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Temperature and Moisture Controls of Soil Respiration in a Dry Dipterocarp Forest, Ratchaburi Province

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ABSTRACT

To quantify soil respiration and to investigate its diurnal and seasonal variations, soil respiration was studied in a dry dipterocarp forest located in Chombung District, Ratchaburi Province (13° 35’ 13.3” N, 99° 30’ 3.9” E). Soil respiration was measured hourly during February to July 2008 using a closed-automatic chamber method. The results showed that soil respiration varied significantly both spatially and seasonally. Among three replicates of measurements and within each hour of measurement, the coefficient of variations could be as high as 80%. On a daily scale, a weak relationship between soil respiration and soil temperature was observed. On a seasonal scale, a negative relationship between soil respiration and temperature was observed. However, a strong positive relationship between soil respiration and soil moisture over the moisture range of 17-19%vol was found. Soil respiration decreased beyond this moisture level. The total CO_2 emissions during the six-month period in dry dipterocarp forest were 1.81 $kgCO_2/m^2$, or 4.9 tonne C/ha.

Key words: soil respiration, spatial and seasonal variations, dry dipterocarp forest, closed-automatic chamber

INTRODUCTION

The estimated pool size of soil carbon is as much as or more than the amount of carbon contained in the atmosphere and live biomass combined (Eswaran *et al.,* 1993). Parts of this organic carbon pool are converted to gaseous CO_2 through biological respiration and subsequently exchanged with the atmosphere through surface emissions. Thus, soil respiration is one of the key components of the global carbon cycle (Kominami *et al*., 2008; Wang and Zho, 2008). Because of its large quantity, it is suggested that only a relatively small change in the soil carbon pool and its fluxes could significantly affect the level of CO_2 in the atmosphere. The current global carbon efflux from the soil is estimated to be between 50 and 75 Gt C yr^{-1} (Raich and Schlesinger, 1992).

Since soil respiration is directly related to both microbial and root activities, its temporal and spatial variations are largely controlled by environmental factors, such as precipitation, soil moisture and temperature. Understanding how soil respiration responds to such environmental factors is fundamental to an accurate prediction of the impacts of climate on carbon cycling. Increased global temperature could stimulate microbial-mediated organic carbon decomposition, and thus,

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CO_2 emission from soil. However, if increased temperature coincides with drier soil conditions, the increase could be dampened (Herbst *et al.*, 2008). Jinyan and Chuankuan (2006) studied soil respiration in northern China and found that much of the variation in soil respiration came from microbial respiration in response to both moisture and temperature. In Harvard forest, USA, roots were very sensitive to temperature, and root respiration represented the main component of seasonal variations in soil respiration data (Boone *et al.*, 1998).

It is known that tropical forests store significant amounts of carbon and have a high capacity to sequester atmospheric CO_2 (1-3 Pg C/ year; Malhi and Grace, 2000). However, understanding their responses to both short-term changes as climate variability and long-term changes as climate change is still very poor. Therefore, improving the knowledge on carbon processes in tropical forests is crucial for evaluating their capacity as sources or sinks, their climatic feedbacks, and hence the overall global carbon cycle. The objectives of the present study were to quantify soil respiration and to investigate the diurnal and seasonal variations of soil respiration in a Thai dipterocarp forest, one of the main forest ecosystems in Thailand (about 20,413.24 km^2 or 12% of the total forest area in 2004, Royal Forest Department, 2004), as well as in Ratchaburi province.

MATERIALS AND METHODS

Site description

This study was carried out in a dipterocarp forest located within King Mongkut's University of Technology Thonburi, Ratchaburi campus in ban Ranbua, tambon Rangbua, Chombung district, Ratchaburi province (13° 35' 13.3" N, 99° 30' 3.9" E). This area has remained as a dry dipterocarp forest for approximately more than 50 years. The forest has been utilized by surrounding communities for energy (wood and charcoal), timber and other products such as mushrooms and for local hunting. As a result, most of the standing trees have resulted from regeneration after occasional clearing by villagers. In 2008, most trees were 3-4 years old and the average height and girth was 4.6 m and 16 cm, respectively. Since 2005, the area has been preserved and protected, and cutting of trees is no longer permitted. The main tree species in this forest are *Dipterocarpus intricatus, D. obtusifolius, D. tuberculatus*, *Shorea obtuse and S. siamensis* (Dipterocarpaceae) (Phiancharoen *et al.*, 2008).

