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SHORT COMMUNICATION

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Soil respiration and soil CO_2 concentration in a tropical forest, Thailand

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Abstract Soil respiration and soil carbon dioxide (CO_2) concentration were investigated in a tropical monsoon forest in northern Thailand, from 1998 to 2000. Soil respiration was relatively high during the rainy season and low during the dry season, although interannual fluctuations were large. Soil moisture was widely different between the dry and wet seasons, while soil temperature changed little throughout the year. As a result, the rate of soil respiration is determined predominantly by soil moisture, not by soil temperature. The roughly estimated annual soil respiration rate was $2560\,g\,C\,m^{-2}\,year^{-1}$. The soil CO_2 concentration also increased in the rainy season and decreased in the dry season, and showed clearer seasonality than soil respiration did.

Key words Soil respiration · Soil CO_2 concentration · Tropical forest · Soil temperature · Soil moisture

Introduction

The concentration of carbon dioxide (CO_2) in the atmosphere is rising due to human activity, and scientists have predicted that this increase will cause critical changes in global climate. Forests are considered as one of the carbon (C) sinks, and the CO_2 budgets of forest ecosystems have been investigated (Lafleur et al. 1997; Granier et al. 2000; Schmid et al. 2000). Soil respiration is one of the largest elements of carbon cycling in forests, so the accurate measurement of soil respiration is essential for understanding the carbon cycle in forest ecosystems. There are many factors that influence soil respiration. However, as numerous studies have shown (Schlentner and Van Cleve 1984; Fang et al. 1998; Goulden et al. 1998; Dong et al. 1998; Ohashi et al. 1999; Londo et al. 1999; Rayment and Jarvis 2000; Morén and Lindroth 2000), temperature and soil moisture are two major factors. Soil respiration is affected by temperature and soil moisture more strongly than by any other factors. In general, soil respiration increases with temperature and varies parabolically with soil moisture (Howard and Howard 1993).

In boreal forests, soil temperature is the main determinant of soil respiration and soil water has little effect (Schlentner and Van Cleve 1984; Goulden et al. 1998; Rayment and Jarvis 2000; Morén and Lindroth 2000). Soil respiration stops during the winter with freezing. In temperate forests, both soil temperature and soil water control soil respiration. Soil respiration changes seasonally with soil temperature and often decreases with decreasing soil water in the summer (Dong et al. 1998; Fang et al. 1998; Londo et al. 1999; Ohashi et al. 1999).

As mentioned above, there are many studies on soil respiration in boreal and temperate forests. However, despite the large C efflux from soil in tropical forests (Malhi et al. 1999), there are few reports on soil respiration in tropical forests compared with other climate regions (Medina et al. 1980; Keller et al. 1986; McGroddy and Silver 2000), especially for Southeast Asia. The difficulty of access to these regions that have tropical forests is perhaps one of the reasons for the shortage of studies of soil respiration in tropical forests. Most tropical forests are located in developing countries at low latitudes. In these places, traffic networks are still inadequate, as are the observation systems available.

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Also, there are so many types of tropical forests; various structures, diversities of species and climate (Whitmore 1990), compared with boreal and temperate forests. Thus, even more studies of soil respiration in tropical forests are needed. Additionally, the soil CO_2 concentration is of interest. The soil CO_2 concentration reflects biological activity in the soil, and a high soil CO_2 concentration affects plant growth (Burton et al. 1997). Moreover, the soil CO_2 concentration is essential for identifying the depth at which CO_2 is produced in the soil (Campbell and Frascarelli 1981; Davidson and Trumbore 1995). Carbon dioxide emitted from the soil surface is produced in the soil and transported to the soil surface. Compared with soil respiration (soil surface CO_2 flux), observations of CO_2 concentrations in soil are rather rare. Observations of both soil respiration and soil CO_2 concentration are important for understanding the mechanism of soil respiration.

