Temperature sensitivity of soil CO_2 production in a tropical hill evergreen forest in northern Thailand

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Abstract

Tropical forests, like boreal forests, are considered key to climate change. The temperature sensitivity of soil CO_2 production in tropical forests is unclear, especially in eastern Asia, because of a lack of data. The year-round variation in temperature is very small in tropical forests, so that it is difficult to evaluate the temperature sensitivity of soil CO_2 production using field observations, unlike temperate and boreal forests. This paper examined the temperature sensitivity of soil CO_2 production in the tropical hill evergreen forest that covers northern Thailand, Laos, and Myanmar; this forest has small temperature seasonality. Using an undisturbed soil sample (0.2 m diameter, 0.4 m long), CO_2 production rates were measured at various steady temperatures. The CO_2 production (SR, $\mathrm{mgCO_2m^{-2}s^{-1}}$) increased exponentially with temperature (T, ℃); the fitted curve was $SR=0.023\, e^{0.077T}$, with $Q_{10}=2.2$. Although still limited, our result supports the possibility that even a small increase in the temperature of this region might accelerate carbon release because of the exponential sensitivity and high average temperature.

***Keywords**: Q_{10}, tropical forest, soil respiration, northern Thailand*

Introduction

Carbon in forest ecosystems is of great concern because forest soil contains an enormous amount of carbon. CO_2 emissions from soil, which are the major form of soil carbon release, are especially important and this process is called soil respiration.

Boreal forest is considered a key ecosystem with respect to climate change (Sellers et al. 1997). Boreal forest has a relatively low temperature, which constrains organic matter decomposition. As a result, boreal forest soil contains more organic matter than that of other ecosystems. This organic matter would release a great deal of carbon in response to global warming. Moreover, the degree of temperature rise is expected to differ among regions, and would be greater in boreal forest (high latitudes) than at low latitudes (Sellers et al. 1997). Many researchers have investigated the carbon cycle of boreal forest and its response to climate change (Baldocchi and Vogel 1997; Lafleur et al. 1997; McCaughey et al. 1997; Morén and Lindroth 2000; Rayment and Jarvis 2000; Pypker and Fredeen 2002; Hirsch et al. 2002). However, tropical forest is also considered a very important ecosystem in relation to climate change. Townsend and Vitousek (1992) constructed a simple model and explored carbon balance of various ecosystems. They then pointed out that tropical forests could dominate the short-term carbon cycle feedback in response to increased global temperatures because they are very sensitive to small changes in temperature due to the exponential response of soil respiration. Moreover, Trumbore et al (1996) investigated the relationships between carbon turnover times and temperature, and found that carbon turnover times decreased with increasing temperature. Their results suggest that tropical forest would respond more quickly, and to a greater degree, to warming, even in response to relatively small changes in temperature, because of high temperature. Nevertheless, there are fewer reports on soil respiration in tropical forests than for other climate regions, and especially few for Southeast Asia.

The temperature sensitivity of soil respiration in each ecosystem is an essential factor for predicting the interaction between soil carbon and global warming, and is included in many models. There are two methods of evaluating the temperature sensitivity of soil respiration. One measures soil respiration in the field, in an area with clear seasonality of temperature. Measuring soil respiration at various temperatures allows us to estimate the relationship between soil respiration and temperature, although these values are subject to several confounding effects, like soil water restrain, plant growth, and litter fall seasonality. The other measures soil respiration with small soil samples in the laboratory, using a system that can control temperature. The laboratory experiments have strong advantages: not only temperature but also other factors can be easily controlled. However, this approach has also disadvantages. Small samples may be strongly affected by sampling disturbance, and then this approach may give the information in a highly disturbed and unusual system. For example, sampling small core sometimes disturbs soil structure and breaks macropores (e.g. Ohte and Suzuki 1990). Also, influence of incubation time on the soil respiration rate, or decrease of respiration with incubation time, tends to be larger in a small sample (e.g. Fang and Moncrieff 2001).

One approach, which should fill the gap between field studies and small core experiments, has been recently reported: the large intact core experiment (Thomson et al. 1997; Fang and Moncrieff 2001; Hashimoto and Suzuki 2002). This approach seems to be an intermediate approach between field observations and small core experiments: This approach can control environmental factors more easily than in a field and has less effects of disturbance. One major weakness may be difficulty to handle due to the large size. However, this approach fills a gap between field study and small core experiments and should give important information.

