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Soil CO_2 emissions measured by closed chamber and soil gradient methods in dry dipterocarp forest and sweet sorghum plots

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ABSTRACT: Soil respiration as a major component of the carbon cycle has received considerable attention because of its role in amplifying global warming and in climate feedbacks of ecosystems. This makes it important for us to devise reliable methods in order to measure soil CO_2 effluxes accurately. In this study, we investigated the variations of CO_2 effluxes for 93 days in sweet sorghum plots and a dry dipterocarp forest by closed chamber and soil gradient methods. The results show that both sites had similar patterns of soil CO_2 emission but CO_2 emission from the sweet sorghum plots was 4 times higher than from the dry dipterocarp forest. Over the study period, the average soil CO_2 efflux and accumulative emission from the dry dipterocarp forest were 360 ± 129 mg CO_2 m^{-2} h^{-1} and 34 g CO_2 m^{-2} and from the sweet sorghum plots they were 2456 ± 614 mg CO_2 m^{-2} h^{-1} and 235 g CO_2 m^{-2}, respectively. Continuous and high temporal-resolution measurements based on the soil gradient method also enabled us to detect the response of soil CO_2 efflux to environmental drivers. We found that rainfall and irrigation events in a short time period could significantly enhance the magnitude of soil CO_2 effluxes. In addition, we also found that an appropriate time for daily soil CO_2 measurements was around noon.

KEYWORDS: CO_2 profile probe, measurement timing, high-resolution measurement, rainfall effects, agricultural soil, forest soil

INTRODUCTION

Increases in atmospheric concentrations of major greenhouse gases (CO_2, CH_4, and N_2O) are the main causes of global warming and global climate change[1]. Reducing the emissions and increasing carbon sequestration in various ecosystems therefore becomes necessary. Before such goals could be achieved, quantifying and understanding the variations of greenhouse gas emissions and their sequestration are needed.

CO_2 emissions from terrestrial ecosystems via soil respiration accounts for the majority of global carbon exchange between land and the atmosphere[2]. Soil surface CO_2 emissions or effluxes are originated from two main sources including decomposition by heterotrophic microorganisms and root respiration by plants (autotrophic)[3,4]. Thus variables such as temperature, soil moisture, and plant activity are often found to be the main controllers of the spatial and temporal variations of soil respiration. Under steady state (no disturbance) soil

CO_2 efflux equates soil respiration as it is directly related to CO_2 production in the soil. Under non-steady state, soil respiration responds dynamically to disturbances[4]. For example, Xu et al[5] found that soil respiration increased rapidly after rainfall. In addition, de Jong et al[6] and Liu et al[7] found that irrigation and addition of water to surface soil could stimulate soil respiration in grasslands. Because of the fast-response of soil CO_2 efflux to environmental changes, some conventional methods such as closed chamber could not capture soil respiration dynamics during such disturbance. This could be the cause of errors associated with CO_2 emission quantification[8–13].

Emission of CO_2 from soil surface can be quantified by using various techniques. The majority of researchers in the past have used chamber methods to estimate soil CO_2 emission because it is economical and its deployment in the field is relatively simple when compared to other methods. However, closed chamber could cause bias if not handled properly[8]. Such bias includes the absorption of CO_2 during photosynthesis in the presence of plant and light. Closed chamber could not be used to either measure continuously or frequently[10]. On the other hand, soil gradient method using CO_2 sensor could serve the CO_2 quantification purpose without significantly modifying the measured systems, including the bias resulted from the presence of plant. Hirano et al[9] used the small GMD20 CO_2 sensors (Vaisala Inc., Finland) to determine soil CO_2 effluxes by burying them in the soil under a deciduous broad-leaved forest in Japan. Tang et al[10] used the GMT222 CO_2 sensors (Vaisala Inc., Finland) in a summer dry season in a Mediterranean savanna ecosystem in California, USA. They found that measuring CO_2 effluxes by this method yielded very close values to that obtained by chamber measurements. Liang et al[11] developed the soil gradient method by burying GMT222 CO_2 sensors in the soil under a larch forest in Japan and compared the results with other methods including LI-6400 chamber, open-top chamber, and automated chamber. They found that the seasonal variations in soil CO_2 effluxes measured by four methods were exponentially correlated with variations in soil temperature at 5-cm depth. They also found that the CO_2 effluxes measured by the gradient method were about 45% higher than the results of the automated chamber. Nevertheless, they found a good correlation between the two techniques. Chayawat et al[12] used the GMP343 CO_2 sensors in wheat and peanut fields in the USA in order to investigate the effect of rainfall on soil CO_2 efflux. They found that soil CO_2 efflux decreased during and immediately after rainfall events. Then a significant increase in soil CO_2 efflux was observed after rainfall for a few hours. The increased rates were different among the growth stages of peanut. After rainfall, there were significant correlations between soil moisture and soil CO_2 efflux. They suggested that soil water replacement by rainfall was a main cause of short-term losses of soil CO_2 efflux after rainfall and high temporal-resolution measurement of soil CO_2 efflux should be made to capture large pulses in CO_2 emissions. The results described above indicate that high temporal-resolution measurements such as by using CO_2 sensors could additionally provide useful information for explaining its temporal and spatial variations. In addition, the soil CO_2 sensor can also be useful to determine the appropriate timing and frequency of measurements, whereby help to reduce the unnecessary measurements and resources. Thus the objectives of this study were to measure CO_2 emissions by using the CO_2 profile probes compared to soil CO_2 effluxes with those obtained from the conventional method (closed chamber) and to determine the appropriate timing and frequency of measurements of soil CO_2 emission in a tropical dry dipterocarp forest and the sweet sorghum plots.