The average annual rainfall over a thirty-year period (1961 -1990) at the site was 1253.1 mm. Average daily maximum and minimum air temperature from 1992 to 2007 was 40.9°C and 19.8°C, respectively [http://www.tmd.go.th/]. Soil pH at the site was acidic with a pH value around 5 throughout the 100-cm profile. Soil bulk density ranged from 1.3 to 1.4 g cm^{-3}. The organic carbon content was 0.3-0.5%. The soil texture for the top 100-cm depth was loamy sand, with a sand particle content of more than 70% and a very small fraction of clay content (Hanpattanakit, 2008).

Instrument setup

Soil respiration was measured by a closed-automated chamber technique during February and July 2008. The measuring system consisted of a chamber system and a data-storing unit (data logger). The chamber had two parts, the cover and base. The acrylic cover had dimensions of 0.3 m width × 0.3 m length × 0.3 m height and the stainless steel base had dimensions of 0.3 m width × 0.3 m length × 0.15 m height. The base was permanently inserted into the soil where gas sampling was conducted. To monitor the net CO_2 exchange through soil respiration and to prevent the effects of photosynthesis, an opaque chamber was used and installed in an area without plants.

The chambers were closed and opened by a hydraulic system, which was controlled by a program on a data logger (CR10x, Campbell Scientific, Logan, Utah, USA) and a two-way solenoid valve. At any given time, the CR10x unit activated the two-way solenoid valve to close the chamber lid, and another one-way solenoid valve was opened. Then, an air sample inside the chamber was pumped (1.5 L min^{-1}) into the measurement unit where the CO_2 concentration was determined by an infrared gas analyzer (Licor-820, Licor Corporation, Lincoln, Nebraska, USA). The data generated were stored in the data logger and downloaded manually. After analysis of CO_2 concentrations, the air sample was channeled back to the chamber through a one-way solenoid valve**.** One sampling cycle took about 7 min. In the present study, soil respiration was measured hourly during February to July 2008. Thus, for each of the three replications, respiration was measured 24 times per day, or about 4300 times during the whole study period of six months. During the course of measurement, the CO_2 level in ambient air was also measured hourly. The system was calibrated with standard CO_2 gas each month. In addition to these measurements, soil and air temperatures and soil water content were continuously measured. Soil temperature was measured at a depth of 5 cm with two Averaging Soil Thermocouple Probes (TCAC, Campbell Scientific, Inc. Logan, Utah, USA). Soil water content was measured at 4 cm depth with two water content reflectometers (CS615, Campbell Scientific, Inc., Logan, Utah, USA).

CO_2 flux calculations and statistical analysis

Soil respiration rates (CO_2 flux) were calculated using the linear portion of the gas concentration change over the chamber's closing period as mentioned above. Only data showing a significant correlation (Pearson correlation coefficient of concentration data versus time was significantly greater than 0 at $p \leq 0.05$) were taken into account to calculate the CO_2 flux. Correlation and regression analysis were used to test the relationship between soil respiration and environmental factors (soil temperature and moisture). Spatial variation of soil and microbe respiration in each chamber was expressed using the coefficient of variation (CV), which was calculated by dividing the standard deviation by the hourly-average CO_2 fluxes.

RESULTS AND DISCUSSION

Diurnal change of soil respiration and its response to temperature and moisture

Diurnal changes in soil respiration have been shown to relate to changes in air and soil temperature (Wiriyatangsakul *et al*., 2006). An example of diurnal changes in soil respiration, temperature and soil moisture is shown in Figure 1. There were clear diurnal changes in air and soil temperature (Figure 1B), both of which were observed during 13-14 hrs. The maximum soil temperatures were about 6-8°C lower than the maximum air temperatures. On the other hand, minimum soil temperatures remained 1-2 °C higher than minimum air temperatures. Soil moisture did not seem to change significantly, staying fairly constant around 21-22 %vol during the few days when there was no rain event. In contrast, over a longer time scale of weeks or months, soil moisture varied significantly (see Figure 3D), especially in association with rainfall events.