A vast evergreen forest covers Thailand, Myanmar, and Laos. This area has a relatively constant seasonal temperature, and experiences distinct dry and rainy seasons. The dry season is longer than in other tropical forests.

In the evergreen forests of eastern Asia, the relationship between soil respiration and soil water, which is a major control of soil respiration, can be evaluated, because the forest has explicit seasonality of soil water. However, the forest experiences very little temperature seasonality, making it impossible to evaluate the relationship between soil respiration and soil temperature. Hence, it is necessary to measure the relationship between soil respiration and soil temperature in the laboratory.

As mentioned above, little is known about soil respiration in a hill evergreen forest in Thailand. One of the reasons is the difficulty to approach such sites. Moreover, soil is delicate material, and needs to preserve the freshness. In this study, we sent the equipments for the experiments and conducted the experiments in Chiang-Mai city, Thailand. We collected a large soil sample from a hill evergreen forest, and measured soil CO_2 production from the sample under various temperature treatments. The objective of this study was to observe the temperature sensitivity of the soil CO_2 production rate in a hill evergreen forest.

Materials and Methods

Site description

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 asl (Table 1). The Kog-Ma Experimental Watershed is covered by dense evergreen forest, dominated by *Castanopsis*, *Lithocarpus*, and *Quercus* sp. Details of this site have been described in Tanaka et al (2003) and Hashimoto et al (2004).

Figure 1 shows the seasonality of air temperature and rainfall. The mean annual precipitation between 1966 and 1980 was 2084.1 mm (Chunkao et al. 1981). This site has clear rainfall seasonality, with dry and rainy seasons (Chunkao et al. 1981). By contrast, the amplitude of the air temperature variation is very small; the highest temperature was observed in April (ca. 23 ℃), and the lowest was observed in December (ca. 17 °C). The average air temperature was about 20 ℃. This kind of tropical forest, a so-called hill evergreen forest, is characterized by a comparatively long dry season and low temperatures (Whitmore 1990).

Figure 1

The average annual litter fall is about 6.88 Mg ha^{-1} y^{-1} (dry weight 1969-1972, Boonyawat and Ngampongsai 1974; Thaiutsa et al. 1979). The monthly litter fall is generally largest in February and smallest in August (Boonyawat and Ngampongsai 1974).

Soil properties were investigated by Udomchock et al (1983). The soil type is Reddish Brown Lateritic. The soil texture of the A layer (0-0.24 m soil depth) is Sandy clay loam. The soil texture of the B layer (0.24-0.49 m soil depth) is Clay loamy. After incubation, the soil sample used in this study was sieved, and C and N contents were analyzed on a NC analyzer (Flash EA1112, Thermo Electron co., Italy). The properties of the samples are shown in Table 1.

Table1

Hashimoto et al (2004) observed the seasonality of soil respiration. In the Kog-Ma watershed, the soil temperature changes little year round, while the soil water changes markedly (6-month dry and rainy seasons). Consequently, the seasonality of soil respiration is controlled by soil water at this site.

Sampling

One sample of undisturbed forest soil, about 0.2 m in diameter and 0.4 m long, was collected on 6 November 2002. In this region, the rainy season ends in early November, and the dry season begins. The process of obtaining the soil core was similar to that described by Fang and Moncrieff (2001). To obtain the soil core, a cylinder with a sharpened rim was forced a few centimeters into the soil, and the soil around the rim was removed carefully with a knife. The cylinder was then pressed further into the soil by hammering the upper end of the cylinder. This process was repeated.

Incubation system

Hashimoto and Suzuki (2002) developed and described the experimental system, shown in Figure 2. This system can measure the CO_2 production rate from a soil sample and the CO_2 gas concentration in the soil sample at various and varying temperatures. The system consists of a sample column with chambers at the top and bottom, a gas circulator, a water control, and a temperature control. The soil sample is placed between the chambers at each end. Thermometers (TR-71S, T&D Co., Japan) were installed at 0.1, 0.2 and 0.3 m depth, and tension meters (DIK-3000-1, Daiki Rika Kogyou Co., Ltd. Japan) were installed at 0.05, 0.15, 0.25, and 0.35 m depth. In this study, TDRs (CS615, CS616, Campbell Scientific, Inc., USA) were also installed at 0.05, 0.15, 0.25, and 0.35 m depth. Holes for equipment were drilled into the sample column before sampling. When installing equipment in the soil sample, we carefully excavated through a hole in the column, with a manual drill, and installed the equipment. A thermo pump (EYELA CTP201, Tokyorikakikai Co., Japan) allows regulation of the soil sample temperature by circulating water at a given temperature in the tubes surrounding the sample column.

