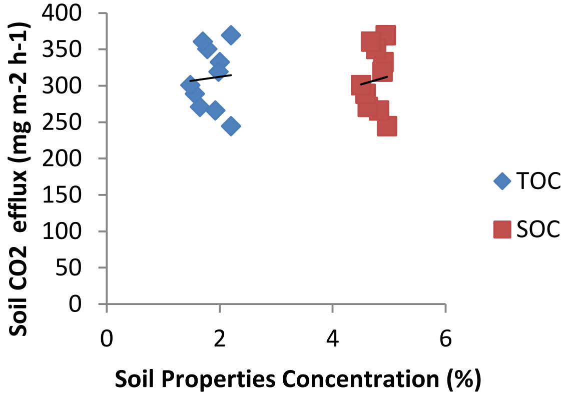
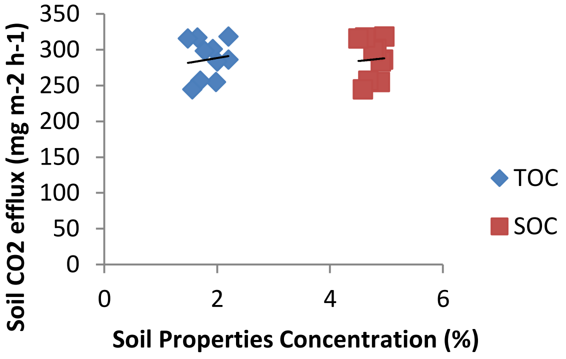
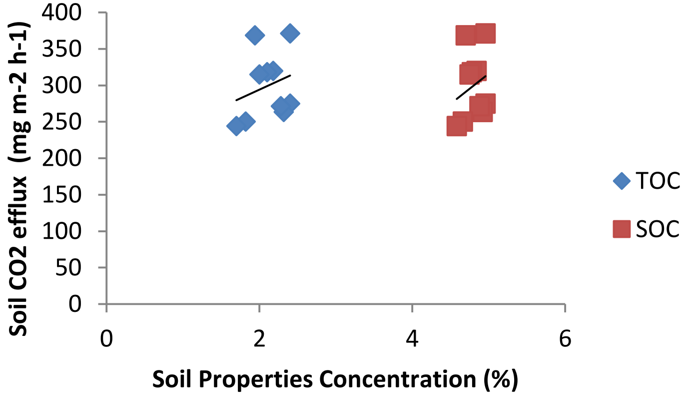
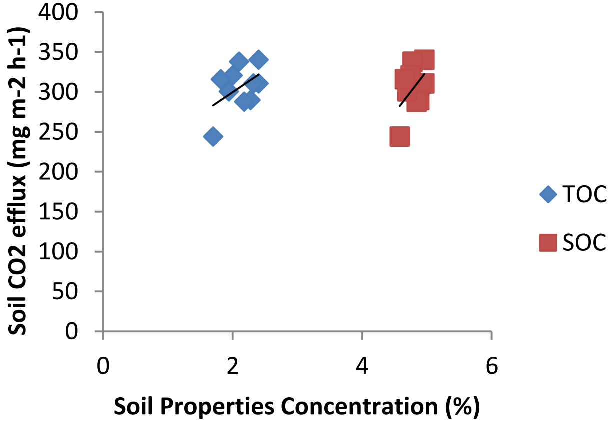

Soil CO2 efflux (mg m-2 h-1)
400
350
300
250
200
150
100
50
0
0
2
4
6
Soil Properties Concentration (%)
TOC
SOC


Soil CO2 efflux (mg m-2 h-1)
350
300
250
200
150
100
50
0
0
2
4
6
Soil Properties Concentration (%)
TOC
SOC

d


Soil CO2 efflux (mg m-2 h-1)
400
350
300
250
200
150
100
50
0
0
2
4
6
Soil Properties Concentration (%)
TOC
SOC


Soil CO2 efflux (mg m-2 h-1)
400
350
300
250
200
150
100
50
0
0
2
4
6
Soil Properties Concentration (%)
TOC
SOC