Soil respiration seemed to increase in response to an increase in temperature. It increased from about 300 $mgCO_2\ m^{-2}\ hr^{-1}$ to the highest values during the day of 500-600 $mgCO_2\ m^{-2}\ hr^{-1}$ at around 14-15 hrs (Figure 1A). After reaching a maximum, soil respiration stayed at a high level until around midnight, after which it declined towards early morning. Although from Figure 1, it seems that soil respiration closely tracked the air and soil temperature, only a weak correlation was obtained between soil temperature and soil respiration during these three days ($r = 0.34$, $p = 0.01$, $n = 55$). Analysis of more data from the whole period may be needed in order to identify a stronger relationship. Similar results were also reported by other researchers. For example, Toshie *et al*. (2002) found that the soil CO_2 flux was strongly correlated with the soil surface temperature. Yoshiko and Hasegawa (2000) estimated the soil CO_2 profiles based on CO_2 production and gas diffusivity. They described diurnal changes in soil CO_2 concentration that were similar to those in soil temperature. However, in an arid ecosystem where the soil moisture level is consistently low, rates of soil respiration at night may be higher than during the daytime due to increased relative humidity at night (Medina and Zelwer, 1972). High humidity favors microorganic activity.

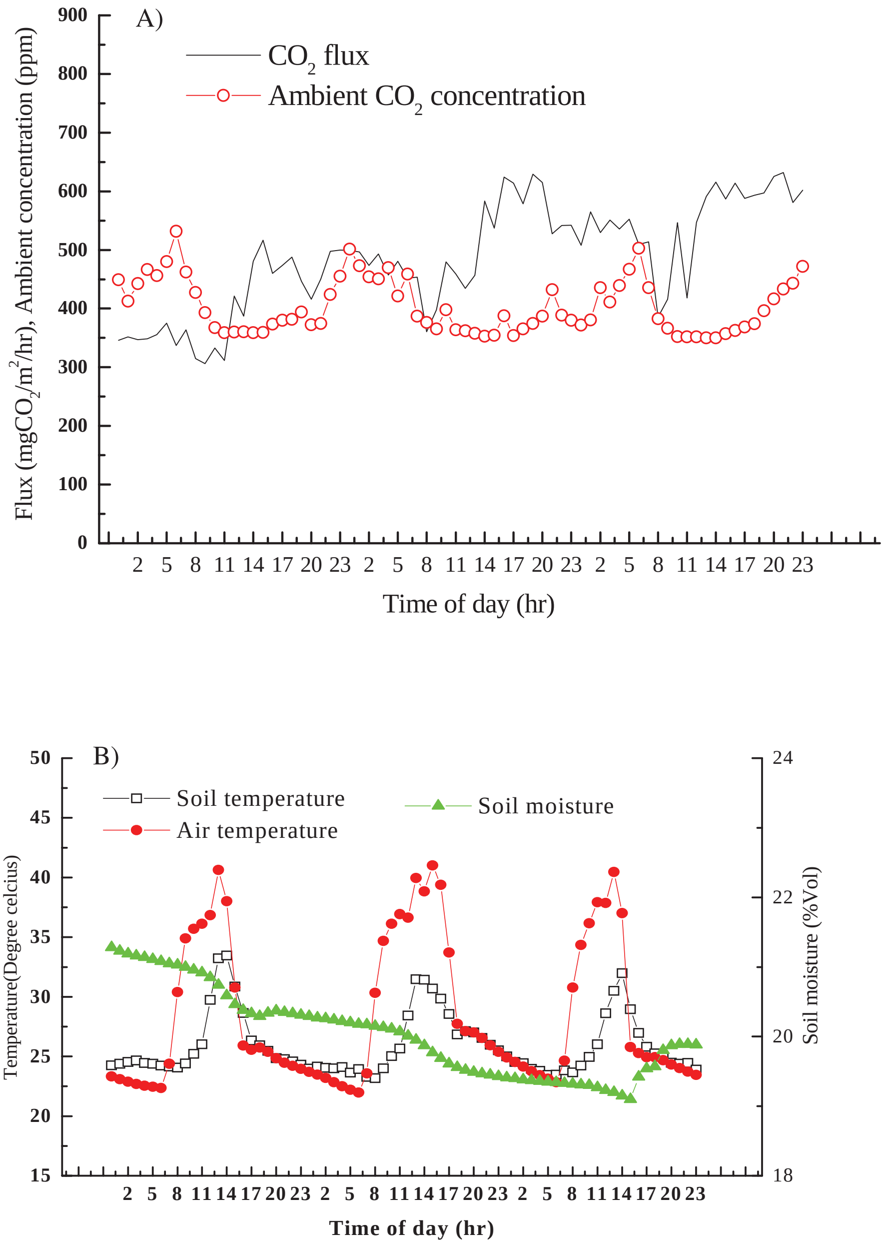

Figure 1 An example of diurnal changes in A) soil respiration and ambient CO_2 concentrations; and B) air and soil temperatures and soil moisture (three days of data are shown).

In addition, CO_2 ambient concentration was also measured. It remained high during nighttime and low during daytime, which was an expected pattern from the interaction between the processes of photosynthesis and respiration. A high soil respiration rate during the night may partly contribute to this high ambient CO_2 concentration.

Increased soil respiration in response to rain events

During the course of measurements, it was observed that occasionally soil respiration increased and this seemed to relate to rainfall events. Figure 2 gives examples of the timing (normalized to hours before and after the rain