Figure 2

The CO_2 flux from the soil surface was measured using the dynamic closed chamber method. The CO_2 concentration in the attached chamber (10 cm long, 20 cm diameter) was measured using a CO_2 analyzer (LI-COR 6252, LI-COR, USA) and an air pump (flow rate: 27.3 cc/s; MP-2N, Shibata Scientific Technology Ltd., Japan), at 1-s intervals for 3-5 min. The CO_2 flux was calculated from the rate of increase of the CO_2 concentration in the chamber.

Incubation conditions

Before incubation, the soil sample was conditioned by saturating and then drained. Only one soil water content was used for the soil sample. The soil suction at a depth of 0.35 m was set at -0.5 m of suction using the soil water control device.

During incubation, the holes in the upper chamber were open and the CO_2 concentration in the upper chamber was equivalent to the atmospheric CO_2 concentration. The holes in the lower chamber were closed, and the CO_2 concentration in the lower chamber was high. These conditions of $CO_{2,}$ low in surface and high at deeper, were relatively similar to those in situ.

Measuring the temperature sensitivity

To determine the temperature sensitivity of the CO_2 production, the soil sample was conditioned at about 10, 21, and 32 °C. First, the soil temperature was reduced to 10 °C, and then increased to 21 °C, and finally to 32 °C. The soil temperature was then decreased to 21 °C, and then to 10 °C. The soil CO_2 fluxes were measured at each temperature when the soil temperature and CO_2 production rate reached a steady state, which was defined in this study by steady temperature and surface CO_2 flux. For reference, surface CO_2 fluxes between steady states were measured; however, we did not use these fluxes to obtain the temperature sensitivity. Hence, this relationship between the CO_2 production rate and temperature did not include a delay in temperature change or CO_2 transport in the soil sample. At each temperature, CO_2 production (the CO_2 flux from soil surface) was measured 3-5 times.

The relationship between soil temperature and the CO_2 flux was fitted using an exponential model,

$$\mathrm{SR}=\mathrm{Ae}^{\mathrm{kT}}$$

where SR is the soil CO_2 flux ($\mathrm{mgCO_2m^{-2}s^{-1}}$), A and k are constants, and T is the soil temperature (°C). We also calculated Q_{10} value.Q_{10} is the factor by which the CO_2 production rate increases when the temperature is increased by 10 °C, and is widely used. Q_{10} can be expressed as:

$$Q_{10}=(A\mathrm{e}^{k(T+10)})/A\mathrm{e}^{kT}=\mathrm{e}^{10k}.$$

Results

Incubation

Figure 3 shows the soil and air temperatures (a), and soil water content (b, c) during incubation. The soil sample was saturated (7 and 8 November 2002) and then drained. Although the soil water content changed during incubation, it changed by only about 0.05 m^3m^{-3} and probably did not affect CO_2 production during this incubation. The soil water content changed most at 0.05 m, which was the shallowest depth. This was because the upper surface was always open in this system and soil water evaporated. The average soil water content at each depth during incubation was 0.34, 0.41, 0.48, and 0.42 m^3m^{-3}, respectively. Soil temperature control began after saturation (8 November 2002), and it took about 18 h for the soil temperature to change from 21 to 10 or 32 °C. Thermal equilibrium took less time, about 12 h, when the soil temperature changed from 10 or 32 to 21 °C, because the air temperature was about 21 °C, which affected the temperature control. These differences in time for equilibrium did not affect the temperature sensitivity calculated in this study, since we used CO_2 fluxes at steady state for calculating temperature sensitivity. There were no differences in temperature between the thermometers at 21 °C and 32 °C; however, there was a slight difference of 1-2 °C, at 10 °C. In this incubation system, the holes in the upper chamber remain open, and fresh air is pumped slowly into one hole and leaves through the other, keeping the CO_2 concentration at atmospheric levels. Hence, it is difficult to control the upper surface temperature in this system, which is a point that needs to be improved.