In this study, we investigated seasonal changes in soil respiration and soil CO_2 concentration in an undisturbed, hillside, evergreen forest, under a tropical monsoon climate in Southeast Asia.

Materials and methods

Study area

The study area, the Kog-Ma Experimental Watershed of Kasetsart University, is situated near the city of Chiang-Mai in northern Thailand, located at 18°48′N, 98°54′E, at an altitude of about 1300 m (Fig. 1). Thai researchers have conducted many ecological and hydrological studies in this experimental watershed since 1965. Thai and Japanese hydrologists began cooperative research in 1997, to estimate energy and water budgets in hillside evergreen forests as a part of GAME (GEWEX-related Asia Monsoon Experiment). Soil respiration and soil CO_2 concentration have been measured, together with soil temperature and soil moisture.

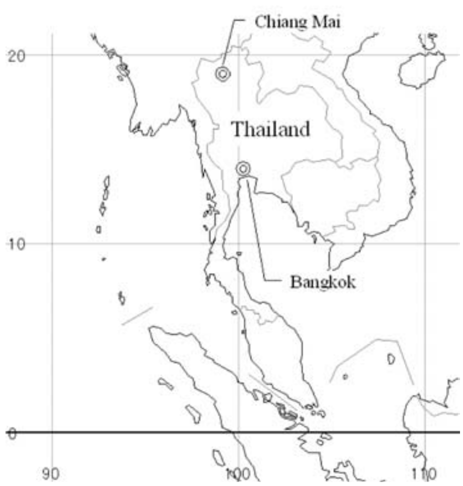

Fig. 1. Kog-Ma experimental watershed of Kasetsart University, situated near the city of Chiang-Mai in northern Thailand

The Kog-Ma Experimental Watershed is covered by dense evergreen forest, mainly dominated by *Castanopsis*, *Lithocarpus*, and *Quercus* spp. The mean annual precipitation between 1966 and 1980 was 2084.1 mm (Chunkao et al. 1981). The rainy season usually starts in April and lasts until November, whereas the dry season occurs from December to March. January and February usually experience no rainfall. Six months of the dry season receive <100 mm of precipitation (November to April between 1966 and 1980; Chunkao et al. 1981). The mean annual temperature at the site is 20°C. This kind of tropical forest, the so-called hill evergreen forest, is characterized by comparatively long dry season and low temperature (Whitmore 1990). The average annual litter fall between 1968 and 1972 was 6.88 $t\,ha^{-1}$ (dry weight; Boonyawat and Ngampongsai 1974; Thaiutsa et al. 1979). Monthly litter fall is generally largest in February and smallest in August (Boonyawat and Ngampongsai 1974).

Methods

We visited the Kog-Ma Experimental Watershed, stayed for about 2 weeks, and carried out various microclimatic observations. Soil respiration was measured on a day without rain during the stay. Soil respiration was measured at three sampling points (A, B, and C) at 3-month intervals beginning in July 1998. The three sampling points were distributed with a distance of about 30 m between them. Point A was located at the base of the watershed, and points B and C were halfway up the watershed.

The closed-chamber method was used with a portable chamber (Hanson et al. 1993; Sellers et al. 1997; Striegl and Wickland 1998). The portable chamber was about 0.00155 m^3 (0.135 m in diameter, 0.105 m high). When measuring soil respiration, we pressed the chamber on the soil surface firmly, but not so firmly that we disturbed the soil surface structure. The chamber edge was not pushed into the soil surface but was on the soil surface (Hanson et al. 1993; Sellers et al. 1997; Striegl and Wickland 1998). The CO_2 concentration in the chamber was measured with a CO_2 analyzer (Model LI6252 or Model LI6262, LI-COR), and was recorded at 10-s intervals for several minutes. The flow rate of the circulation pump was approximately 0.017 l/s.

At each point (A, B, and C), one plot (0.3 × 0.3 m) was set up. Measurements were taken two to three times in each plot. The position of the chamber was changed for every measurement in each plot.