MATERIALS AND METHODS

Site description

The study site was located at King Mongkut's University of Technology Thonburi (KMUTT), Ratchaburi Campus, Rang Bour, Chombueng, Ratchaburi, western Thailand. Two plots including a dry dipterocarp forest and a sweet sorghum plot were prepared. This is one of the AsiaFlux network's sites, known as a Dry Dipterocarp Forest Flux Ratchaburi (DFR site) (13° 35′ 13.3″ N, 99° 30′ 3.9″ E). The site was a tropical monsoon forest. The mean annual temperature and precipitation during 2009–2010 were 26.5 °C and 1125 mm, respectively. The DFR site was situated at 118 m asl elevation. The total forest area was 88.9 ha. The vegetation type was a dry dipterocarp forest and the dominant species were *Dipterocarpus intricate*, *D. obtusifolius*, *D. tuberculatus*, *Shorea obtuse*, and *S. siamensis*[14]. The canopy was about 5–7 m height and diameter at breast height of the stem was about 8 cm (measurement in 2009). The soil was a loamy sand soil, with organic carbon content of 0.5% in the 0–20 cm soil layer[15]. Small scale land use change was made in 2010, converting this dry dipterocarp forest into sweet sorghum plots (SS). Clear cutting of trees for the cropland was done by a backhoe. Groundcovers, herbs, and small parts of trees from the clearing were incorporated into the soil. The total area that had been converted was 0.27 ha. Three plots with 15×15 m^2 for each site were made and the sweet sorghum cultivar KKU40 was planted within-row spacing of 25 cm and between-row spacing of 75 cm by direct seeding method. The composite fertilizer 15-15-15 was applied at 30 days after germination at the rate of 312.5 kg/ha. The crop plantation was started after ploughing for a week then an automated sprinkler system was used for irrigation which operated once a day[16]. The measurement results reported here were obtained during the 3rd crop production cycle after land conversion occurred or during the 72nd day of year (DOY72) to DOY164 in 2012.

Micrometeorological variables

Air temperature was measured by a Vaisala sensor (HMP45C, Vaisala Inc., Finland). At the same depths with the CO_2 sensors, soil temperature and soil moisture were continuously measured for every 15 s by thermocouple sensors and water content reflectometers (CS615, Campbell Scientific, Inc., USA), respectively. The water content reflectometers started to collect the data at the same time as with the CO_2 sensors. The bulk density and the particle density of soil were measured by using soil cores at depths of 0–5 cm, 5–10 cm, 10–15 cm and 15–20 cm and analysed at the laboratory of Office of Science for Land Development, Land Development Department.

Measurement of soil respiration

This study estimated and compared soil respiration from two methods; closed-automated chamber and soil gradient method using soil CO_2 sensors. The chambers were closed and opened by a hydraulic system which was controlled by solenoid valves and a program on a data logger. A chamber was made of acrylics (3 mm thick) with the dimension of $30 \times 30 \times 30$ cm^3. Its stainless steel base which was installed permanently on soil surface to the depth of 10 cm had the dimension of $30 \times 30 \times 15$ cm^3. Three replications were made at both the DFR and the SS sites. The CO_2 concentration was determined by an infrared gas analyser (Licor-820, Licor Corporation, Lincoln, Nebraska, USA) and was stored in a data logger. A cycle of CO_2 sampling was about 7 min. Soil CO_2 effluxes were measured hourly[17].

