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Effects of Moisture and Temperature on Respiration in Tropical Forest and Agricultural Soils

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ABSTRACT

Soil respiration in tropical uplands was studied in agriculture (maize) and dry evergreen forest soils. The objective of this study was to investigate the effects of moisture and temperature on soil respiration. Diurnal variations of *in situ* soil CO_2 efflux was studied in May 2004 and February 2005. In the laboratory, soil respiration in a short-term incubation was measured under various moisture contents (air-dry, 25, 50, 75 and 100%WHC) and various constant temperatures (10°C to 45°C). *In situ* soil CO_2 flux showed strong diurnal patterns correlated with both air and soil temperature. CO_2 efflux from both study sites increased to the maximum values during the late afternoon, usually 2-4 hours after a peak in air temperature. The total soil CO_2 fluxes integrated over the measurement period were 1354 and 3082 mg CO_2 m^{-2} day^{-1} at agricultural site and 1467 and 12851 mg CO_2 m^{-2} day^{-1} at forest site in May 2004 and February 2005, respectively. The Q_{10} value for agricultural site estimated from relationship between soil temperature at 5 cm and CO_2 flux was 3.37 (May 2004). For the forest site, the Q_{10} was 2.04 (February 2005). Results from laboratory study indicated that the topsoil layer (the top 20 cm) contributed mainly to the overall respiration. Soil respiration was highest at moisture between 50% and 75% WHC. The Q_{10} values of agricultural soil were higher than of that of the forest soil, indicating relatively higher sensitivity of the agricultural soil to temperature change than the forest soil. Laboratory results also indicated that subsoil was more sensitive to temperature and moisture changes than topsoil.

Key words: tropical upland soils, soil respiration, soil temperature, soil moisture and Q_{10}

INTRODUCTION

Carbon dioxide (CO_2) is the most abundant greenhouse gas and contributes about 60% to current global warming (IPCC, 2001). Its averaged concentration in the atmosphere has increased from 285 ppmv (part per million by volume) in 1850 to 376 ppmv in 2003 (Keeling *et al*., 2004). Most of these increases are attributed to human activities such as fossil fuel combustion and change in land use.

Soil contains large portion of the global carbon pool (about 2000 Pg C in soil compared to 750 Pg C in the atmosphere, 1 Pg = 10^5 g; Sarmiento and Gruber, 2002) and the CO_2 evolved from soil respiration constitutes a large portion of

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CO_2 flux to the atmosphere (about 60 Pg C yr^{-1}). Due to its large reservoir, small changes in the flux rate of soil respiration could potentially affect atmospheric CO_2 concentration. Schlesinger *et al.* (1997) suggested that a 1% increase in the rate of CO_2 evolution from soil globally would be equivalent to a 14% increase in the annual flux of CO_2 to atmosphere from fossil fuel.

Agricultural and forest soils store great amount of organic carbon. They are the important sinks of atmospheric CO_2 (Lal, 2004). Carbon stock in agricultural soil is subject to anthropogenic influences. A number of practices (e.g. improved crop rotation, no-till, conservation reserves) have been demonstrated to increase carbon storage in soils. Houghton *et al.* (1999) reported that such cultivation practices led to increase of carbon in agricultural soil in the USA of about 0.14 Pg C yr^{-1} during the 1980s. However, disturbance by variety of agricultural practices (e.g. plowing, fertilization, irrigation) tends to enhance CO_2 emission due to increased decomposition of soil organic matter. Efficient management of agricultural land, therefore, provides a potential tool for mitigating atmospheric CO_2 through carbon sequestration in soils.

Many factors have been reported to affect soil respiration but soil temperature and soil moisture are among the most important factors controlling the CO_2 flux in various ecosystems (Bowden *et al*., 1997; Scott-Denton *et al*., 2003). On short time-scales, warming tends to increase the rate of heterotrophic respiration, but the extent to which this effect can alter land-atmosphere fluxes over longer timescales is not yet fully understood. On the other hand, regional changes in precipitation patterns and cloudiness are also likely to bring about changes in terrestrial moisture regime and respiration. Therefore, soil respiration is one of the important processes to be affected by climate change. Soil climate feedbacks, in turn, can have significant impacts on atmospheric CO_2 concentration.

Generally, relationship between temperature and soil respiration is described in terms of Q_{10} value, which indicates an increase in respiration rate for every 10 °C increase in temperature. This Q_{10} value varies depending on both edaphic and climate conditions (Bowden *et al*., 1997; Frang and Moncrieff, 2001). There are many studies conducted in North America and Europe showing that temperature strongly affects soil respiration. Mielnick and Dugas (2000) found that soil CO_2 flux had a seasonal pattern that was correlated more strongly with soil temperature than soil water. Regressed separately, the exponential relationship between soil CO_2 flux and soil temperature accounted for approximately 46% of flux variability. Similarly, other studies found that the CO_2 flux was strongly influenced by soil temperature. For example, the minima and maxima of the CO_2 flux were closely followed those of the temperature with a delay of 2-3 h (Eriksen and Jense, 2001). Nakadai *et al.* (2002) measured diurnal change of CO_2 flux from bare soil in agricultural field in central Japan. They found that the soil CO_2 flux showed significant diurnal changes and these patterns were highly correlated with the soil surface temperature. The calculation results indicated that the soil horizon above 10 cm depth was a major CO_2 source of soil respiration.

While responses of soil respiration to change in temperature and moisture are relatively well understood in the temperate soils, there are only a few published reports of soil respiration study in tropical upland soils (Scala Jr. *et al.*, 2000; Li *et al*., 2004). Since tropical ecosystem is the main component in global carbon dynamics, gaining knowledge on soil respiration in the tropics is crucial for understanding global carbon cycle and its response to climate change. Accordingly, this study measured CO_2 flux in two different land use types (forest and agriculture) with the main objective to understand the relationship between soil respiration rate in tropical upland soils and changes in temperature and moisture.

MATERIALS AND METHODS

Site description

In this study, CO_2 emission from soil was studied in the tropical forest and agricultural sites. The forest site was a dry evergreen type forest located in Phanom Sarakarm District, Chachoengsao Province (757659°E 1523475°N, Elev. of 16 m above mean sea level). *Dipterocarpus alatus* Roxb is the main plant species at this site. An agricultural field planted to maize (variety Chat-ngen "F_1 Hybrid") was selected for comparison. This site was located within Khao Hin Sorn Royal Development Study Center, Phanom Sarakarm District, Chachoengsao Province. Most area was undulating with slope of 2 – 5 %. The region had a savannah climate with an annual rainfall of 1,247 mm (from 1994-2004) and almost all of the rainfall occurred between May and October. The mean annual temperature was 29.4 °C, with mean monthly minimum and maximum values of 23°C and 36°C in December and April, respectively. Agricultural site was planted to maize two crops per year. Plowing was carried out three times per crop and farmyard manure was applied at the rate of 25 ton ha^{-1}. A composite fertilizer was applied during cropping at approximately 1400 kg ha^{-1}. At this site, plowing was carried out a few days (20 February 2005) before gas sampling in February 2005.