All instruments were transported from Japan on each occasion, except for the chamber. The calibration of the CO_2 analyzer was conducted in Japan before leaving Japan.

The soil CO_2 concentration was measured at sampling point B, at depths of 0.1, 0.2, 0.4, and 0.6 m at 1-week intervals, beginning in February 1998. Soil air collection probes were installed at each depth. We extracted 100 ml of soil air directly from the probes using gas detector tubes with a gas-sampling pump (GV-100S; Gastec, Japan). The length of the color-changed zone in the gas detector tube indicated the CO_2 concentration in soil air after a few minutes. This method is widely used in Japan (Hamada and Tanaka 2001).

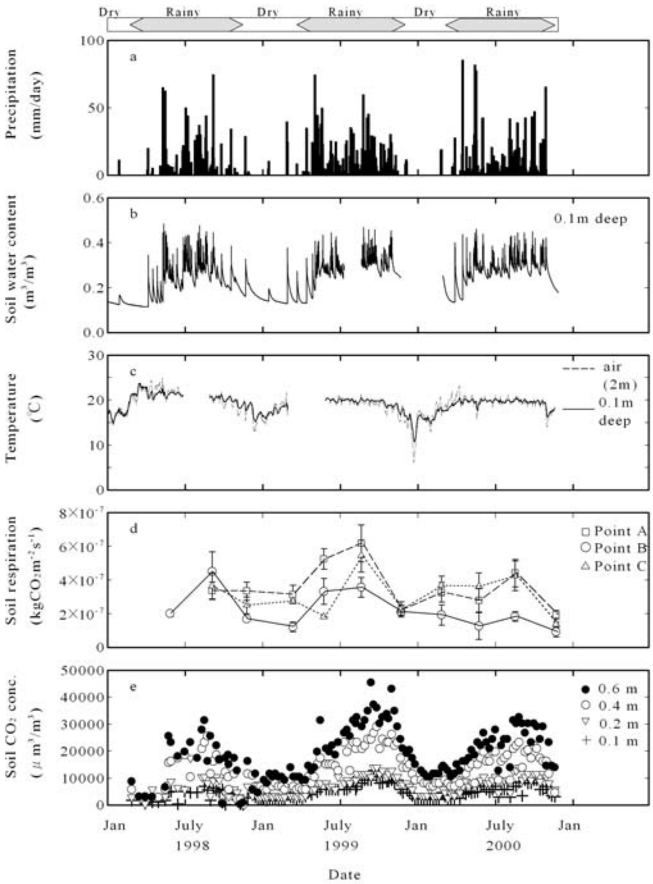

Fig. 2. Seasonal variations in precipitation (**a**), soil water content (**b**), soil temperature (**c**), soil respiration rate (**d**, *bars* indicate standard deviation) and soil CO_2 concentration (**e**)

The soil temperature was measured at sampling point B, at depths of 0.02, 0.1, and 0.3 m using a thermistor (CT-UU-A10-2A; Grant) with a logger (SQ1259; Grant). The soil water content was measured at sampling point B, at depths of 0.1, 0.2, 0.3, 0.4, and 0.5 m using TDR sensors (CS615; Campbell Scientific) with a logger (CR10X; Campbell Scientific).

Results and discussion

Seasonal changes in precipitation, soil water content, air and soil temperature are shown in Fig. 2a, b, and c, respectively. The average annual precipitation and air temperature from 1998 to 2000 were 1657 mm and about 19°C, respectively. The rainy season started in April and lasted until November. During the dry season, the area received very little rain. Corresponding to the patterns of precipitation, the soil moisture content was high from April to November and low from January to March. Soil temperature was high in the rainy season and low in the dry season. During the 8-month rainy season, soil temperature changed little. The air temperature and soil temperature in the 1998 rainy season were slightly higher than in 1999 and 2000. The precipitation in the 1998 rainy season was less than in a normal year.