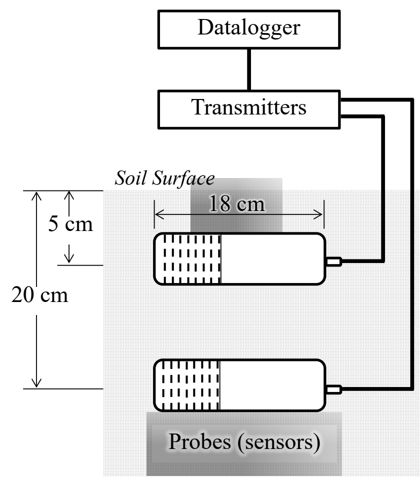

Fig. 1 Placement and position of the GMP343 probes in the soil profile for soil CO_2 concentration measurements.

For measuring soil CO_2 concentrations by using gradient method, the soil CO_2 sensors (GMP343, Vaisala Inc., Finland) were horizontally buried at soil depths of 5 cm and 20 cm (Fig. 1). The sensors scanned for concentration determination for every second and recorded the average value for every 15 s. These sensors were connected with a transmitter, a data logger and a computer for data recording. In this study, three replications were made at both the DFR and the SS sites. All sensors were originally calibrated by the manufacturer and occasionally calibrated when required following the user manual during the study period. Different frequencies of the next calibrations were considered by checking the data and the sensors in the fields. We found that measurements at the SS site needed more frequent maintenance and calibration due to coating of soil and mud on the sensor surface, brought about by daily irrigation. Under such conditions, we calibrated the sensor once a month at the DFR site and once a week at the SS site.

Soil CO_2 emissions were calculated using data on the soil CO_2 concentrations (μmol/mol or μmol/m^3) combined with environmental factors as described below. We followed the steps of the calculations from Tang et al[10]. The soil CO_2 effluxes (F, μmol m^{-2} s^{-1} or mg CO_2 m^{-2} h^{-1}) were determined as follows;

$$F = -D_s \frac{dC}{dz}, \quad (1)$$

where F is soil CO_2 efflux (μmol m^{-2} s^{-1}), D_s is CO_2 diffusion coefficient in the soil (m^2/s), dC/dz is the vertical soil CO_2 gradient, C is CO_2 concentration (μmol/m^3) and z is depth (m).

$$D_s = \xi D_a, \tag{2}$$

where D_a is the CO_2 diffusion coefficient in the free air (m^2/s) and ξ is the gas tortuosity factor.

$$D_a = D_{a0}\left(\frac{T}{293.15}\right)^{1.75}\left(\frac{P}{101.3}\right), \tag{3}$$

where D_{a0} is the reference value of D_a at 20 °C (293.15 K) and 101.3 kPa, and is given as 14.7×10^{-3} m^2/s, T is the air temperature (K) and P is the air pressure (kPa).

There are several empirical models for computing ξ [18]. We used the Millington-Quirk model[19] similar to Tang et al[10] as

$$\xi = \alpha^{10/3}/\varphi^2, \tag{4}$$

where α is the volumetric air content and φ is the porosity.

$$\varphi = \alpha + \theta = 1 - \rho_b/\rho_m, \tag{5}$$

where θ is the volumetric soil water content, ρ_b is the bulk density (g/cm) and ρ_m is the particle density for the mineral soil (g/cm). The bulk density and the particle density for the calculations at the DFR site were 1.42 and 2.68 g/cm and at the SS site were 1.49 and 2.67 g/cm, respectively.

Statistical analysis

Independent-samples t-test (at a significance level of 0.05) were applied to compare soil CO_2 effluxes measured by sensor and chamber methods and to determine appropriate measurement timing of soil CO_2 emission at both sites. Pearson's correlation coefficient was applied to investigate their relationships (with $p < 0.05$) with soil temperature and moisture. Furthermore the mean absolute percentage error was applied for comparing the efflux means obtained from chamber and sensor methods, and calculated as

$$M = \frac{100\%}{n}\sum_{t=1}^{n}\left|\frac{A_t - F_t}{A_t}\right|, \tag{6}$$

where A_t is the actual value (measured by the chambers) and F_t is the estimated value (measured by the sensors).