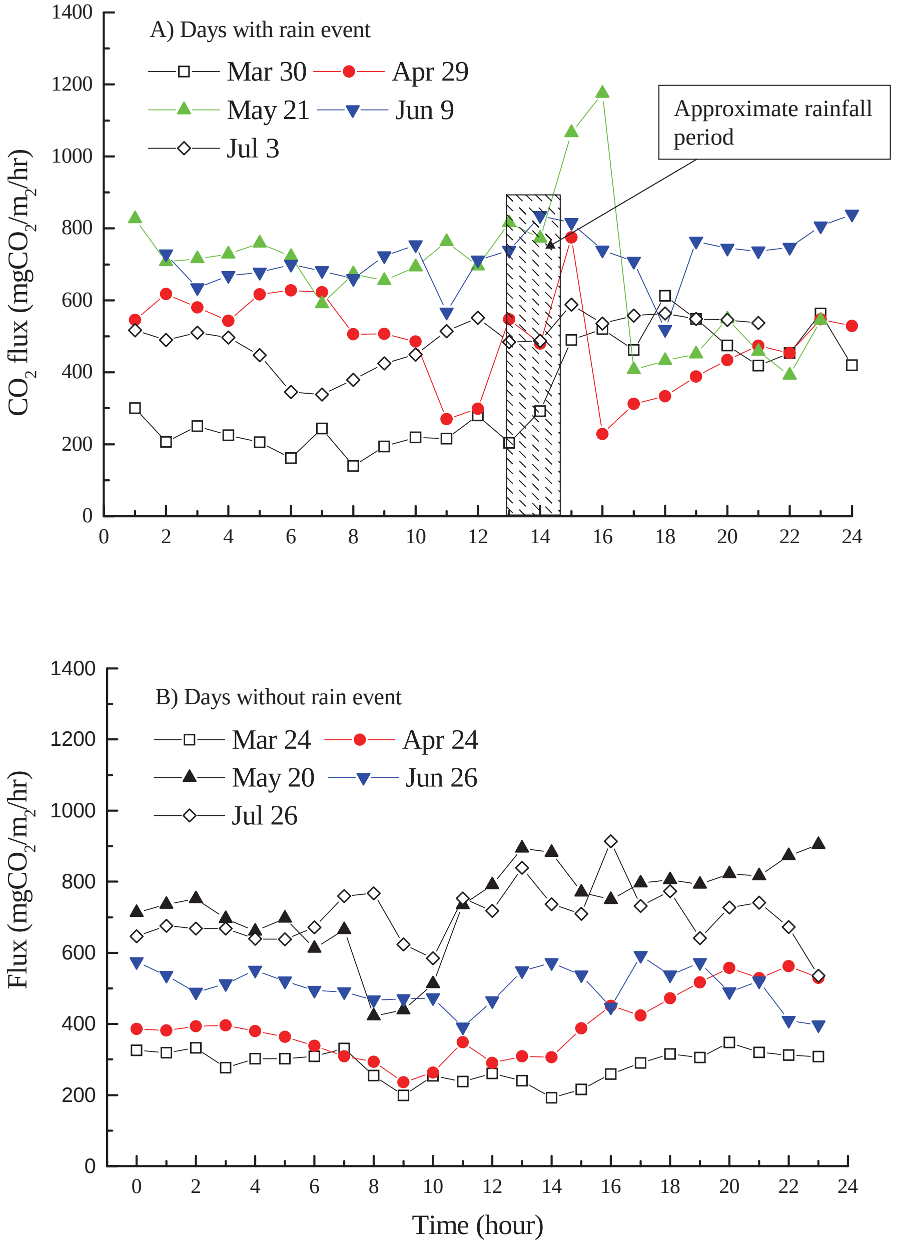

Figure 2 Response of soil respiration to rainfall events. The shaded area indicates the normalized time of the rainfall event.

event) and magnitude of the soil respiration increase in responses to such rain events. It is noted that these data are only approximate, as both rain intensity and duration should affect soil respiration, but both data were not available in this study. The rainfall records were thus, only qualitative, i.e. only the timing of the rainfall event, and not the amount was recorded. Quantitative analysis will be possible in future, after a rain gauge has been installed at the site.

The examples in Figure 2 show that soil respiration indeed increased during and following the rainfall events (Figure 2A), when compared to a day without rainfall (Figure 2B). The pulse emission existed for a few hours after rainfall, after which it was generally lower than that observed before the rainfall event. The magnitude of the emission increase depended on the time of the year. During the dry season or when there was a long period without a rain event (March, April and May), the increase was up to twice the daily average. On the other hand, the response to a rain event was moderate during the period when the soil was relatively wet (June, July). The pulse emission of CO_2 following a rain event is well documented. Luo and Zhou (2006) give the explanation that after a long period without rainfall, soil water content decreases due to excessive evaporation and this is gradually filled up with air, partly contributed by gases released from soil respiration. As rainfall comes, water fills up the air space causing a consequent rush of air from the soil surface.

Seasonal variations