The forest soil was classified as Typic Paleustults (USDA). Soil profile was divided into three main layers within 100 cm depth (S. Jaiarree, personal communication). These included A_l layer (0-20 cm), BA layer (20-40 cm) and Bt layer (40 to 100 cm). Agricultural soil was classified as siliceous Typic Ustipsamments. The profile was also divided into three main layers, including Ap layer (0-20 cm), AB layer (20-30 cm) and C layer (30-100cm). General soil characteristics are listed in Table 1. The texture classification of the forest soil was sandy loam, total carbon content varied between 0.05% and 0.72% and soil pH was acidic. For agricultural soil, it was also classified as a sandy loam (except below 60 cm), total carbon content ranged from 0.13% to 1.17%. In addition, bulk density in forest soil ranged from 1.2 to 1.6 g cm^{-3}, while that in agricultural soil was 1.5 to 1.8 g cm^{-3}. Higher bulk density in agricultural soil than forest soil was expected since agricultural practices such as plowing and tilling might lead to such soil compactness.

Table 1 General soil properties as forest and agricultural sites.

A) Forest soil. (6 May 2004)

Sampling Depth (cm)	pH (H_2O)	C	N (%)	Bulk density (%)	Water content (g cm^{-3})	Texture (% by wt)
0-20	4.03±0.11	0.72±0.04	0.07±0.02	1.35±0.05	12.64	Sandy loam
20-30	4.37±0.25	0.14±0.01	0.01±0.001	1.36±0.10	6.34	Sandy loam
30-70	4.56±0.01	0.05±0.001	0.01±0.001	1.51?0.07	5.10	Sandy loam

B) Agricultural soil. (21 February 2004)

Sampling Depth (cm)	pH (H_2O)	C (%)	N (%)	Bulk density (g cm^{-3})	Water content (%by wt)	Texture
0-20	6.82±0.02	1.17±0.15	0.12±0.02	1.51±0.04	11.8	Sandy loam
20-50	6.92±0.02	0.85±0.03	0.09±0.003	1.66±0.14	11.6	Sandy loam
60-100	7.16±0.02	0.13±0.05	0.03±0.003	1.67±0.06	6.99	Loamy sand

There were no significant differences between groups (p>0.05)

All data in the tables are given as mean ± standard deviation.

CO_2 flux measurement

Soil CO_2 flux was measured throughout the day (24 hours) on 27 May 2004 and 23 February 2005 by difference in the season and tillage practiced at agricultural site. Soil CO_2 flux (May 2004) was measured by using a close chamber technique (Knief *et al.*, 2005). For each site, five chamber bases were placed randomly within the field. The chamber was made of cylindrical PVC with 21-cm internal diameter and 15-cm height. The 5-cm bottom edge of the chamber base was inserted into the soil surface. The gas samples (10 mL) from the chamber headspace were collected by using 20-mL disposable syringe at 0, 5, 10, 15 and 20 minutes after chamber closing. Concentrations of CO_2 were determined using a gas chromatograph (Shimadzu GC-14B) with a Porapak Q column maintained at 120 °C, and injector and detector temperature at 100°C and 300 °C, respectively. Helium at flowing rate of 65 mL min^{-1} was used as carrier gas.

In February 2005, soil CO_2 flux was measured by using the LCi-001 portable photosynthesis system (Li-Cor Inc., USA) fitted with a soil chamber with a volume of 968 cm^3 and an area of 97.5 cm^2. Ten chambers distributed randomly were inserted into in the fields (7 cm depth). The headspace gas was introduced to the gas detector by using a pump at the flow rate of 100 μmol of air per second. Increase in the CO_2 concentration was recorded. Flux in this case was based on the increase of CO_2 inside chamber's headspace relative to the background concentration values. Additionally, the same procedure as that employed in May 2004 was also used for crosscheck. CO_2 flux calculated based on these two methods was not significantly different ($p = 0.05$ using analysis of variance). Soil temperature in the vicinity of the chambers was measured at depths of 5 and 10 cm during the entire gas-sampling period using a glass thermometer. Soil respiration rates (CO_2 flux) were calculated using the linear portion of the gas concentration change over the 20-min time period. For both dates of measurement, only data from chambers with a significant correlation of the measurement points (Pearson correlation coefficient of concentration data versus time was significantly > 0 at the $p \leq 0.05$ level) were taken into account to calculate the average CO_2 flux. The flux value reported for each sampling time represents the average of all chambers used that showed a significant correlation between sampling time and concentration change as mentioned above.

Soil incubation

Soil samples were obtained from 0-100-cm depth at the agricultural site and 0-70-cm depth at the forest site for laboratory incubation (6 May 2004). Soil moisture contents at sampling time are shown in Table 1. The samples were divided into three layers following the depth of soil profile and based on the color difference among layers of each site. The soil samples were air-dried, crumbled into fragments and subsequently the roots and gravels were removed. Soil was sieved through a 2-mm mesh before use.

Soil incubation was carried out at different temperatures and moistures. Three replicates for each depth layer were adjusted to have the water contents of between air-dry soil and water-saturated soil (air dry, 25, 50, 75 and 100% of WHC). To estimate the water holding capacity (WHC), 300 g of air-dried soil were added with water and left for several days until the samples became water-saturated. Subsequently, soil was drained. WHC (g water g $soil^{-1}$) was determined gravimetrically by drying soil at 105 °C to constant weight.

Individual soil samples (approximately 60 g air-dried soils) were placed in a glass vial (240 mL) and then adjusted to targeted water content with de-ionized H_2O. After that the soil samples were incubated under constant temperature at 10, 20, 25, 30, 37 and 45°C for forest soil and at 20, 30 and 45°C for agricultural soil for 30 days. CO_2 production rate was measured weekly during incubation. Preliminary results indicated that CO_2 production decreased by >50% from the initial value during the first-two weeks (data not shown). After the second week, soil respiration rates decreased and became relatively constant as the incubation approached the 4th week. As a result, soil acclimatization was carried out under these conditions for 30 days before investigating for its response to moisture and temperature. When soil respiration was measured, headspace gas samples (0.2 mL) were collected at 0, 5, 10 and 15 min by using a 250-µl pressure lock syringe. Concentrations of CO_2 were measured using a gas chromatograph as described above.