RESULTS AND DISCUSSION

Soil CO_2 concentrations in forest and agricultural soils

Comparing soil CO_2 concentrations at the depths of 5 cm and 20 cm between both sites, we found that there were significant differences ($p < 0.05$) in both soil depth and sites. Over the study period, average soil CO_2 concentrations at depths of 5 cm and 20 cm at the DFR site were 2555 ± 1054 and 3672 ± 1103 μmol/m ($n = 91$), respectively (Fig. 2a1). At the SS, these were 3080 ± 1075 and $10\,246 \pm 1455$ μmol/m ($n = 71$), respectively (Fig. 2a2). At both sites, higher CO_2 concentrations in a deeper layer than a surface layer were due to transport of CO_2 through soil profile to surface[4,10,20]. Such high concentration of CO_2 in soil was commonly found in other forest areas[4,10,12].

Compared to DFR site, higher concentration of CO_2 and bigger difference between concentrations at 5 cm and 20 cm were found for SS site (Fig. 2a1–a2). This may be interpreted as conversion of forest to agricultural land could stimulate the decomposition of soil organic carbon leading to higher CO_2 production. Cultivation practices such as ploughing, planting, and irrigation could also alter some key soil properties, resulting in slow transport of CO_2 through the soil profile[4,21]. In addition, agricultural soil at SS site was excessively wet because of rainfall events and daily watering system. This enhanced the occurrences of mud and puddle at soil surface. CO_2 transport to soil surface may be slowed under such conditions[4].

Soil CO_2 efflux and their relationships with environmental variables

At the DFR site the average soil CO_2 efflux was 360 ± 129 mg CO_2 m^{-2} h^{-1} (Fig. 2b1), significantly lower than that at the SS site (2456 ± 614 mg CO_2 m^{-2} h^{-1}, Fig. 2b2). This was a direct consequence of higher soil profile gradients of CO_2 concentration at SS site than at the forest site. Accumulative emission for 93 days at the forest site was 34.05 g CO_2/m^2 and at the sweet sorghum plots was 234.77 g CO_2/m^2, respectively. Higher soil emission from the SS site than the DFR sites was observed despite the fact that soil temperatures, air temperature (Fig. 2c1–c2) and soil moisture were not significantly different (Fig. 2d1–d2). Thus the main reason behind higher emission from agricultural soil was probably mainly due to different land use and cultivation activities, but not due to other environmental drivers such soil temperature and moisture. Similar results were also reported by Tulaphitak et al[22] that the newly cropped plots (which did both slash and burn) released more CO_2 than an uncut forest plot in Thailand. The examples of factors affecting CO_2 production and emission include quality of organic materials, environment

