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Measurement of Soil CO_2 Efflux Using a Closed Dynamic Chamber System

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폐회로 역학 챔버 시스템을 이용한 토양 이산화탄소 플럭스 관측

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ABSTRACT

Soil CO_2 emission is one of the primary components in carbon balance of terrestrial ecosystems. To accurately assess their net ecosystem exchange of CO_2 and net primary production, measurement of soil CO_2 efflux is required along with that of canopy CO_2 flux. In this paper, soil CO_2 flux measurement technique using closed dynamic chamber systems is briefly reviewed. Preliminary results on soil CO_2 exchange and inter-comparison of different measurement systems currently used in Korean regional network of tower flux measurement sites (KoFlux) are also reported.

Key words : **soil CO_2, flux, chamber method, forest, rice paddy, KoFlux**

I. INTRODUCTION

Soil CO_2 efflux is produced by the respiration of root, microbes and soil fauna, and by chemical oxidation of carbon compounds and can be the second largest component of ecosystem carbon balance (Valentini *et al.*, 2000). Quantification of its magnitudes and assessment of its controlling factors are therefore prerequisites for an accurate estimation of ecosystem carbon budget and partitioning.

There are several methods available for measuring soil CO_2 efflux, with large differences in accuracy, spatial and temporal resolution, and applicability. Naturally, uncertainties are involved in the measured efflux by employing different measurement techniques and instruments. For many decades, soil CO_2 efflux has been typically measured using chambers covering soil surface. Chamber method is broadly classified with either static or dynamic systems. The former includes methods of Alkali, Soda lime and Syringe; whereas the latter includes closed and open chambers with dynamic flow controlling system (e.g., Norman *et al.*, 1997; Longdoz *et al.*, 2000; Davidson *et al.*, 2002).

Static chamber systems tend to overestimate small

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fluxes and underestimate large fluxes (Nay *et al.*, 1994; Yim *et al.*, 2001) and to underestimate when compared with closed dynamic chamber systems (Norman *et al.*, 1997; Janssens *et al.*, 2000). One of the main advantages of using closed static chambers, however, is that the fluxes of several gas species can be measured simultaneously. Recently, open and closed dynamic chamber systems have been widely used. Open chamber systems are extremely sensitive to pressure difference between the chamber and the atmosphere (Rayment and Jarvis, 1997; Lund *et al.*, 1999). Closed systems are usually equipped with venting tube to minimize leakage (Norman *et al.*, 1992; Welles *et al.*, 2001), and tend to slightly underestimate when compared to open systems (Norman *et al.*, 1997; Rayment and Jarvis, 1997; Longdoz *et al.*, 2000; Rayment, 2000). On the other hand, Longdoz *et al.* (2000) argued that open systems underestimated the efflux because perturbation of the horizontal wind velocity distribution did not lead to dramatic variations of the soil CO_2 efflux. So far, only closed chamber systems have been available commercially (e.g., LI-COR 6000-09 and LI-COR 6400, LI-COR Inc., Lincoln, Nebraska; PP Systems SRC-1 and EGM-2, PP Systems, Hertfordshire, U.K) partly because of difficulties in avoiding measurement artifacts generated by pressure perturbation.

We have conducted soil CO_2 efflux measurements using closed chamber systems along with continuous micrometeorological canopy CO_2 flux measurements at the selected KoFlux sites. The objectives of this study were to reassess soil CO_2 efflux measurement procedures that would minimize errors involved in chamber measurement and to report the results from our pilot experiments over forest floors and agricultural fields in Korea.

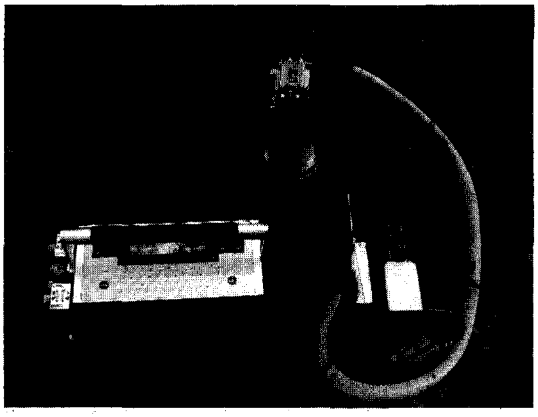

Fig. 1. Closed dynamic chamber system (LI-COR 6000-09 and LI-COR 6400-09, LI-COR Inc., Lincoln, Nebraska) and soil temperature (LI-6000-09TC, LI-Cor, Inc.) and soil moisture content (Hydro Sense, Campbell Scientific, Inc.).