Determination of Q_{10} value

The relationship between soil respiration rate and temperature was analyzed using Q_{10} value. The Q_{10} value indicates the average increase in respiration rate for a 10 °C increase in temperature. The empirically derived equation of van't Hoff function (van't Hoff, 1998) was used to describe the dependence of CO_2 evolution on soil temperature (Eq. 1);

$$F = Ae^{\beta T} \qquad (1)$$

Where F is the soil respiration rate measured at 30 days of incubation (µg CO_2 g soil^{-1} d^{-1}), T is the temperature (°C) and *A* and β are regression coefficients. From Eq. (1), the Q_{10} value was calculated as indicated in Eq. 2.

$$Q_{10} = e^{10\beta} \qquad (2)$$

RESULTS AND DISCUSSION

***In situ* diurnal variations of ambient CO_2 concentration**

Figure 1 shows the diurnal patterns of CO_2 concentration at the forest and agricultural sites measured on 23 February 2005. At the forest site, ambient CO_2 concentration varied from around 430 ppm during the daytime (10:00 – 18:00 hr) to 460-540 ppm during the nighttime. For agricultural site, the daytime concentration was

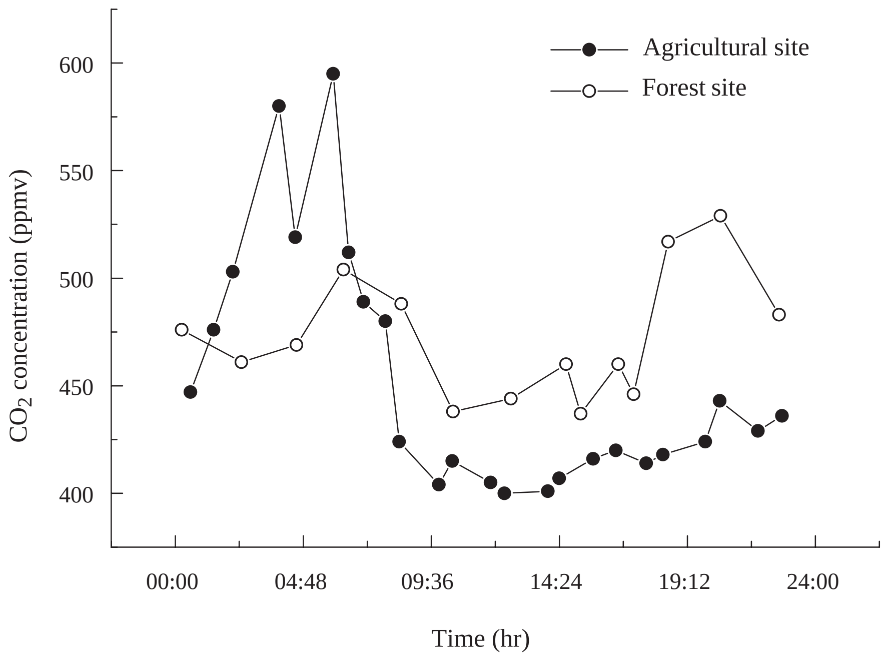


Figure 1 Ambient concentration of CO_2 at forest and agricultural sites measured in February 2005.

usually below 450 ppm while during the nighttime it increased up to about 600 ppm. These results indicated a clear distinction in CO_2 concentration between daytime and nighttime, and to a lesser extent, between forest and agricultural sites. The pattern of CO_2 change was possibly caused by interplay between respiration and photosynthesis processes. The CO_2 concentration was highest at nighttime due to CO_2 release during respiration (by both plant and soil). In contrast, plant photosynthesis during the daytime took up atmospheric CO_2, resulting in a relatively low ambient CO_2 level as observed.

***In situ* CO_2 flux**

1) CO_2 flux at forest site

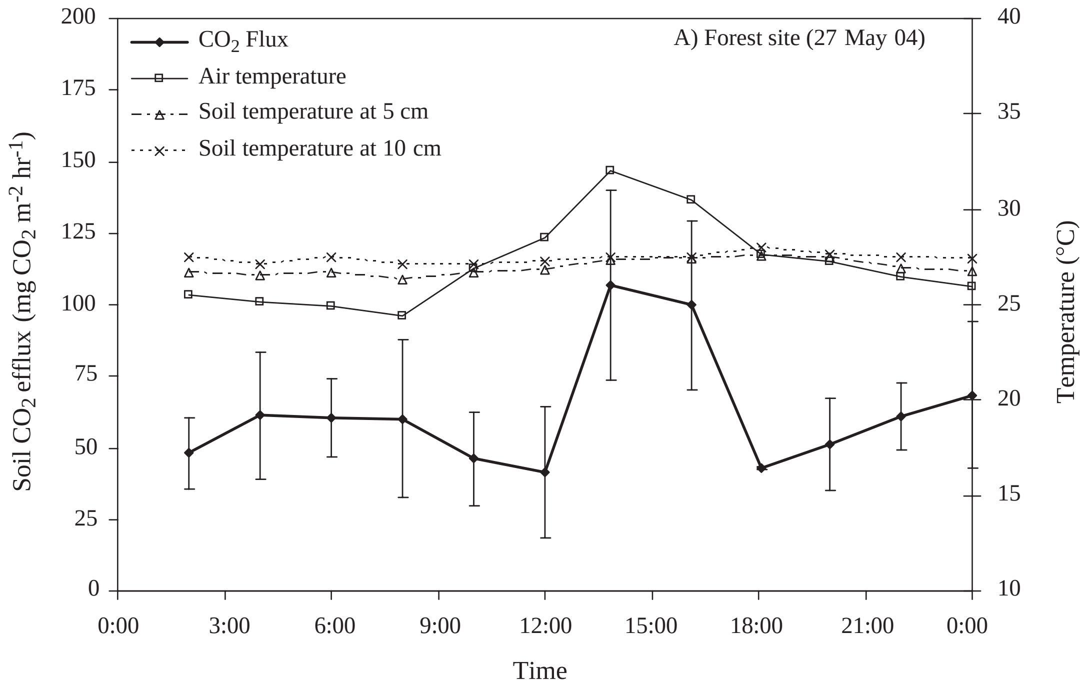
The results of soil CO_2 flux and temperature changes during a 24-hr period are shown in Fig 2. When compared between the variations of soil and of air temperature, daily changes of temperature were more remarkable in air than in soil temperature. On each sampling day, soil temperatures at 5-cm and 10-cm depth stayed fairly constant throughout the day and soil temperatures of both soil depths were not significantly different ($p \leq 0.05$). The ranges of temperature were 24.4–32.1 °C, 26.3–27.5 °C and 27.1–28.0 °C for air, soil temperature at 5 cm and 10 cm depth (27 May, 2004), respectively. On 23 February 2005, the ranges of temperatures were 24.2–33.8 °C and 25.6–28.0 °C for temperature of air and soil 5 cm depth, respectively. Similar to that of May 2004, soil temperature on this date was almost constant throughout the day and this was different from soil temperature of maize cultivation site where large variations in the daily soil temperature were observed (Figures 2 and 3). Existence of forest canopy was possibly the main reason that kept the temperature at relatively constant when compared to the agricultural site.