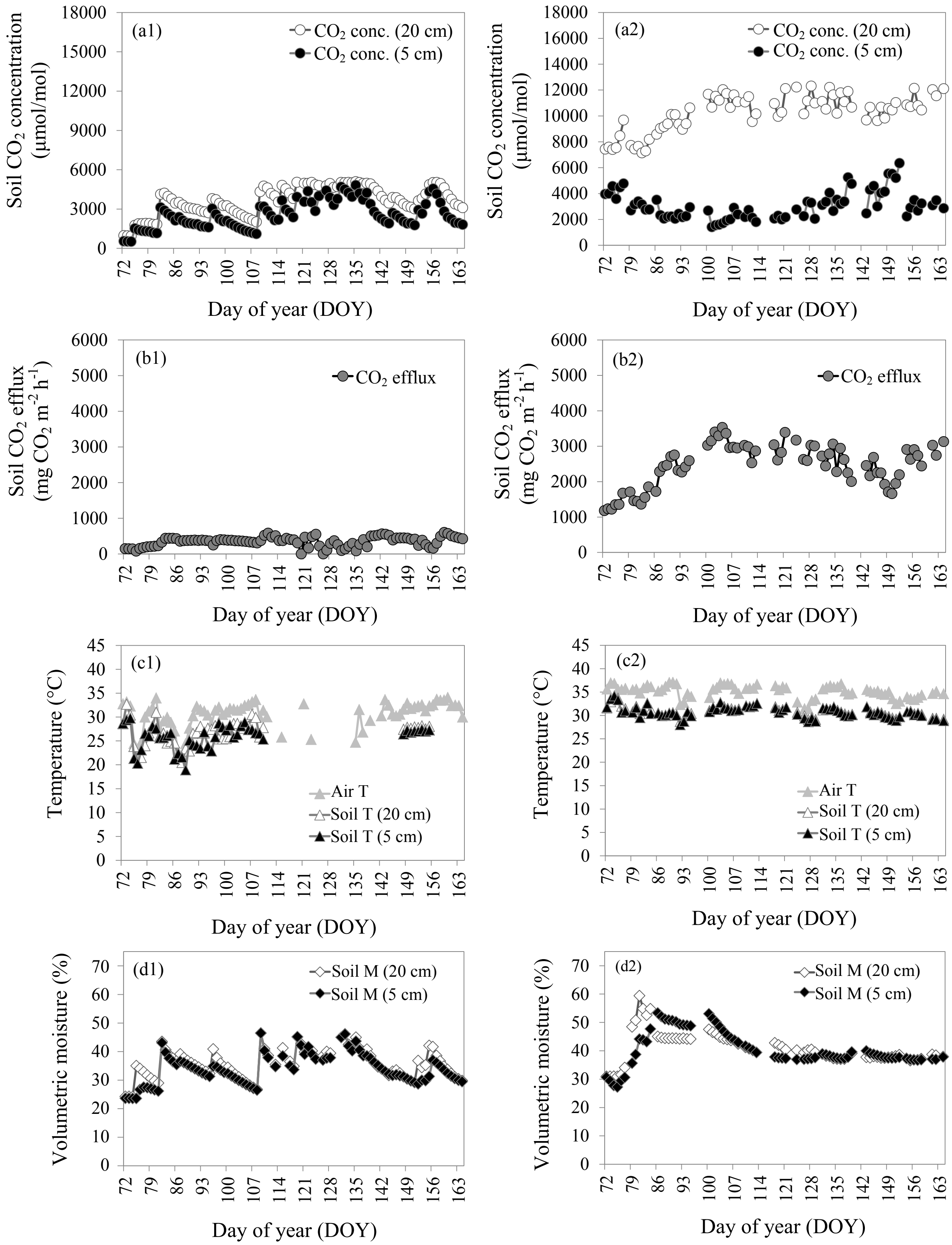

Fig. 2 Variations of (a) soil CO_2 concentration, (b) soil CO_2 effluxes, (c) air and soil temperature, and (d) soil volumetric moisture at depths of 5 and 20 cm (a1, b1, c1, and d1 were at the dry dipterocarp forest (DFR) and a2, b2, c2, and d2 were at sweet sorghum plots (SS)).

Table 1 Comparison of soil CO_2 emissions between chamber and sensor methods.

Methods	Daily average efflux ($mg\ CO_2\ m^{-2}\ h^{-1}$)		Accumulative CO_2 ($g\ CO_2/m^2$)	
	DFR site	SS site	DFR site	SS site
Sensor	360 ± 129	2456 ± 614	34.05	234.77
Chamber	478 ± 232	664 ± 253	38.34	53.36

(including aeration, pH, temperature, and moisture in soil), and microbial population (microbial biomass). Crop cultivation could change soil basic properties (such as pH), soil environments (aeration and moisture) and the type of organic materials (such as crop residues)[4].

Comparisons between soil CO_2 emissions measured by the sensor and the chamber methods

Soil CO_2 emissions between DOY72 and DOY164 for 93 days from the measurements of two methods were presented in Table 1 and Fig. 3. Over the study period, the average soil CO_2 efflux and accumulative emission measured by the gradient method at the dry dipterocarp forest (DFR) were 360 ± 129 mg $CO_2\ m^{-2}\ h^{-1}$ and 34.05 g CO_2/m^2, and at the sweet sorghum plots (SS) were 2456 ± 614 mg $CO_2\ m^{-2}\ h^{-1}$ and 234.77 g CO_2/m^2, respectively. On the other hand, the average soil CO_2 efflux and accumulative emission measured by the closed chamber method at DFR site were 478 ± 232 mg $CO_2\ m^{-2}\ h^{-1}$ and 38.34 g CO_2/m^2, and at SS site were 664 ± 253 mg $CO_2\ m^{-2}\ h^{-1}$ and 53.36 g CO_2/m^2, respectively.