II. MATERIAL AND METHOD

2.1. Closed dynamic chamber system

In a closed dynamic chamber system, the flux is calculated from the rate of increase of CO_2 concentration in the chamber headspace of known volume shortly after the chamber is placed over the soil or collar. At KoFlux sites, we used two types of closed dynamic chamber systems with infrared gas analyzers (IRGAs) for CO_2 quantification. One of these systems is a potable leaf photosynthesis measuring system attached to a soil chamber (Model LI-6400, fitted with 6400-09 Soil Respiration Chamber, LI-COR, Lincoln, NE) (Fig. 1). The mass balance of CO_2 for the soil chamber is given by

$$sf_c = \rho v \frac{\partial c}{\partial t} + \mathrm{uc} \qquad (1)$$

(CO_2 In=Storage+CO_2 Out)

where s is the soil surface area (m^2) enclosed by the chamber, v is the volume (m^3) of the chamber and IRGA, f_c is the flux of CO_2 coming out of the soil surface (mol CO_2 $m^{-2}s^{-1}$), ρ is the density of the air (mol m^{-3}), c is the CO_2 concentration (mol CO_2 mol^{-1}), and u is the flow rate (mol s^{-1}) of escaping air from the system, largely due to soil evaporation into the system (LI-COR, 1997). The final flux, Fc, is calculated in μmol m^{-2} s^{-1}.

The chamber has a perforated manifold for mixing the chamber air and a pressure equilibration tube. The pressure difference between the inside and the outside of the chamber becomes negligible by using the pressure relief vent tube, which keeps the pressure in the chamber headspace in equilibration with atmospheric pressure. During measurements, the pressure differentials are around 0.02Pa, which are within the noise level of the pressure sensor (Welles *et al.*, 2001).

The other closed dynamic chamber instrument is PP Systems SRC-1 (PP Systems, Hertfordshire, U.K). This soil chamber is connected to EGM-2 CO_2 analyzer (infrared gas analyzer, PP Systems, Hertfordshire, U.K). The theory of calculation of soil respiration is given by

$$R = \frac{(Cn - Co)}{Tn} \times \frac{V}{A} \tag{2}$$

where R is the soil respiration rate (in g CO_2 per unit area per unit time), Co is the concentration at T=0 and Cn is the concentration at a Tn later, A is the area of soil exposed and V is the total system volume (PP Systems, 1993). The measurement unit of this system is g CO_2 m^{-2} $hour^{-1}$. Prior studies reported that SRC-1 system tended to overestimate soil CO_2 fluxes when compared to those from other systems (Norman *et al.*, 1997; Law *et al.*, 2001).

2.2. Study sites

Flux measurements were conducted at two forest floors, rice paddy and farmland during September and October in 2001 and July in 2002. The two forest sites, located in Kwangneung (37°44'N, 127°9'E, 340 m m.s.l) in Korea, are hardwood forest (H site) and mixed forest (M site). Both sites are located within 1 km as a part of the KoFlux network of micrometeorological tower flux measurement (Kim *et al.*, 2002, Choi *et al.*, 2003). Hardwood forest is an old natural forest (80 - 200 years) whereas the mixed forest is a younger plantation (70 - 80 years). In terms of species composition, H site is dominated by *Quercus serrata* and *Carpinus laxiflora* while M site is predominantly *Pinus koraiensis, Quercus Mongolia, and Quercus serrata.* Soil types are loam (including small pebbles) and silt loam with abundant humus at the H and M sites, respectively. The rice paddy and the farmland sites are located, respectively, at Hari (37°4'N, 126°2'E) (Moon, *et al.*, 2003) and at Haenam (34°5'N, 126°5'E) (Lee *et al.*, 2003) in west central and southwestern part of Korea. The soil types are the silt loam in surface soil (0 - 20 cm), and the silt in deep soil (20 cm - 40 cm) for the rice paddy and clay loam for the farmland site. Due to irrigation management in the paddies, the averaged depth of floodwater ranged from 0.04 to 0.10 m. The standing water in the paddy field usually absorbs CO_2 from the soil surface, resulting in negligible CO_2 emission from the water column. Hence we measured soil CO_2 efflux from the paddy site just before the harvest when there was no standing water above the ground.