Soil CO_2 flux ranges in May and February were 32-107 and 469-592 mg CO_2 m^{-2} hr^{-1}, respectively. Large spatial variations were observed. The coefficients of variation (CV) averaged among five chambers were 35% (May) and 23% (February). Maximum flux was observed in the afternoon between 14:00 and 15:00 hr. Temporal changes in soil CO_2 flux were related to the changing pattern of air temperature. The maximum and the minimum of the soil CO_2 flux closely followed those of the air temperature with a delay about 2-3 hrs. The total soil CO_2 fluxes were 1466 and 12851 mg CO_2 m^{-2} day^{-1} in May and February, respectively. Emission during daytime was higher than during nighttime on both days (816 and 6610 mg m^{-2} for daytime, and 650 and 6250 mg m^{-2} for nighttime in May and February, respectively).

The results of field measurement in February 2005 showed higher CO_2 flux than in May 2004. This might be caused by the relatively long-lasting period of high temperature in February 2005 than in May 2004 (Figure 2). On the other hand, the amount of organic carbon input (litter fall) into soil might also be different between in February 2005 and in May 2004. These results suggested that temperature could partly explain the diurnal soil CO_2 flux. However, the other factors such as moisture content and aboveground litter inputs might be also important as suggested by Li *et al.* (2004). The values obtained in this study were in the same ranges as those reported by of Gupta and Singh (1981). These authors measured soil respiration in tropical grassland and found that the soil respiration rate was 49-448 mg CO_2 m^{-2} hr^{-1}. They also found that soil CO_2 flux correlated more strongly with the air than with soil temperature.

2) CO_2 flux at agricultural site

The results in agricultural soil showed the similar patterns of maximum temperature at the noontime as that observed in forest soil (Figure 3). More remarkable changes in air than in soil temperature were also observed here. The range of air temperature was 24.9 – 40.1 °C, while that for soil temperature at 5 and 10-cm depths were 26.2 – 34.8 °C and 26.5 – 33.7 °C (27 May 2004),



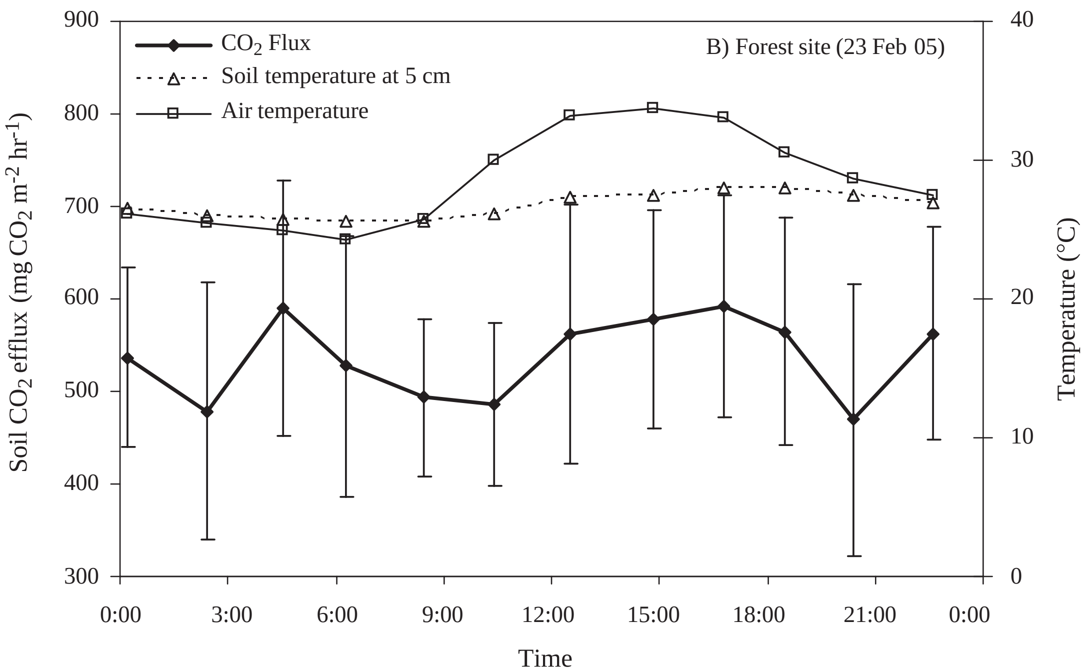


Figure 2 Diurnal variations of CO_2 flux at forest site, measured in A) May 2004 and B) February 2005. Error bars indicate S.D. with flux results of five chamber measurements.