Our results show that there were significant differences in soil CO_2 emissions measured by sensor and chamber method at the DFR sites ($p = 0.001$, $n = 55$) and the SS site ($p = 1.8 \times 10^{-32}$, $n = 33$). The soil CO_2 emission measured by the gradient method was 34.05 g CO_2/m^2, and by the closed chamber method was 38.34 g CO_2/m^2. Comparisons by Mean Absolute Percentage Error, this was about 26% lower by sensor than by the chamber method. On the other hand, at SS site the CO_2 emission measured by sensor was 60% higher than that by the closed chamber.

The results mentioned above indicate there are discrepancies in soil CO_2 emissions amounts between that were measured by the closed chamber and the soil gradient methods, and these could be quantitatively significant. The two methods applied different concepts in quantifying soil CO_2 emissions.

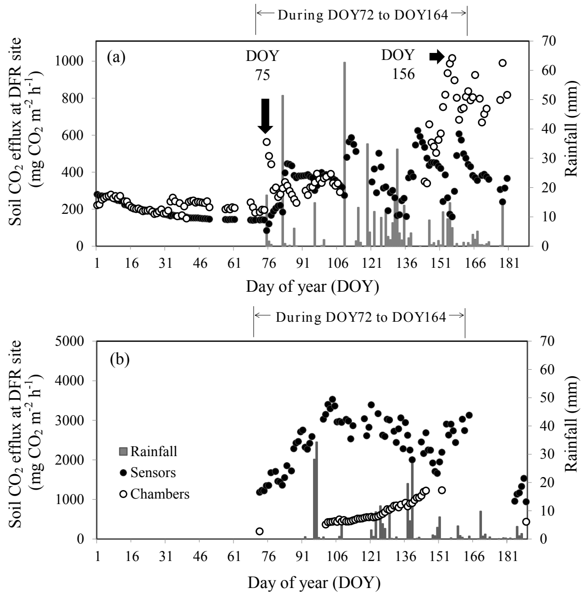

Fig. 3 Comparisons between soil CO_2 effluxes measured by sensors and chambers; (a) at the dry dipterocarp forest (DFR) and (b) at sweet sorghum plots (SS).

Chamber method captures the emitted CO_2 from the soil surface while the gradient method estimates the CO_2 emission from the difference of CO_2 concentrations between two soil layers. Under steady state, measurement results from both methods should be more or less the same. This is reflected in the results from the forest where no cultivation activity was going on, and the CO_2 emission obtained from both methods were more similar to each other than those from the agricultural site (Fig. 3). In addition, sprinkler irrigation at the SS site combined with other cultivation activities may somehow have prevented the transport of CO_2 from the soil profile to the atmosphere. These disturbances may cause biases when CO_2 emissions are measured by both methods.

Theoretically, CO_2 emissions from soil responses to changes in various factors encountered in the field conditions such as changes in precipitation intensity and frequency, agricultural cultivation, nitrogen deposition and fertilization and substrate supply[4]. To demonstrate the measurement of soil CO_2 emissions to such factors, we have investigated the emissions as it was influenced by rainfall at the DFR and SS sites. We found that the response of CO_2 emission to rainfall event was different when this was observed from the closed chamber and sensor methods. Based on the sensor measurement, right after the rainfall event surface emission of CO_2 decreased. This was maintained for few hours after