Discussion

The monthly patterns of soil CO_2 efflux

Soil CO_2 efflux in the 10-year-old forest was significantly higher than that in the older forests, the rate decreased as the forest age increased. The magnitude of the fluctuations in soil CO_2 efflux in response to changes in microclimate condition, forest biomass and soil properties also increased with forest age. A few previous studies have reported the effect of recovering forest at different forest ages on soil CO_2 efflux. A trend of decreasing soil CO_2 efflux with the increase in recovering forest was previously examined and reported for various forest ecosystems (Saiz et al. 2006; Tedeschi et al. 2006). Furthermore, soil CO_2 efflux in response to environmental factors influence has been widely reported in the poplar plantations of northwest China (Zhang et al. 2011), multiple ecosystems in central Japan (Tomoharu et al., 2012) and successional forests in Southern China (Huang et al., 2011). The chronosequence approach has been used in forest soil studies with different ages (Yanaiet at al. 2003; Sartori et al. 2007). In these forest ecosystems of the study area, there was a significant difference in soil CO_2 efflux between the forest ecosystems of different ages. A high soil CO_2 efflux rate was recorded in the 10-year old-forest at a range between 100.22 and 553.40 mg m^{-2} h^{-1} similar to that of the subtropical forest of China (Ren et al., 2007) and the canopy cover in the tropical spare forest of China (Jin et al. 2009). The high soil CO_2 efflux rate in the 10-year-old forest is a result of the high soil temperature due to the lower canopy cover than the older forests. Other factors may be due to the high physiological activity that is associated with root growth respiration, as studies have shown that increasing respiration is associated with the synthesis of new tissue (Chen et al., 2009). The soil CO_2 efflux rate in the 30-year-old recovering forest was recorded to be 99.23 to 500.22 mg m^{-2} h^{-1}, which is similar to the Pasoh forest reserve of Peninsular Malaysia (Adachi et al. 2006). The average soil CO_2 efflux recorded in the 50-year-old recovering forest from February to June ranged from 100.13 to 424.99 mg m^{-2} h^{-1}, similar to Jin et al. (2009) and Hu et al. (2004) for the tropical forest Central Hokkaido, Japan. The 70-year-old forest emitted a soil CO_2 efflux rate at an average of 92.09-528.67 mg m^{-2} h^{-1}, similar to the deciduous forest of Japan due to seasonal change (Lee et al. 2003). The decrease in the soil CO_2 efflux rate in the older forests is in relation to the increasing forest age, and the respiration by microorganisms and roots both decreasing gradually and then tending to stabilize (Gong et al., 2012). Furthermore, the bacterial ratio decreases with forest age, as fungal dominated soil communities may enhance C storage and slow the turnover of soil organic matter because the fungi changes the physical properties of the soil (Six et al. 2006). Also fungi grow faster than filamentous bacteria and have a stronger ability to take up nutrients, and, therefore, use soil organic carbon and nitrogen more efficiently to form their own biomass storage and reduce soil CO_2 efflux (Thiet et al. 2006). Therefore, the lower soil CO_2 efflux in the older forests would improve the efficiency of carbon sequestration. The change in the soil CO_2 efflux rates as these forests age may further affect the long-term carbon balance of the forest.

Factors affecting soil CO_2 efflux

Soil CO_2 efflux is controlled by biotic and abiotic factors, such as soil temperature, soil moisture, water potential, soil organic carbon content, vegetation type and management of the forest (Neergaard et al. 2002; Adachi et al. 2006; Subke et al. 2006). In general, soil temperature, soil moisture and water potential are the key factors that affect the spatial and temporal variation in soil CO_2 efflux (Rey et al. 2002; Iqbal et al. 2008). In our study, a similar correlation was found, but soil temperature was more strongly correlated with soil CO_2 efflux than soil moisture, water potential and soil properties. Also, a significant positive correlation was found between soil temperature, soil moisture, water potential and soil properties, which agrees with the results of previous studies (Tang et al. 2006).

The partial correlation analysis employed confirmed that soil temperature, soil moisture and water potential were significantly positively correlated with soil CO_2 efflux, but with soil temperature playing the dominant role in soil CO_2 efflux, as it was also reported in the previous studies of the tropical forests (Mande et al. 2014). When other factors, such as SOC, TOC and SOCstock, were added to the analysis, it was found that soil CO_2 efflux was strongly influenced. These results showed that SOC, TOC, SOCstock, soil moisture and water potential were strongly positively correlated with soil temperature. Rising soil temperature can increase the microbial physiological activity, leading to higher decomposition rates and higher soil CO_2 efflux rates (Han et al. 2007). The lower degree of canopy cover in the 10-year-old forest than in the older forests leads to increased soil temperatures, which would have increased microbial activity.

The findings revealed that the major factors responsible for the soil CO_2 efflux rate in the various forest ages were the combined factors of soil temperature, soil moisture, water potential, SOC, TOC and SOCstock. Soil CO_2 efflux was significantly positively correlated with SOC, TOC and SOCstock ($R=0.92$, $P<0.001$), thus showing that the soil properties significantly affect soil CO_2 efflux in forests of different ages. The SOC, TOC and SOCstock were higher in the older forests than in the 10-year-old forest. The soil properties are the major energy source for soil microorganisms (Adachi et al. 2006) and higher soil properties have strong physiological functions as they increase the uptake capacity of nutrients by microorganism activities, which emit soil CO_2 at high soil temperatures (Pregitzer 2002; Chen et al. 2009). The C/N ratio was significantly positively correlated ($R=0.82$) in the older forests compared to the 10-year-old forest, and a high C/N ratio is conducive for litter decomposition, fungi and actinomycetes breeding (Laughlin & Stevens 2002). Fungi have a stronger ability to take up nutrients and therefore use soil organic carbon and nitrogen more efficiently to form their own biomass and reduce CO_2 efflux (Thiet et al. 2006).

Conclusion

This study has proven that soil CO_2 efflux varies significantly as a function of forest age. Soil CO_2 efflux in the younger forest is remarkably higher than for the older forests as a result of higher soil temperature and less canopy cover, which lead to less carbon storage and more soil CO_2 efflux. Soil CO_2 efflux in the 30-, 50- and 70-year-old forests is low due to the low physiological activity of low soil temperature, low microorganism activity and high soil properties, which is likely to improve the efficiency of carbon sequestration. Forest age may therefore affect the carbon balance of the forest. The contribution of microclimate condition, forest biomass and soil properties on soil CO_2 efflux varies with the season and forest age. The results indicate that soil temperature, soil moisture, water potential, SOC, TOC, SOCstock, bulk density, soil pH and forest biomass carbon input are the dominant factors that control the spatial and temporal variation in soil CO_2 efflux. Therefore, to accurately estimate soil CO_2 efflux all the affirmative factors have to be taken into cognisance. Furthermore, root production, microbial community structure and microbial production could influence the soil CO_2 efflux and should be further explored.

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