Figure 3

The CO_2 fluxes measured at the upper soil surface are shown in Figs. 3 (d). The CO_2 flux increased with temperature, from about 0.05 to 0.26 $mgCO_2m^{-2}s^{-1}$.

Temperature sensitivity

The relationship between soil temperature and the CO_2 flux from the soil sample (*i.e.*, the total CO_2 production from the soil sample) is shown in Fig. 4. The soil temperature was the average temperature of each layer. The CO_2 flux from the soil sample increased exponentially with increasing soil temperature.

Figure 4

The fit gives A=0.023and k=0.077. The Q_{10} value that we obtained was Q_{10}=2.2. In this study, the temperature sensitivity was calculated using the soil CO_2 flux data measured when the soil sample was in thermal and gaseous equilibrium. Hence, this relationship between the CO_2 production rate and temperature did not include a delay in temperature change or CO_2 transport in the soil sample.

Discussion and conclusion

Temperature sensitivity

Due to the limited space, electric power and the length of our stay, the number of sample was only one, and the steady state was set only at 10, 21, 32 °C, which may have been insufficient; however, we believe the results well demonstrated the reality. First, the sample size was quite larger than other studies, which a larger sample size generally provides data more typical of a site. Second, the scattering of surface CO_2 flux was very small compared to the field studies, which enables us to detect the exponential trend easily.

Our results reveal a strong relationship between the CO_2 production rate and temperature in the hill evergreen forest of Thailand, as reported in studies of other ecosystems. The CO_2 production rate increased exponentially with increasing soil temperature. The Q_{10} value obtained in this study was 2.2, which is comparable to results of global surveys. Based on the compilation of an extensive literature survey of *in situ* measurements, Raich and Schlesinger (1992) obtained a median Q_{10} value for total soil respiration of 2.4. Also, Lenton and Huntingford (2003) reported the mean Q_{10} value for field studies of 2.54 and for laboratory studies of 2.51. The ranges they found were between 1.3 to 5.6 for field studies and between 0.8 to 12.92 for laboratories. The Q_{10} that we obtained in the laboratory was similar to the median or mean Q_{10} values which were obtained in these review papers.

There have been few reports on the temperature sensitivity of soil respiration in tropical regions. Meir et al (1996) conducted field observations in a rainforest in Amazonia, and investigated the seasonal relationship between soil respiration and soil temperature at the depth of 0.01 m using an exponential model. They obtained $Q_{10} = 2.3$ for a temperature range of 22 to 24 °C, which is similar to our value. In contrast, Kiese and Butterbach-Bahl (2002) carried out a laboratory study because they failed to reveal a significant influence of soil temperature on soil respiration in field observations in three different tropical forest sites in Australia. They studied the relationship between soil respiration and soil temperature at temperatures of 20 to 30 °C, and found Q_{10} values of 3.0, 3.6, and 5.0, which are larger than that of this study. The range of soil temperature controlled to obtain the Q_{10} value in this study (ca. 10-32 °C) was wider than those of above two studies in tropical regions.

Difficulty of separating root respiration

We used an undisturbed soil sample, which has an advantage of minimizing the disturbance of sampling or sieving; on the other hand, using an undisturbed soil sample has uncertainty: root respiration. The temperature sensitivity of soil and root may be different (Boone et al. 1998); the temperature sensitivity obtained was probably a lumped temperature sensitivity.

Also, fine roots which might be cut by the sampling could stop respiration during the incubation, which would result in the decrease of CO_2 flux from the soil sample. It is also possible that these cut fine roots were decomposed during the incubation, which would result in the increase of CO_2 flux. Separating root respiration remains difficult (e.g. Hanson et al. 2000).

Timing of soil sampling

The amount of soil CO_2 production may be different if soil sampling was conducted in other seasons. The carbon cycle in tropic regions is very rapid (e.g. Trumbore 2000), which indicates that the seasonality of litterfall or surface litter should affect the seasonality of soil CO_2 production in tropic regions, especially through CO_2 production at shallower depths (e.g. Butterbach-Bahl et al. 2004; Goulden et al. 2004). In other words, the amount of labile soil organic matter should differ among seasons and affect the seasonality of CO_2 production rate. Our sampling was conducted in November, the end of the rainy season and the beginning of the dry season; the most surface litter might have been decomposed, and the amount of labile soil organic matter might have been smaller.