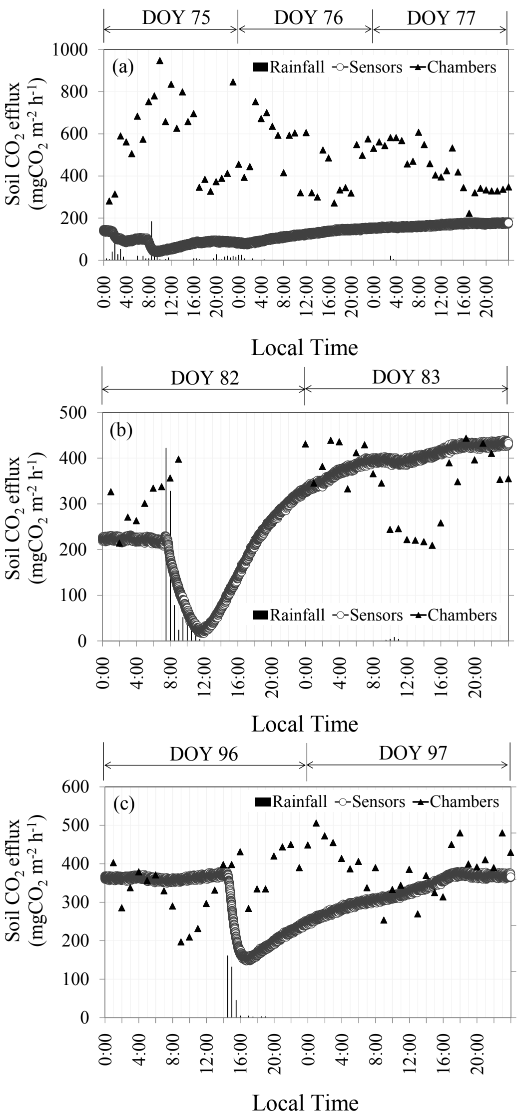

Fig. 4 Effects of rainfall events on soil CO_2 emission; (a) DOY75–77, (b) DOY82–83, and (c) DOY96–97, shown as the examples of large pulses from effects of rain events at the dry dipterocarp forest (DFR).

which it recovered to the level before rainfall. In contrast, emission measured hourly by the closed chamber was increased after rainfall event and this too lasted for few hours (Fig. 4). However, at the SS site we did not observe the dynamics of CO_2 effluxes in responses to rainfall events as those were observed at the DFR site. The routine irrigation schedule and temporarily water-saturated condition during sprinkler operation may have influenced the values observed in the SS compared to the DFR site. As mention above, CO_2 emission at the SS site by sensor method was about 4 times higher than that of by chamber. The soil was possibly under water saturation due to irrigation during cultivation at SS site while the soil was relatively dry at DFR site during the beginning of rainy season. Hence it was expected that the effects of a rainfall event on CO_2 pulse at SS site would not be as obvious as observed at the DRF site. However, at SS site it is obvious that large amount of CO_2 is accumulated in the soil profile and in our case this CO_2 was not emitted during the cultivation period. Thus continuous measurement long after cultivation ceased may be needed to accurately quantify the emissions. In addition, the results shown here indicate that selecting the appropriate method for measuring soil CO_2 emission depends also on site characteristics. Chamber and sensor methods may result in either over or underestimation of the emission and thus careful consideration and comparison among methods needs to be studied before it deployments.

Appropriate timing and frequency for measurements of soil CO_2 emission

Most of the methods including chamber method cannot be used to continuously monitor CO_2 emission due to its effects on surface physical condition. Thus we used the sensors that enabled us to determine the frequency and the appropriate timing for measuring soil CO_2 effluxes during the day. Firstly, we compared the average flux value among different measurement intervals and compared them with that were obtained from the average flux estimated from 15 s measurements (the highest temporal resolution available in our study; reference value). We found that in general, the average fluxes were not significantly different when CO_2 emissions were measured for every 15 s, 5 min, 15 min, 30 min, 60 min, and 1 day. But if CO_2 measurement were to be done weekly, this could make the difference as much as 20% from that of the 15 s average flux (Table 2). Thus it was concluded that CO_2 emission could be measured at least daily to accurately quantify its emissions and to reflect the temporal variations more appropriately.

From the previous research results [17], CO_2 emissions exhibited a strong diurnal pattern. Determining the appropriate timing of measurement during the day is therefore important when the measurement is carried out once a day. To determine such timing, we used data from DFR site and compared the effluxes at different time during a day (the effluxes measured by gradient and chamber methods were shown in Fig. 5a1–a2 and Fig. 5b1–b2, respec-

Table 2 Average value of soil CO_2 emissions using different measurement intervals at the DFR site.

Measured by sensors	15 s	5 min	15 min	30 min	60 min	1 day	1 week
Accumulative CO_2 (mg CO_2 m^{-2} h^{-1})	34 054	34 054	34 051	34 037	34 013	33 233	27 311
Absolute percentage error (%)	reference value	0.00	0.01	0.05	0.12	2.41	19.80