In addition to short-term variations in soil respiration, seasonal variation is an important component of soil respiration. Seasonal variations are related to climatic factors and plant physiology, including the quantity and quality of substrates. Thus, seasonal variations depend on site-specific characteristics and quantifying and understanding these are important to evaluate respiration at local and regional scales.

Seasonal variations of soil respiration in dry dipterocarp forest at Ratchaburi

Figure 3 shows soil respiration throughout the measurement period as measured by the daily average emission from the individual chambers, with variation parameters expressed as both a standard deviation and coefficient of variation, and the changes in soil temperature and moisture. The average soil respiration ranged between 200 and 700 $mgCO_2\ m^{-2}\ hr^{-1}$ (Figure 3A). Generally, soil respiration was relatively high during the period when soil moisture was high (Figure 3D), indicating the positive effects of soil moisture. The emissions from individual chambers showed high variations (Figures 3A and C), but the seasonal trends from all chambers were similar. This indicates that such high seasonal variations were caused by intrinsic heterogeneity characterizing individual measurements spots. The standard deviations and the coefficients of variation among the three chambers throughout the season ranged between 50 and 350 $mgCO_2/m^2/hr$, and 10 and 80%, respectively (Figure 3C). The average soil CO_2 emission during the six-month period (R_s) was 400.08 $mgCO_2/m^2/hr$. Throughout this six month period, the total amount of CO_2 released from soil respiration was 1.8 $kgCO_2\ /m^2$, equivalent to 4.9 tonne C/ha (approximately 9.8 tonne C/ha/yr). The ranges obtained in this study, therefore, are within those reported in other forest types in Thailand of 13.37, 12.14 and 10.67 tonne C/ha/yr for dry evergreen, mixed deciduous and dry dipterocarp forests, respectively (Panuthai *et al.,* 2006).