2.3. Measurement

2.3.1. Measurement location

For soil CO_2 efflux measurement, we selected location and size of the plot, which can be related to the micrometeorological tower flux measurement in the context of flux footprint. Typically, the size of flux footprint depends on wind direction, atmospheric stability and surface roughness. The number of sampling points and the plot size further depends on the spatial heterogeneity of soil/vegetation distribution, ecophysiology and site topography (Yim *et al.*, 2002). Spatial variations in soil CO_2 emission are associated with those of fine root biomass, surface litter and humus amount and soil porosity at the site. The plot size (and direction) was 15 m×30 m (NE), 15 m×30 m (SE), and 10 m×10 m (SW and NE), which were aligned with the prevailing wind direction at H site (1 plot), M site (1 plot) and rice paddy site (2 plots), respectively. The vegetation cover in the farmland in Haenam includes various crops (e.g., sesame, bean, sweet potato and Indian millet) and bare soil. We randomly selected measurement points mainly on bare soil for intercomparison of the two different systems.

2.3.2. Collar installation

In the field, chambers can be either inserted directly into the soil or used with collars that are inserted into the soil prior to measurements. When inserting the chamber directly, soil surface can easily be disturbed. Therefore, it is better to allow at least half an hour after insertion before making the first measurement. By using pre-installed soil collars, one can minimize disturbance of soil surface and make repeated measurements on any collars. In our measurements, PVC collars (0.08 m high, 0.106 m diameter) were installed in the soil surface several days in advance. Collars were inserted about 0.02 to 0.04 m into the soil layer. Some measurement points were installed with higher collars (0.1 m high) because of the presence of thick humus and litter layer in forest. The vegetation was removed from inside the collars but surface litter was retained within the collars. Foam gasket rings are used as an airtight seal between the chamber and the collars. On the average, soil CO_2 efflux measured 24 hours after the collar installation was 4% lower than that made one hour after at similar soil temperatures (Norman *et al.*, 1997).

2.3.3. Sampling procedure

Before making actual measurements, IRGA was warmed up and calibrated under the targeted environmental conditions. When the chamber system was ready, we determined the ambient CO_2 concentration near the soil surface at each collar (i.e., target CO_2 concentration). Then, based on the expected magnitudes of CO_2 efflux, the measurement range for increasing CO_2 concentration was placed. The surface area and the depth of each collar were documented and then the chamber was gently placed on the collar. At this stage, care was exercised to avoid contamination of the sample with high CO_2 concentration of the observer's exhalation. In order to obtain statistically meaningful data, measurements were repeated three times for each collar.

2.3.4. Measurement of environmental factors

Soil CO_2 efflux is dependent on conditions of vegetation, soil and the atmosphere. Among other things, soil temperature, organic matter content, moisture content (associated with precipitation and evaporation) and soil physical properties are the primary controlling factors. In particular, soil temperature is the most predominant factor affecting temporal and spatial variability of soil CO_2 efflux (e.g., Kim and Verma, 1992; Fang and Moncrieff, 2001; Rey *et al.*, 2002). Other factors can become more significant under special periods or conditions (e.g., drought, fertilization). We measured soil temperature (LI-6000-09TC, LI-Cor, Inc.) and soil moisture content (Hydro Sense, Campbell Scientific, Inc.) for the 0.1 m soil layer. Also, we analyzed organic matter content along with other chemicals (e.g., C, N, pH) and physical properties (e.g., porosity, bulk density) of soil from the collars.

III. RESULTS AND DISCUSSION

3.1. Forests

Soil CO_2 efflux was measured at 10 sampling locations for both H and M sites on 14-15 and 21-22 September 2001, respectively. Diurnal variation of soil CO_2 efflux was measured for each site during these two day period. Each data point in Figs. 2 and 3 represents a mean