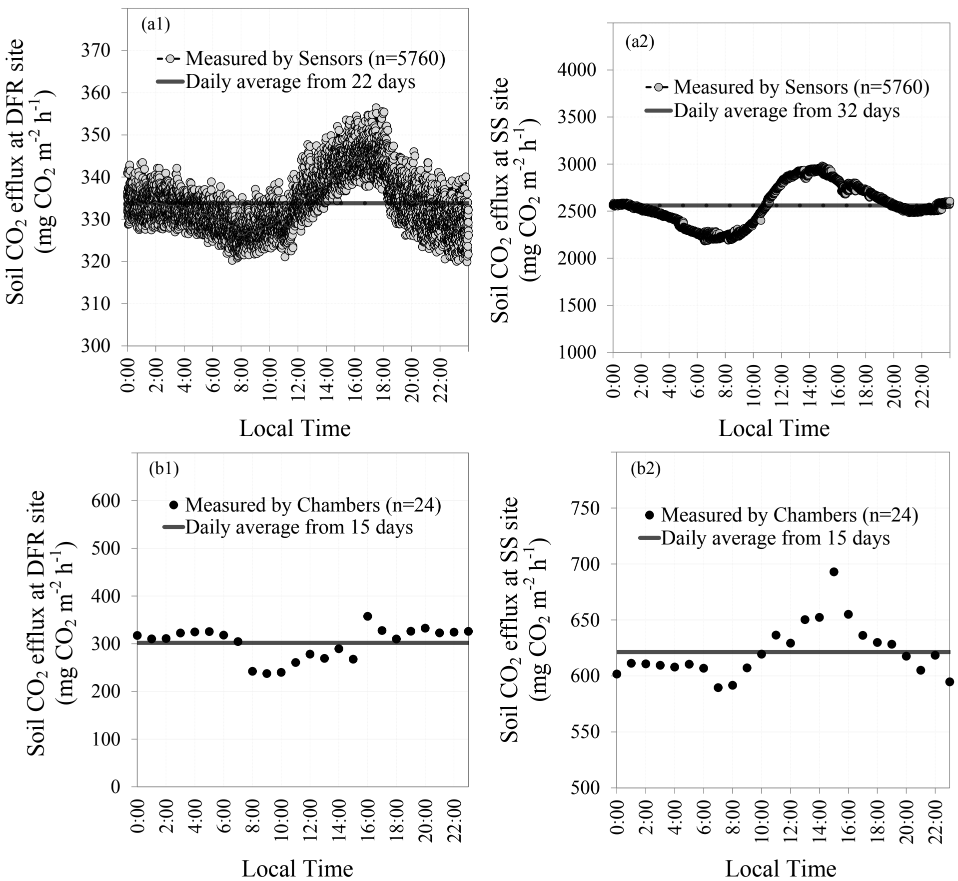

Fig. 5 Diurnal pattern of soil CO_2 effluxes, plotted in reference to the daily average; (a) measured by sensor method and (b) measured by chamber method (a1 and b1 were at the dry dipterocarp forest (DFR) and a2 and b2 were at sweet sorghum plots (SS)).

tively). The daily average soil CO_2 efflux (based on 22–32 day daily average values) was 332.6 ± 6.3 mg CO_2 m^{-2} h^{-1}. However, in reality emissions fluctuated; 320.0 mg CO_2 m^{-2} h^{-1} as its minimum at 7:20 h and 356.4 mg CO_2 m^{-2} h^{-1} as its maximum at 17:30 h, respectively (Fig. 5a1). At the SS site, the minimum and maximum values were 2182.75 mg CO_2 m^{-2} h^{-1} at 6:30 h and 2981.09 mg CO_2 m^{-2} h^{-1} at 14:55 h, respectively (Fig. 5a2). Based on this information, the daily average efflux came from the measurements around 12:00 h. Thus we recommend that the measurements should be carried out between 11:30 and 13:30 h with a sampling error of 0.60%. The appropriate time during the day at the SS site was around 11:00 h. We recommend that the measurements should be carried out between 10:00 and 12:00 h with a sampling error of 3% ($n = 480$) and another time during the night was between 20:00 and 22:00 h with a sampling error of 2% ($n = 480$). Thus at both sites it can be said that the appropriate measurement timing is during noon.

In conclusion, we demonstrated that the quantified soil CO_2 emissions could be significantly different when different methods are employed. Within the site, the difference may arise from the combination of timing and frequency of measurements and the responses of soil CO_2 emissions to environmental drivers such as rainfall event. Between the sites, this difference may come from site activities that affect soil gas transports. At the SS site where frequent disturbances such as irrigation, field, and crop maintenance occur, measurements of soil CO_2 emissions may be biased. In such case, continued measurements after crop harvest may be necessary as large amounts of soil CO_2 remain trapped in the soil. At a less disturbed site such as DFR, both sensor and chamber methods agreed with each other reasonably well. However, appropriate timing in a day and sufficient measurement frequency should be determined to improve the accuracy of the emission estimate.

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