Table 1 summarizes the average soil respiration for each month, together with the average standard deviation and CV. The data presented are intended to show the spatial variation of soil respiration. On a monthly basis, the CV ranged from 42 to 65%. It is well known that a large spatial variability in soil CO_2 efflux is common. This usually occurs at the stand level, even in relatively homogeneous soil with physical properties (soil texture, soil moisture, bulk density, soil porosity, soil water content, etc), nutrient availability (carbon and nitrogen content, litter deposit and nitrogen mineralization), and biological characteristics (biodiversity of animal and microbial community). Due to the large heterogeneity of the natural soil, spatial differences in soil respiration have been observed in various ecosystems with a high CV, including: grasslands (CV = 35%, Polvan *et al.*, 1998), CV = 10 to 100%, Hanson *et al.*, 1993, Jensen *et al.*, 1996, Law *et al.*, 1999), rainforests (CV = 15 to 70%, Schwendenmann *et al.*, 2003), pine plantations (CV = 21 to 55%, Fang *et al.*, 1998, Xu and Qi, 2001), tropical rainforest in Southeast Asia (CV =

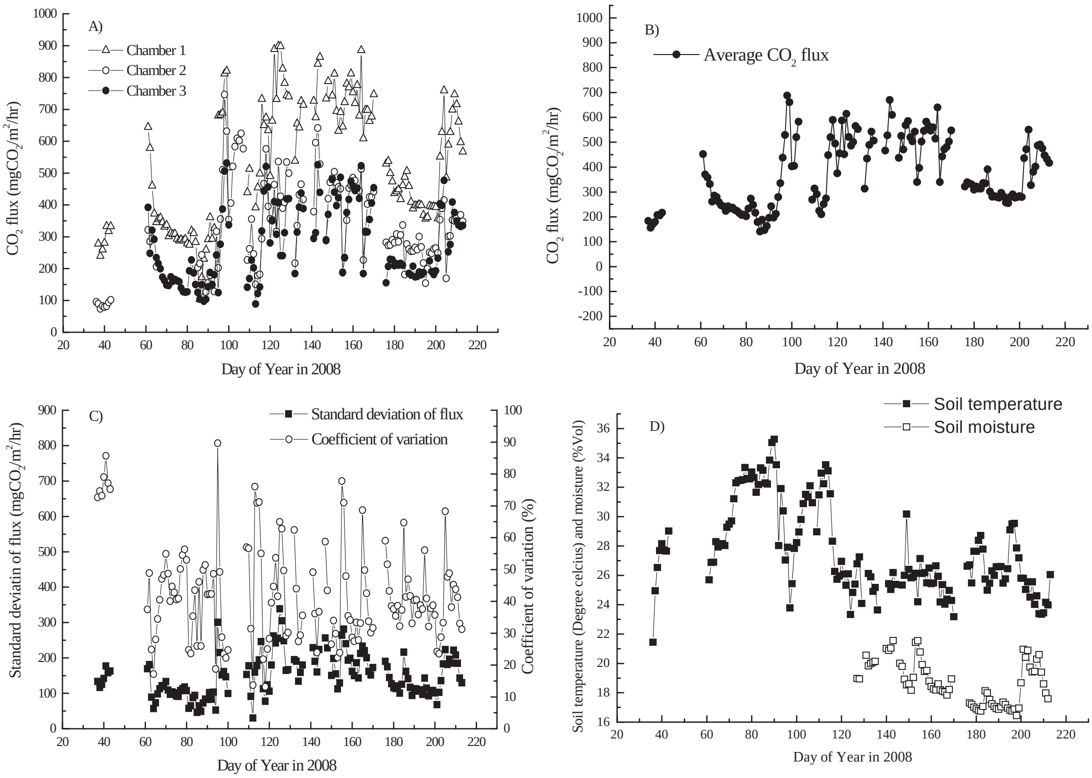

Figure 3 Seasonal variations in A) soil respiration from individual chambers; B) the daily average respiration values; and (C) its variation components; and D) soil temperature and moisture.