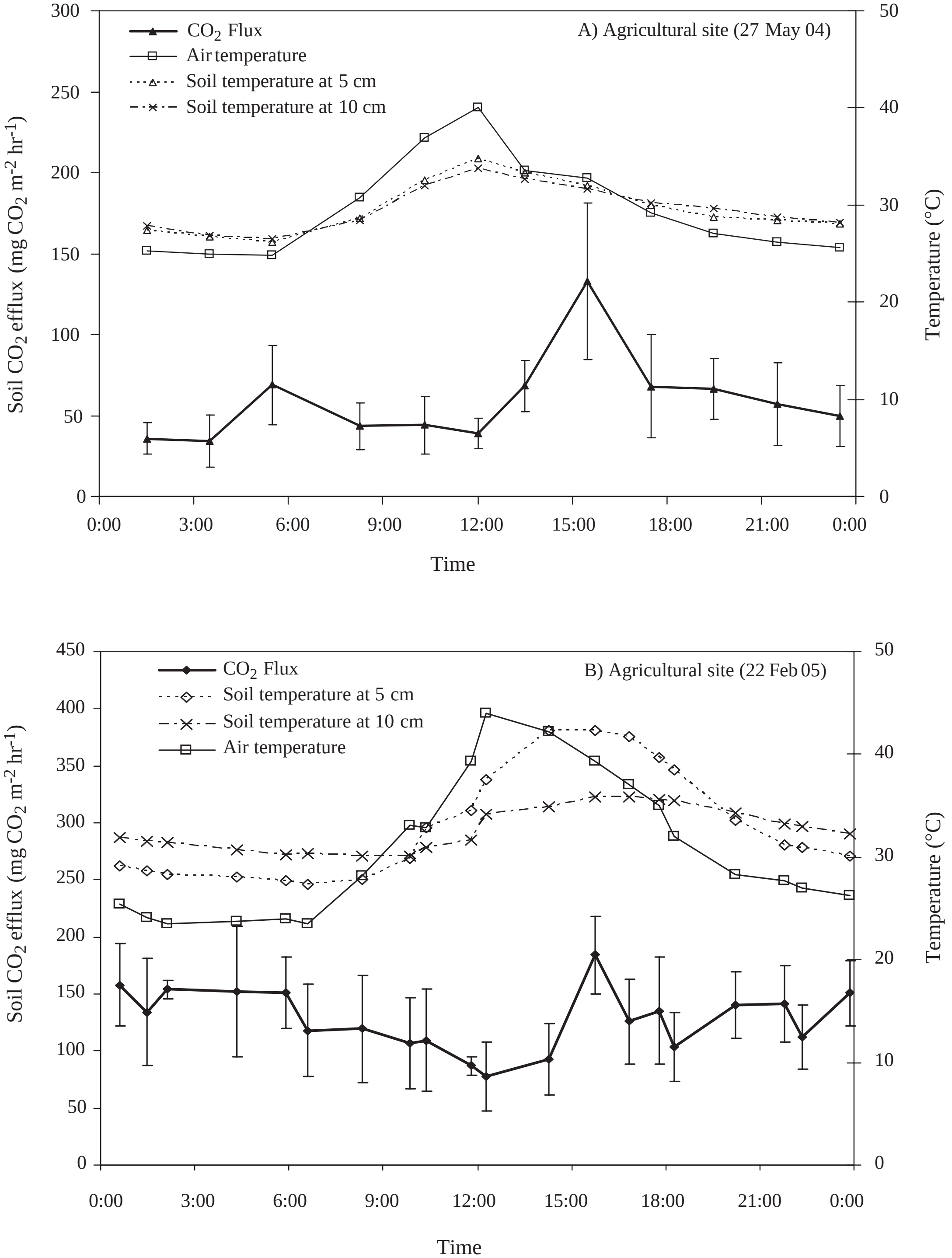


Figure 3 Diurnal variations of CO_2 flux at agricultural site, measured in A) May 2004 and B) February 2005. Error bars indicate S.D. with flux results of five chamber measurements.

respectively. On 23 February 2005, the ranges of temperatures were 23.5 – 44.0 °C, 27.4 – 42.3 °C and 30.1 – 35.9 °C for temperature of air, soil at 5-cm and soil at 10-cm depth, respectively. Higher temperature on February 2005 than that in May 2004 was noted.

The diurnal patterns of soil CO_2 fluxes were similar when compared between the measurements results of May 2004 and February 2005 (Figure 3). In May 2004, the soil CO_2 flux increased from 39 mg CO_2 m^{-2} hr^{-1} at 12:00 hr to 133 mg CO_2 m^{-2} hr^{-1} at around 15:00 hr and then dropped thereafter. In addition, the soil CO_2 flux increased slightly in the early morning, possibly due to moisture increase from dew (as observed by Gupta and Singh 1981). In February 2005, the soil CO_2 flux was less than 100 mg CO_2 m^{-2} hr^{-1} at noon and then increased to184 mg CO_2 m^{-2} hr^{-1} at 15:30 hr. After 18:00 hr, it varied from 100 to 150 mg CO_2 m^{-2} hr^{-1}. CO_2 flux of both days increased between 10:00 hr and 18:00 hr and the maximum rate of CO_2 flux occurred in the late afternoon. The total soil CO_2 fluxes were 1354 and 3082 mg CO_2 m^{-2} day^{-1} in May and February, respectively. This was divided into emission during daytime (797 and 1342 CO_2 m^{-2}) and nighttime (557 and 1740 CO_2 m^{-2}). Daytime CO_2 emission in February was lower than during nighttime. This could be due to relatively higher soil temperature during nighttime as shown in Figure 3.

When compared a daily CO_2 flux between forest and agricultural soils, it was found that soil CO_2 fluxes from forest site were higher than of agricultural site for both dates. Namely, soil CO_2 flux at forest site was 4.2 times in February and 1.2 times in May greater than those at agricultural site. From soil profile description (S. Jaiarree, personal communication), plant root at forest site were larger in size and amount than in agricultural site, especially in the upper soil layer. Several studies showed that root respiration is a key source of CO_2 from terrestrial ecosystem. The proportion of roots respiration to the total soil respiration ranges was 40-50 % in temperate forest (Epron *et al.*, 1999), and 17-60 % in tropical grasslands (Dugas *et al.*, 1999). Thus, high density of root in forest soil might contribute to the relatively higher CO_2 flux when compared to agricultural soil.

Relationship between *in situ* CO_2 flux and temperatures

1) Relationship observed at forest site

In forest soil, the Q_{10} value was calculated after fitting CO_2 flux and temperature data to the function described in Eq. 1. It was found that the Q_{10} values for a range of air temperature of about 24-34 °C were 2.38 in May 2004 and 1.20 in February 2005, with the correlation coefficients (r) of 0.77 and 0.86, respectively ($p \leq 0.05$, Fig. 4). On the other hand, strong correlation between soil temperature at 5 cm depth and soil CO_2 flux in February 2005 was also observed. The Q_{10} value estimated for this date was 2.04 over a range of soil temperature of 25.5-28.0 °C, with the correlation coefficients (r) of 0.85 ($p \leq 0.05$). It was not able to calculate the Q_{10} value for May 2004 due to temperature change was less than 2° C during the entire measurement period (Figure 4). These Q_{10} values obtained from tropical forest soils were generally lower than those found in temperate and arctic soils (Bekku *et al.*, 2003), indicating a relatively less sensitivity of tropical soil to temperature change than in the temperate soil.

These results indicated that soil CO_2 emission was strongly affected by both air and soil temperatures. Air temperature alone could explain approximately 59% in May 2004 and 74% in February 2005 of flux variability. The rest was possibly controlled by the other factors such as moisture (moisture content was 4.6%vol in May 2004 and 2.3%vol in February 2005) and aboveground organic matter inputs (Li *et al.*, 2004). Therefore, the effects of temperature vary temporally, as the Q_{10} value changed when time of measurement was changed from May 2004 to February 2005.