Table 1. Average soil respiration with standard deviation in parentheses

Period for average	Soil respiration ($\times 10^{-7}$ kg CO_2 $m^{-2}s^{-1}$)
Rainy season 1998 (May, September, November)	2.96 (1.11)
Dry season 1999 (March)	2.40 (0.91)
Rainy season 1999 (May, September, November)	3.45 (1.66)
Dry season 2000 (March)	2.88 (0.94)
Rainy season 2000 (May, September, November)	2.45 (1.36)

There were no significant differences between proximate dry and rainy seasons ($P < 0.05$).

Soil respiration

Soil respiration and the soil CO_2 concentration are shown in Fig. 2d, e. Soil respiration rates ranged from 0.94×10^{-7} to 6.2×10^{-7} kg $CO_2 m^{-2} s^{-1}$. Soil respiration was comparatively high from August to September, and was comparatively low between December and February. The rates of soil respiration were relatively high in 1999 and low in 1998 and 2000. The rates of soil respiration were relatively high in the rainy season and low in the dry season; however, the fluctuations among the years and among the sampling points were large, and there was no clear difference in soil respiration between the dry and rainy seasons (Table 1).

Figure 3 shows the relationship between soil respiration and soil water content. Soil respiration increased with increasing soil moisture. This agrees with other studies (Bowden et al. 1998; Zak et al. 1999). Soil water content measured in terms of soil respiration measurements ranged between 0.15 and 0.35. In some studies, decreases in soil respiration were observed when the soil was rather wet. In this study, the decrease was not observed. The saturated soil water content in this forest was reported to be about 0.5–0.6 (Udomchock et al. 1983). The maximum soil water content that was observed in our soil respiration measurements was about 0.35. We could not obtain data for soil respiration when the soil was wetter than this. It is unknown whether soil respiration in this site decreases or not when soil is rather wet. This is one of the subjects for future study.

Figure 4 shows the relationship between soil respiration and soil temperature. Soil temperature was relatively constant. The narrow temperature range is due to both the limited number of observations, and the small variation in temperature during the rainy season. No clear relationship between soil respiration and soil temperature was found. Except for the hot rainy season in 1998 and a very cold day in the winter of 1999, the soil temperature at 0.1 m deep ranged from 15° to 20°C, and the temperature range was much smaller during the rainy season. In this region, the seasonal variation in soil moisture is large, while that of soil temperature is small. Therefore, in this region, soil moisture

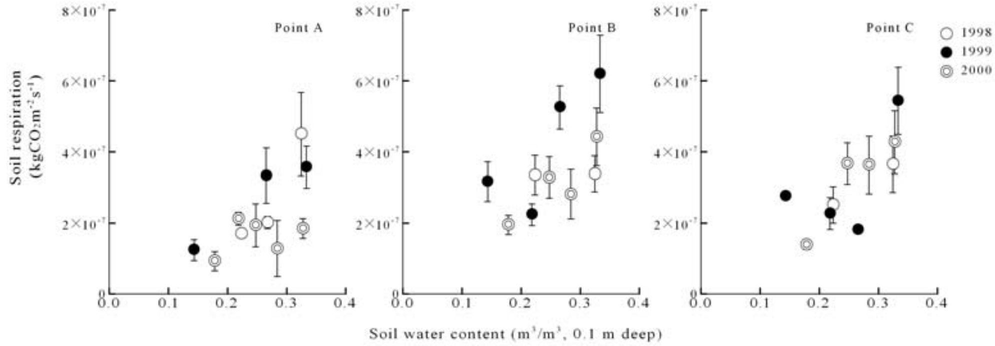

Fig. 3. The relationships between soil water content and soil respiration rate (*bars* indicate standard deviation)