Table 1 Summary of average CO_2 flux from each chamber and coefficient of variation (CV) of soil respiration during the period February to July 2008. Note that * = a significant difference among chambers in each month at the 99% confidence level.

Month in 2008	Soil respiration($mgCO_2/m_2/hr$) Chamber 1	Chamber 2	Chamber 3	Average ($mgCO_2/m_2/hr$)	CV (%)
February	269.07	85.18	-	192.30*	42.5
March	319.21	213.42	178.58	265.04*	58.04
April	598.86	391.57	319.05	456.51*	64.57
May	757	444.15	368.96	599.93*	62.2
June	652.74	367.77	335.09	491.98*	57.83
July	495.85	285.89	264.29	396.20*	45.73

26 to 62%, Yoshiko *et al*., 2007) and sugarcane plantation in east Thailand (CV = 4 to 54%, Yuttitham and Chidthaisong, 2006). Such large variations could also be due to various factors besides heterogeneity at the sites as mentioned above, including variations in the amount and quality of litter fall and different responses to climatic variables from different components of soil respiration (microbial versus root respiration, Luo and Zhou, 2006). At the current study site, the leaves fall mainly during February-March. However, at this time the forest floor is still very dry. When rain comes in April, active decomposition of litter fall combined with active root growth may result in increased soil respiration in the following months, as shown in Figures 3A and B.

Relationship between soil respiration and soil moisture

In arid and semiarid ecosystems, soil moisture is the main factor limiting soil respiration. Thus, seasonal patterns of soil respiration closely follow the dynamics of soil moisture (Davidson *et al*. 2000). In the Amazon basin, for example, where the seasonal variation in temperature is not large, while variation in soil water content was substantial, soil respiration in pastures and forests correlated significantly with water-filled pore space in the soil (Salimon *et al*., 2004). Under Mediterranean-climate regimes, with cold, wet winters and hot, dry summers, water usually constrains biological activity in summer. Seasonal patterns of soil respiration are largely determined by soil water availability. Soil respiration rates correlate positively with soil water content and negatively with soil temperature in sandstone and serpentine grasslands (Xu and Qi, 2001).

The results from the current study indicated that total soil respiration was relatively high during rainfall events compared to when there was no rain. The relationship between soil moisture and soil respiration was further investigated (Figure 4). In the dry dipterocarp forest, respiration increased linearly and significantly ($r^2 = 0.62$, $p < 0.0001$, n = 48) within the moisture range of 16 to 19 %vol, and, at the same time, soil respiration increased about 150

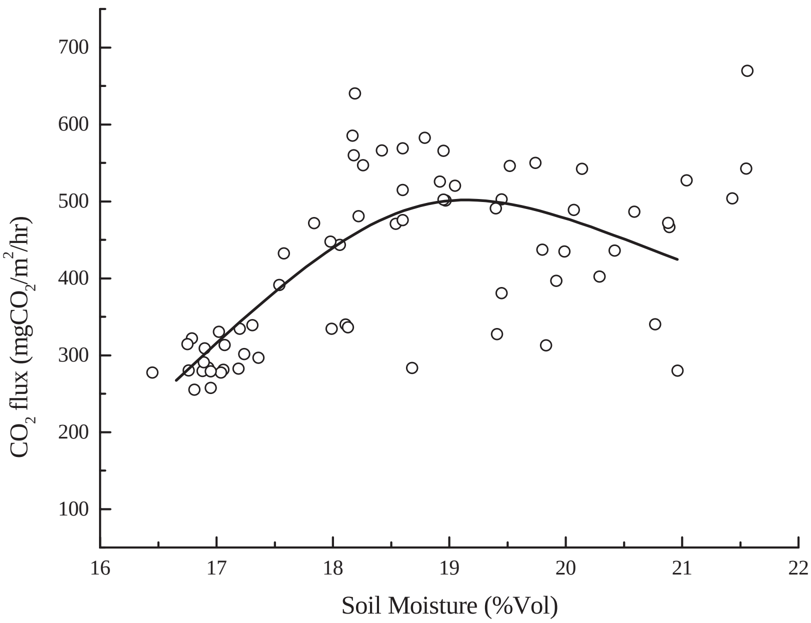

Figure 4 Relationship between soil respiration and soil moisture.