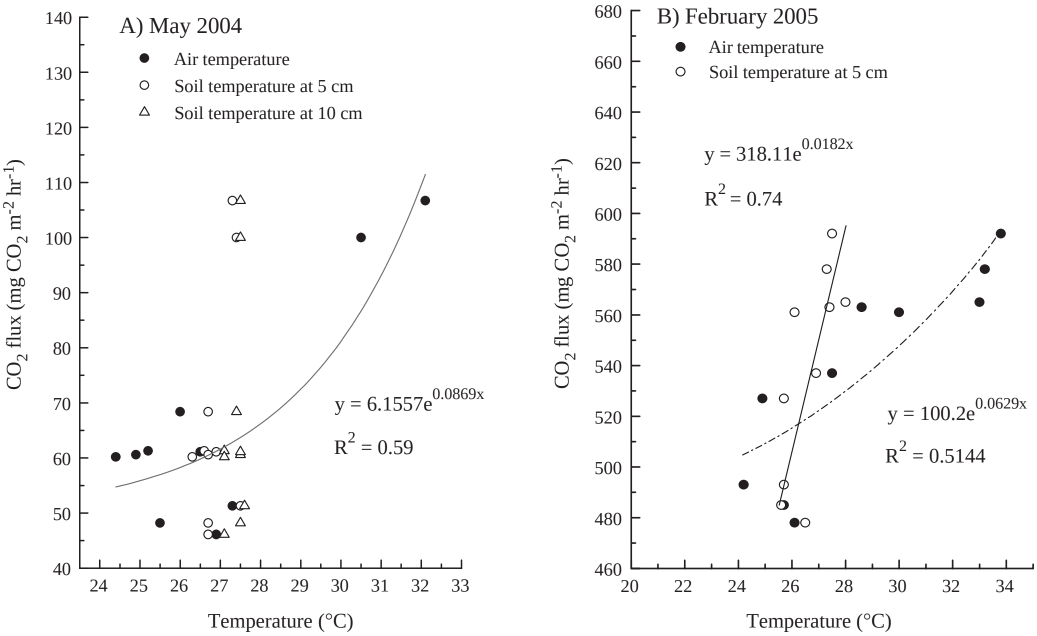


Figure 4 Relationship between flux and temperature at forest sites that was used to estimate Q_{10} value, measured in A) May 2004 and B) February 2005.

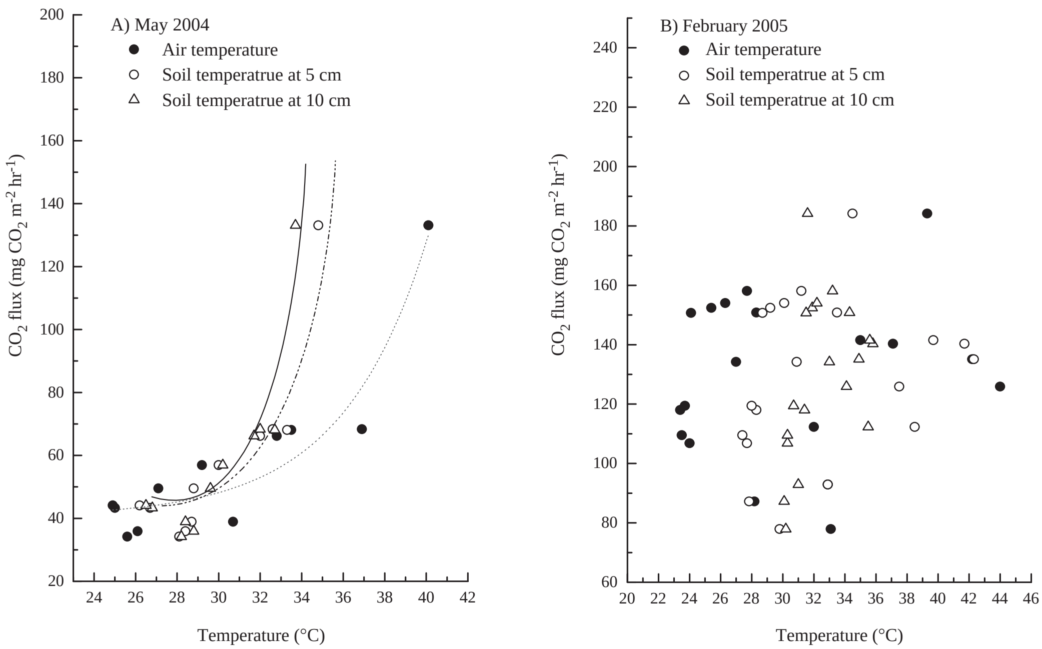


Figure 5 Relationship between flux and temperature at agricultural site used to estimate Q_{10} value, measured in A) May 2004 and B) February 2005. In February 2005, no significant relationship was found thus Q_{10} value was not estimated. Relationship between flux and temperature for May 2004 is expressed as flux = $7.0306e^{0.0673t}$, R^2=0.78; flux = $1.4076e^{0.1216t}$, R^2=0.76 and flux = $0.8252e^{0.1398t}$, R^2=0.73 for air temperature, soil temperature at 5 and 10 cm, respectively.

2) Relationship observed at agricultural site

At agricultural site, a strong correlation between temperature and CO_2 flux was also found (Figure 5). The best fit was obtained by using temperature at 4-hour delay after emission peak. The obtained Q_{10} values over the temperature range of about 24 – 40 °C were 1.96 (r = 0.88), 3.37 (r = 0.87) and 4.05 (r = 0.86) from a plot with air temperature, soil temperature at 5-cm and 10-cm depth, respectively ($p \leq 0.05$). Results from agricultural site showed that soil CO_2 flux was more sensitive to change in soil (both at 5 and 10 cm) than in air temperature. This differed from those found at the forest site as mentioned above. Unlike forest soil, agricultural soil was not covered by a dense canopy and by organic materials from litter fall. This canopy effect resulted in a smaller variation in daily soil temperatures than in air temperature at forest site as opposed to that observed in agricultural site (Figures 2 and 3). Therefore, a clearer and stronger correlation between soil temperatures and CO_2 flux was observed at agricultural site and *vice versa* at forest site. No clear relationship between CO_2 flux and temperature at agricultural site in February 2005 was observed (Figure 5B). This might be due to soil plowing a couple of days before measurements that modified CO_2 flux and blurred its relationship with temperature.

CO_2 production in the laboratory incubation

1) Effects of soil water content on CO_2 production

Soil samples taken from different sites and soil depths were incubated under various water contents. Soil respiration rate differed among these soil layers. The typical example for response of soil respiration to moisture is illustrated in Figure 6. In forest soil, regardless of moisture content the topsoil layer (0-20 cm) showed the highest respiration rate (Figure 6A). Except for soil from 20-30 cm, respiration rate increased with increase in moisture content from air-dry to 100% WHC. Similarly, in agricultural soil the topsoil generally showed higher respiration than other layers (Figure 6B). Except for the top layer of forest soil, moisture content range of 50-75%WHC seemed to be suitable for soil respiration. Air-dry or water saturated soil appeared to inhibit soil respiration in most cases. Soil moisture can limit soil respiration by limiting microbial contact with available substrate or water stress. Saturated soil condition also reduces oxygen diffusion and subsequently soil respiration (Bowden *et al*., 1997 and Fierer *et al.,* 2003). From these results, soil respiration increased about 8-10 times in the topsoil of both sites when moisture increased from air-dry condition to 50%WHC (Figure 6). The results agreed well with those reported by Winkler *et al*. (1996), in which soil from temperate forest was incubated for several months at 4°C to 38°C. They found that soil respiration varied significantly with time of incubation and the A-horizon (0-28 cm) had highest respiration rates, followed by the B- (84-184 cm) and E-horizon (28-61 cm) soils for each temperature.

In summary, it could be said that there was an optimal moisture range for soil respiration in tropical upland soils. Furthermore, majority of soil respiration occurred in the topsoil layer of within 20 cm from the surface. In tropical ecosystem, changes in soil moisture usually associates with seasonal timescale, thus, moisture may play the major role in regulating temporal flux variations. Further study is needed before such effects and responses can be understood.