Soil water condition

Only one soil water content was used in this study, which was neither too wet nor too dry. In general, soil CO_2 production decreases under both excessively wet and dry conditions. If CO_2 production was measured under different soil water condition, the rate would be different.

The importance of tropical forests for future changes of carbon cycle

Due to our limited results, it is difficult to apply the results to whole tropical evergreen forest and to other tropical forests; however, our results showed the strong temperature sensitivity of soil respiration in tropical evergreen forest. If the result could be generalized, this raises the possibility that the increment of soil respiration may be enormous even in possible small warming because of the exponential sensitivity and high average temperature, as other studies did (Townsend and Vitousek 1992). Although the amount of carbon stock and the quality of organic matter should be considered, tropical soils could become significant sources of atmospheric CO_2.

Nevertheless, studies on soil respiration in tropical regions are lacking, as compared to other regions, so more studies are needed for accurate prediction of soil carbon response to future climate change, especially studies under laboratory conditions. Because tropical regions generally have very small temperature seasonality, and some tropical regions even have little seasonality of water, measurements of soil respiration under various environmental conditions in laboratories are therefore essential.

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Table

Table 1: Site location, climate, and soil properties in the Kog-Ma watershed.

Location				
Latitude	18°48'N			
Longitude	98°54'E			
Climate*				
Mean annual precipitation (mm)	2084.1			
Mean annual temperature (°C)	20			
Properties				
Depth (m)	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4
Rock (>2 mm) (g/layer)**	69.9	82.6	91.5	224.7
Large organic matter (>2 mm) (g/layer)**	7.0	3.5	4.4	3.7
Small non-organic particles (<2 mm) (g/layer)**	1205.7	1759.8	2216.1	2354.9
Small organic matter (<2 mm) (g/layer)**	320.3	352.2	365.9	341.1
Bulk density (kg m^{-3})	510.2	699.7	852.4	930.8
Sand (%)***	45.0		42.1	
Silt (%)***	28.9		27.1	
Clay (%) ***	27.1		30.8	
Texture ***	Sandy Clay Loam		Clay Loam	
C (%)	7.6	5.5	3.7	2.5
N (%)	0.57	0.44	0.31	0.23
C/N ratio	13.3	12.5	12.0	10.7
Total porosity (m^3/m^3)	0.74	0.73	0.62	0.60