$mgCO_2/m^2/hr$ for each percentage increase in soil moisture. However, any further increase in soil moisture dampened the respiration. Thus, it seems that the optimal soil moisture in this case was around 18-19 %vol.

Relationship with soil temperature

Regression analysis of the soil respiration data revealed that it was negatively correlated with soil temperature (Figure 5), with an r^2 value of 0.64. Based on the number of data points used in the regression analysis, the correlation was significant at $p < 0.01$. This result was quite different from the common perception that an increase in temperature could result in increased respiration up to a certain point, beyond which the respiration was expected to decrease. However, this was not the case. During the dry months, such as March and April, the soil temperature at the site could be as high as 36°C and the air temperature greater than 40°C (see Figure 1). Under such high temperatures and dry conditions, soil respiration was minimized. When plotting the relationship between soil respiration and temperature for the whole period, the lowest emission coincided with the time of highest temperature, and thus, a negative correlation resulted as shown in Figure 5. It is expected that if there had been data available associated with a lower range in temperature, an increase in soil respiration for certain temperature ranges (i.e. up to 25°C) would have been observed, as suggested by Flanaga and Veum (1974). A positive relationship could be found associated with much lower temperature ranges than this, if not in a tropical climate. The collection of data to cover the whole year is underway, so that data during cooler months, such as December and January, should be available for future analysis of the annual relationship between soil respiration and temperature.

CONCLUSIONS

The results from this study indicate that soil respiration varied significantly both spatially and seasonally. On a diurnal scale, variations are likely to have been controlled by temperature. In addition, a rain event also may have contributed to such diurnal variation. On a seasonal scale, soil

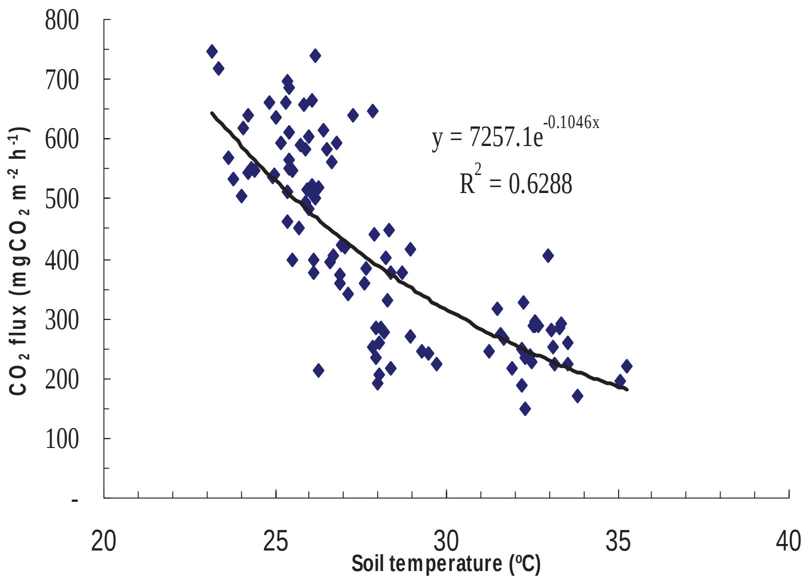

Figure 5 Relationship between soil respiration and soil temperature at 5 cm depth.

respiration was positively correlated with soil moisture. However, there seemed to be an optimal moisture level beyond which an increase in soil moisture did not result in an increase in soil respiration. In the dry dipterocarp forest with sandy soil texture, the optimal soil moisture was around 18-19 %vol. It is interesting to note that the relationship between soil temperature and soil respiration was negative. Integrating throughout the measurement period of six months, the total amount of CO_2 emitted from soil respiration in the dry dipterocarp forest was 1.81 $kgCO_2/m^2$, or 4.9 tonne C/ha. This amount was similar to the CO_2 released from soil respiration in other types of tropical forests found in Thailand.

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