2) Effects of temperature

In the tropics, soil experiences changes in temperature both in a short time scale such as daytime and nighttime variations, and in a longer timescale such as temperature change between summer and winter. In addition, land use significantly affects on temperature profile of sites. Figures 2 and 3 illustrate that under forest cover temperature difference between daytime and nighttime is less than 10°C while under agriculture the difference can be as high as 20°C. Thus, diurnal temperature change is comparable or even higher when compared to seasonal temperature change. Temperature, therefore, was the main factor regulating diurnal variation in soil respiration as shown in this study. Except when there was heavy precipitation, diurnal moisture change could be considered minimum.

Relationship between temperature and

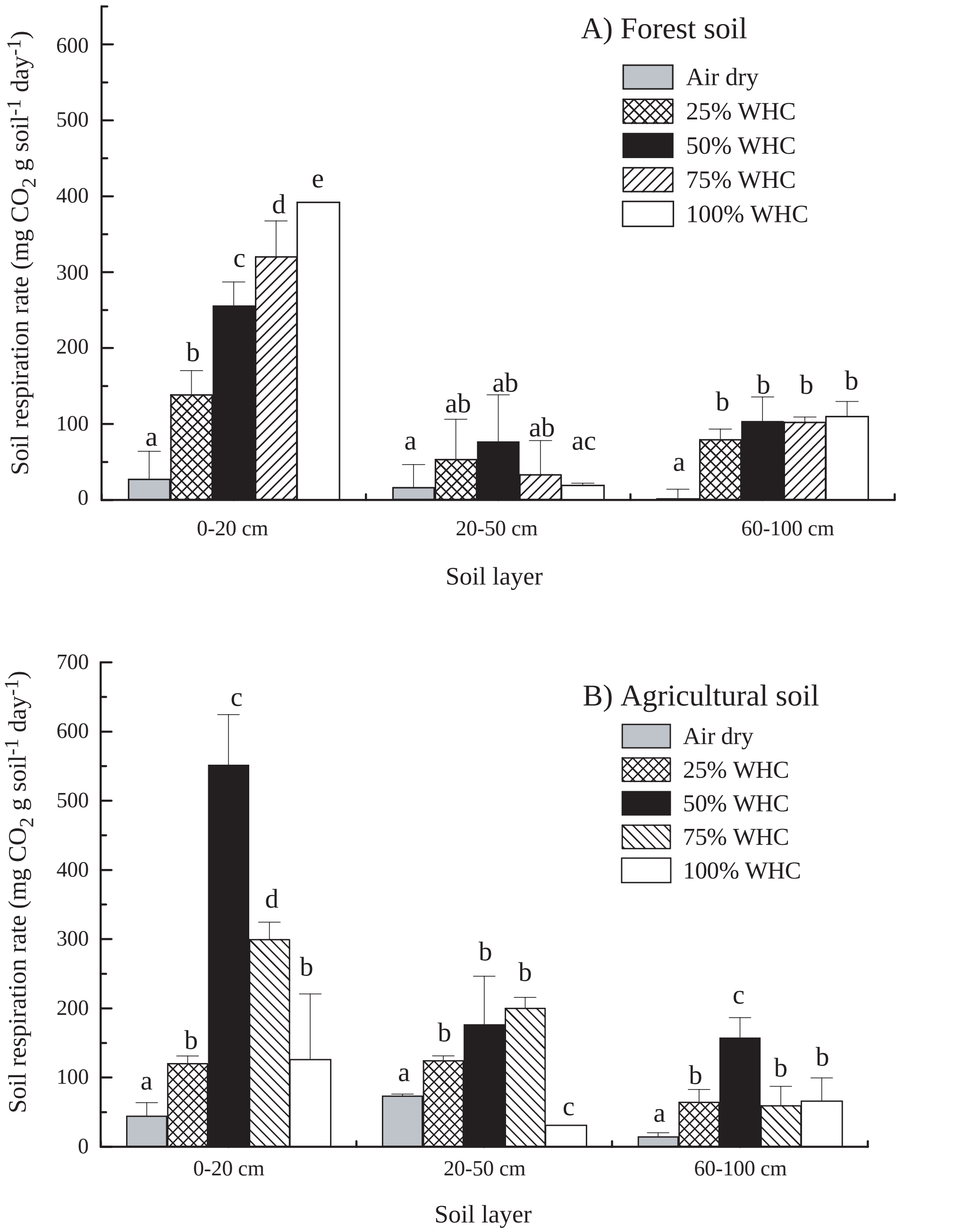


Figure 6 Changes in soil respiration rate corresponded to alteration of soil moisture contents. The incubation temperature was maintained at 30 °C. The error bars represent standard deviations (n=3). Means designated with the same letter within each soil layer are not significant different from each other ($p<0.05$).

soil respiration was studied in detail in the laboratory incubation. Increase in temperature in the range of 20-45°C generally led to increased soil respiration (data not shown). Response of soil respiration to increase in temperature within the range of 20-37°C and under different soil moisture contents was described in term of Q_{10} (Table 2). The Q_{10} values varied according to soil layers and soil moisture content. Based on these Q_{10} values, it seemed that soils under air-dry and water-saturated conditions were more sensitive to temperature changes than under other moisture levels. Conant *et al*. (2004) incubated soil samples under four soil moisture contents. They found that the Q_{10} values decreased with decrease in soil moisture (ranged from 3.15 to 2.06) and the Q_{10} values were usually greater for the wet than for the dry soils. Based on the average throughout the profile, this study revealed that agricultural soil was more sensitive to temperature changes than forest soil (Table 2). The averaged Q_{10} range for each soil depth layer of agricultural soil was 2.1-2.8, which was higher than the range that found in forest soil (1.2-2.4, Table 2) for all soil moisture content. Statistical analysis yielded no significant difference ($p \leq 0.05$) in these Q_{10} values among different soil moisture contents, nor among soil layers. The exception was soil from 60-100 cm of agricultural site that showed significantly higher averaged Q_{10} values than other layers at $p \leq 0.10$. The averaged Q_{10} value from agricultural site (2.52±1.10, n = 10) was significantly higher than that of the forest site (1.43±0.34, n = 10). Since in this case, agricultural soil contained more carbon than forest soil, the potential to lose soil carbon under a warmer future climate was higher from agricultural soil than from forest soil.

CONCLUSION

Soil CO_2 flux was high during late afternoon, 2-4 hr delaying after the peak in air temperature. The Q_{10} values estimated for diurnal changes in air temperature was 2.38 and 1.2 on

Table 2 Q_{10} values for soils incubated under different soil moisture contents (0-100% WHC) and temperatures (20-45°C).

A) Forest soil.