* Chunkao et al. 1981, from 1966 to 1980

** The volume of one layer was 0.0031 m^3 (0.2 m diameter, 0.1 m long)

*** Udomchock et al. 1983, USDA basis

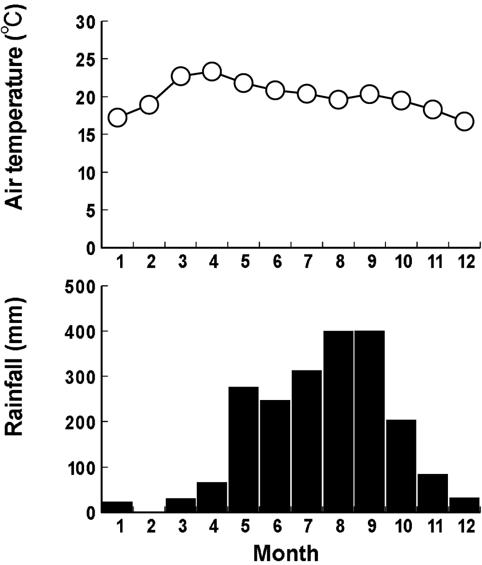
Figure legends

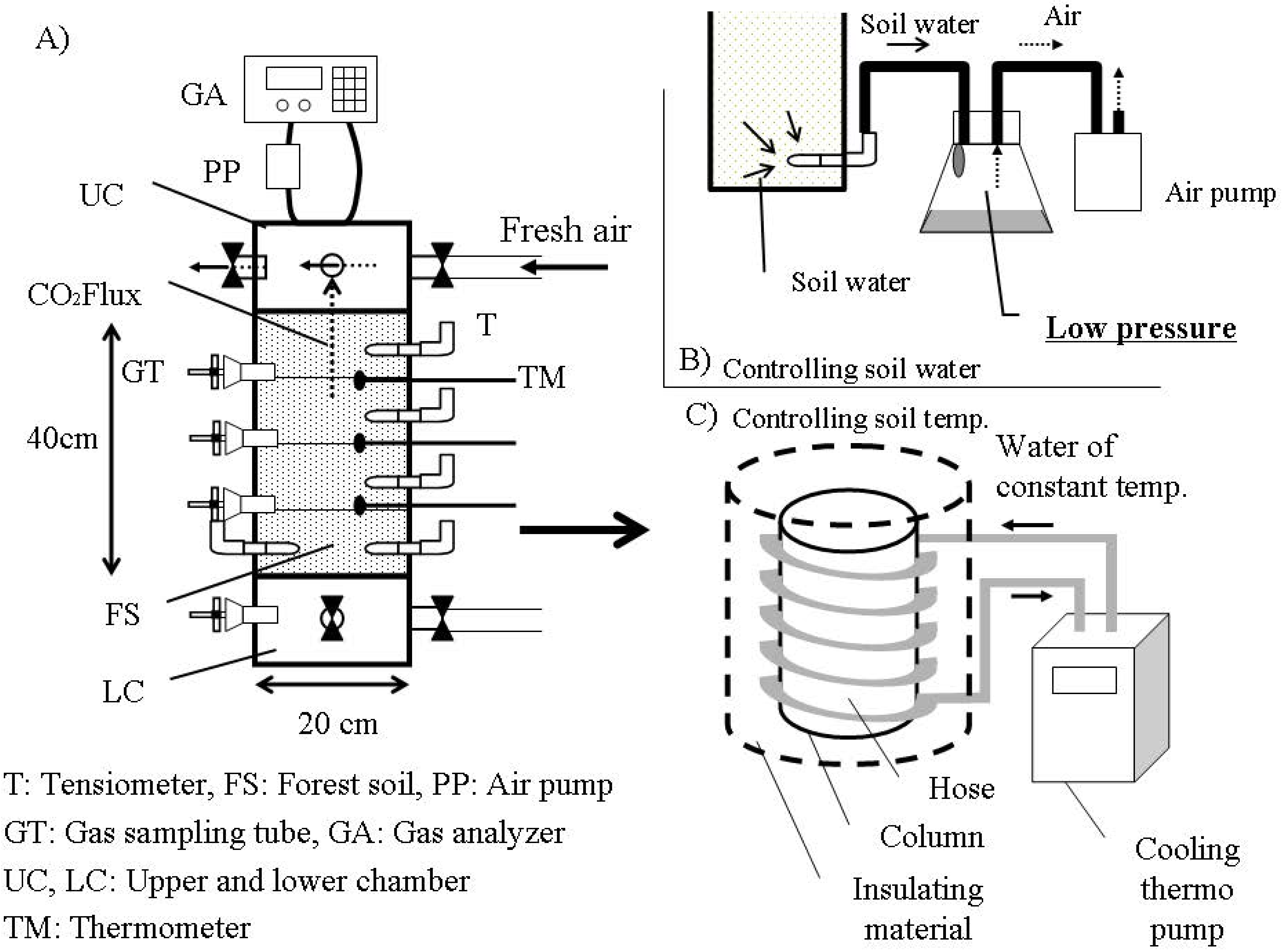
Figure 1: Seasonality of air temperature and rainfall in Kog-Ma watershed (Chunkao et al. 1981).