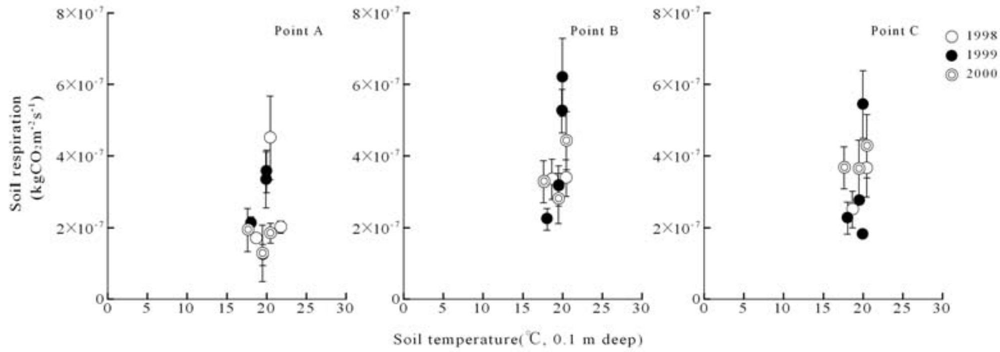

Fig. 4. The relationships between soil temperature and soil respiration rate (*bars* indicate standard deviation)

plays a greater role in governing soil respiration than soil temperature does. Generally, soil respiration increases exponentially with temperature. In boreal and temperate forests, there is a wide range of seasonal temperatures and large seasonality (Malhi et al. 1999). Therefore, soil respiration also shows large seasonality in boreal and temperate forests. By contrast, the relationship between soil respiration and soil moisture is parabolic (Bowden et al. 1998; Zak et al. 1999) or linear (Leirós et al. 1999). Hence, it is reasonable to expect the seasonality of soil respiration, which is limited by soil moisture, to be small in tropical regions.

To compare annual soil respiration rate with other studies, the annual soil respiration rate was roughly estimated using the average value of soil respiration at sampling points A, B, and C:

$$SR = (\Sigma^n Y_i \times 10^3 \times 12/44 \times 3600 \times 24 \times 365)/n$$

where SR is the average soil respiration ($g\,C\,m^{-2}\,year^{-1}$), *Yi* is the measured soil respiration ($kg\,CO_2\,m^{-2}\,s^{-1}$), and n is the number of measurements; although the estimated value using this simple equation and the limited number of data points perhaps implies some uncertainty. The estimated value was $2560\,g\,C\,m^{-2}\,year^{-1}$; Raich and Schlesinger (1992) reviewed the measured rate of soil respiration in terrestrial and wetland ecosystems, and the value reported here is as high as the highest they reported. They proposed a simple model describing the relationship between annual soil respiration rate (SR, $g\,C\,m^{-2}\,year^{-1}$) and two climate variables, mean annual temperature (T, °C) and mean annual precipitation (P, mm): $SR = 9.88T + 0.0344P + 0.0112TP + 268$. Using this relationship, the estimated annual soil respiration of the Kog-Ma watershed would be $870\,g\,C\,m^{-2}\,year^{-1}$. The value estimated in our study is about three times as large. However, a similar value was reported in a study of the Amazon (Davidson et al. 2000), which also pointed out that soil respiration might have been underestimated in old reports based on soda-lime techniques.

Soil CO_2 concentration

The CO_2 concentration in soil increased with increasing depth and exhibited a distinct seasonal trend. The CO_2 concentration in soil ranged from 10000 to $40000\,\mu m^3/m^3$ at a depth of 0.6 m, and ranged from 2000 to $12000\,\mu m^3/m^3$ at a depth of 0.1 m. The highest soil CO_2 concentrations were recorded from August to September, and the lowest values were recorded from December to February. The soil CO_2 concentrations were similar to values reported in other studies (Kursar 1989; Davidson and Trumbore 1995).

CO_2 concentration profile in soil results from CO_2 production in soil and its transport. The depth at which CO_2 is mostly produced at is very important information in order to understand the mechanism of soil respiration and predict the impact of global warming on soil respiration. Analyzing CO_2 profiles in soil will show vertical distributions of CO_2 production rate (Davidson and Trumbore 1995). This is also the subject of our future study.

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