Soil moisture (%WHC)	Q_{10} value for forest soil			Average±S.D (n = 3)
	0-20	20-30	30-70	
0	3.31	1.27	1.56	2.05±1.10
25	1.56	1.46	1.54	1.52±0.05
50	1.10	1.44	1.14	1.23±0.19
75	1.27	1.10	0.93	1.19±0.17
100	3.35	2.01	1.87	2.41±0.82

B) Agricultural soil.

Soil moisture (%WHC)	Q_{10} value for agricultural soil			Average±S.D. (n = 3)
	0-20 cm	20-50 cm	60-100 cm	
0	3.79	1.63	1.6	2.34±1.26
25	1.8	1.46	2.99	2.08±0.80
50	2.61	1.99	4.37	2.99±1.23
75	1.42	1.29	3.51	2.07±1.25
100	1.98	2.58	3.8	2.79±0.93

May and February in forest site, respectively. In agricultural site, the Q_{10} was 1.96 and 3.37 for air and soil at 5-cm depth, respectively. Significant difference was between daytime and nighttime CO_2 emission, but daytime emission was relatively higher than nighttime in general. On the other hand, ambient CO_2 was clearly higher during the nighttime than during the daytime. Temperature was the important factor controlling the diurnal variability of soil CO_2 flux in the tropics. Over a longer time scale, however, moisture and temperature may be both the controlling factors for CO_2 release from soil. Soil moisture could significantly induce change in soil respiration rate. Under a constant temperature, respiration rates were relatively higher at moisture content between 50 and 75% WHC. Both lower and higher moisture contents than this reduced soil respiration rate. When temperature was varied, soils under both dry and wet (water-saturated) were mores sensitive to temperature changes than under other moisture ranges. The obtained Q_{10} values indicated relatively higher sensitivity of soil under agriculture than that under natural forest.

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LITTERATURE CITED

Bekku, Y. S., T. Nakatsubo, A. Kume, M. Adachi and H. Koizumi. 2003. Effect of warming on the temperature dependence of soil respiration rate in arctic, temperate and tropical soils. **Appl. Soil Ecol.** 22:205-210.

Bowden, R.D., K.M. Newkirk and G.M. Rullo. 1997. Carbon dioxide and methane fluxes by a forest soil under laboratory-controlled moisture and temperature conditions. **Soil Biol. Biochem.** 30: 1591-1597.

Conant, R.T., P. Dall-Betta, C.C. Klopatek and J.M. Klopatek. 2004. Controls on soil respiration in semiarid soils. **Soil Biol. Biochem.** 35: 945-951.

Dugas, W.A., M.L. Heuer and H.S. Mayeux. 1999. Carbon dioxide fluxes over bermudagrass, native prairies, and shorghum. **Agri. For. Meteorol.** 93**:** 121-139.

Epron, D., Y. Nouvellon, O. Roupsard, W. Mouvondy, A. Mabiala, L. Saint-André, R. Joffre, C. Jourdan, J.M. Bonnefound, P. Berbigier and O. Hamel. 2004. Spatial and temporal variation of soil respiration in a Eucalyptus plantation in Congo. **For. Ecol. Manag.** 202: 149-160.

Eriksen, J. and L.S. Jensen. 2001. Soil respiration, nitrogen mineralization and uptake in barley following cultivation of grazed grasslands. **Biol. Fert. Soils** 33: 169-145.

Fierer, N., J.P. Schimel and P.A. Holden. 2003. Controls on microbial CO_2 production: a comparison of surface and subsurface soil horizons. **Global Change Biol.** 9: 1322-1332.

Frang, C. and J.B. Moncrieff. 2001. The dependence of soil CO_2 flux on temperature. **Soil Biol. Biochem.** 33: 155-165.

Gupta, S.R. and J.H. Singh. 1981. Soil respiration in a tropical grassland. **Soil Biol. Biochem.** 13: 261-268.

Houghton, R.A., J.L. Hackler and K.T. Lawrence. 1999. The U.S. carbon budget: contributions from land-use change. **Science** 285: 574–578.

Nakadai, T., M. Yokozawa, H. Ikeda and H. Koizumi. 2002, Diurnal changes of carbon dioxide flux from bare soil in agricultural filed in Japan, **Appl. Soil Ecol.** 19: 161-171.

IPCC. 2001. Climate Change 2001: A Scientific Basis, Intergovernmental Panel on Climate Change, p. 396 *In* J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, C.A. Johnson and K. Maskell (eds.). Cambridge University Press. Cambridge, U.K.

Keeling, C.D., T.P. Whorf and the Carbon Dioxide Research Group. 2004. Atmospheric CO_2 concentrations (ppmv) derived from in situ, Scripps Institution of Oceanography (SIO), University of California La Jolla, California USA 92093-0444. http://cdiac.esd.ornl.gov/ftp/trends/co2/maunaloa.co2

Knief, C., S. Vanitchung, N.V. Harvey, R. Conrad, P.F. Dunfield and A. Chidthaisong. 2005. Diversity of methanotrophic bacteria in tropical upland soils under different land uses. **Appl. Envi. Microbiol**. accepted April 2005.

Lal R. 2004. Soil carbon sequestration to mitigate climate change. **Geoderma** 123: 1-22.

Li, Y., M. Xu, O.J. Sun and W. Cui. 2004. Effects of root and litter exclusion on soil CO_2 efflux and microbial biomass in wet tropical forest. **Soil Biol. Biochem.** 36: 2111-2114.

Lloyd J. and J.A. Taylor. 1994. On the temperature dependence of soil respiration. *Functional Ecology*, **8**, pp. 315-323. *In* M. Reichstein, F. Bednorz, G. Broll and T. K?tterer. 2000. Temperature dependence of carbon mineralization: conclusions from a long-term incubation of subalpine soil samples. **Soil Biol. Biochem.** 32: 947-958.

Sarmiento J.L. and N. Gruber. 2002. Sink for anthropogenic carbon. **Physics Today**. 55: 30-36.

Scala Jr, N.La., J. Marques Jr, G..T. Pereira and J.E. Corá. 2000. Caebon dioxide emission related to chemical properties of a tropical bare soil. **Soil Biol. Biochem.** 32: 1469-1473.

Scott-Denton, L. E., K. L. Sparks and R. K. Monson. 2003. Spatial and temporal controls of soil respiration rate in a high-elevation, subalpine forest. **Soil Biol. Biochem**. 35: 525-534.

Schlesinger, W.H. 1997. Biogeochemistry: an Analysis of Global Change, 2nd ed, **Academic Press, San Diego**, CA, USA. 588 p.

van't Hoff, J. 1998. Lectures on Theroretical and Physical Chemistry. Part 1, Chemical Dynamics, pp. 224-229. *In* Edward Arnold, (ed.). Academic Press, London, 224-229.

Winkler, J.P., R.S. Cherry and W. Schlesinger. 1996. The Q_{10} relationship of microbial respiration in a temperate forest soil. **Soil Biol. Biochem**. 28: 1067-1072.