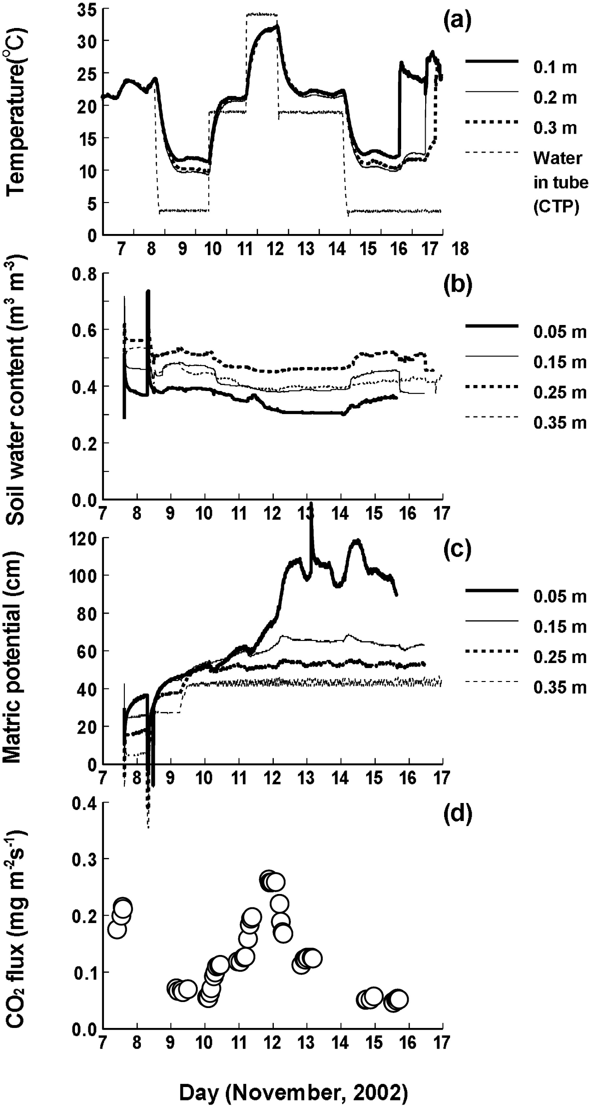
Figure 2: The incubation system (adapted from Hashimoto and Suzuki 2002). A TDR sensor was added at each layer in this study at 0.05, 0.15, 0.25, and 0.35 m depth.

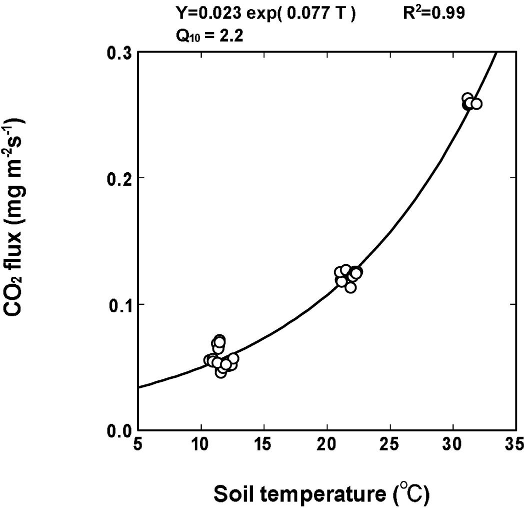
Figure 3: Incubation conditions and measured CO_2 flux from the soil surface during incubation. Temperature (a), soil water content (b), suction (c), and CO_2 flux from the soil surface (d).

Figure 4: The temperature dependence of the soil surface flux (total CO_2 production from the soil sample). The air temperature affected the soil temperature near the surface, while the soil temperatures below the surface were similar. Therefore we used the average soil temperatures of each depth.


Air temperature (°C)
30
25
20
15
10
5
0
1
2
3
4
5
6
7
8
9
10
11
12
Rainfall (mm)
500
400
300
200
100
0
1
2
3
4
5
6
7
8
9
10
11
12
Month


A)
GA
PP
UC
Fresh air
CO2Flux
T
GT
TM
40cm
FS
LC
20 cm
T: Tensiometer, FS: Forest soil, PP: Air pump
GT: Gas sampling tube, GA: Gas analyzer
UC, LC: Upper and lower chamber
TM: Thermometer
Soil water
Air
Air pump
Soil water
Low pressure
B) Controlling soil water
C) Controlling soil temp.
Water of
constant temp.
Hose
Column
Insulating
material
Cooling
thermo
pump


(a)
Temperature(°C)
35
30
25
20
15
10
5
0
7 8 9 10 11 12 13 14 15 16 17 18
0.1 m
0.2 m
0.3 m
Water in tube (CTP)
(b)
Soil water content (m3 m-3)
0.8
0.6
0.4
0.2
0.0
7 8 9 10 11 12 13 14 15 16 17
0.05 m
0.15 m
0.25 m
0.35 m
(c)
Matric potential (cm)
120
100
80
60
40
20
0
7 8 9 10 11 12 13 14 15 16 17
0.05 m
0.15 m
0.25 m
0.35 m
(d)
CO2 flux (mg m-2s-1)
0.4
0.3
0.2
0.1
0.0
7 8 9 10 11 12 13 14 15 16 17
Day (November, 2002)



$Y = 0.023 \exp(0.077\,T)$ $R^2 = 0.99$

$Q_{10} = 2.2$