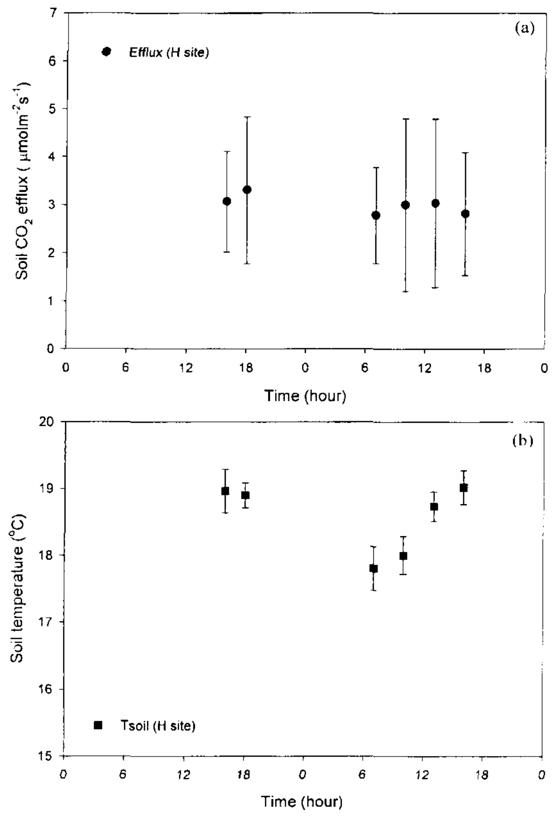

Fig. 2. Diurnal variation of soil CO_2 efflux (a) and soil temperature (b) in hardwood forest site (H site), Sept. 14 and 15.

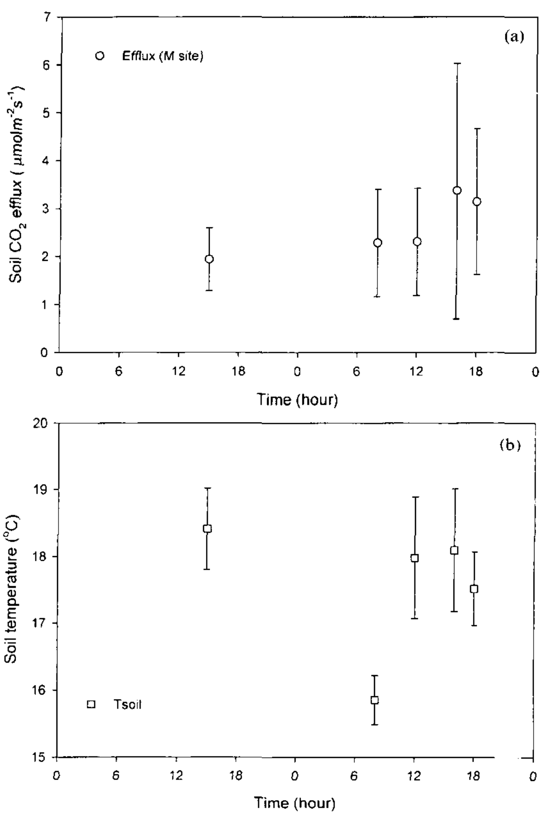

Fig. 3. Diurnal variation of soil CO_2 efflux (a) and soil temperature (b) in Mixed forest site (M site), Sept. 21 and 22.

value of 10 sampling locations. Soil CO_2 efflux at H site varied from 1.5 to 5.0 μmol $m^{-2}s^{-1}$ (with a daily mean of 3.0 μmol $m^{-2}s^{-1}$) but did not show any discernable diurnal pattern for these two days, likely due to small diurnal changes in soil temperature (<1°C). At M site, soil CO_2 efflux ranged from 0.8 to 6.0 μmol $m^{-2}s^{-1}$ (on average, 2.6 μmol $m^{-2}s^{-1}$) and again the diurnal changes in soil temperature was <2°C. The coefficient of variation for the measured soil CO_2 efflux was very large (i.e., 47% for H site and 52 % for M site), suggesting that factors other than soil temperature were responsible for such spatial variability. Currently, more comprehensive and systematic measurements such as the profiles of soil CO_2 concentration, moisture and temperature are being implemented at these sites to better understand these processes (e.g., Tang *et al.*, 2003).

3.2. Rice paddy

Soil CO_2 efflux in rice paddy was measured on 20 and 26 September 2001, before harvest. When irrigated, the standing water in the paddy field suppressed the CO_2 emission, resulting in insignificant amount of CO_2 efflux. We, therefore, measured the efflux when the soil surface was dry. Daytime soil CO_2 efflux, measured at 11 sampling locations, ranged from 2.0 to 3.8 μmol $m^{-2}s^{-1}$ with a mean value of 2.7 μmol $m^{-2}s^{-1}$ (Fig. 4). Overall, soil moisture content was similar (30 - 40%) for these two days. However, soil temperature was higher on 20 September, resulting in higher rate of soil CO_2 emission. We noted that CO_2 emission from the collar No. 3 and 8 were much greater than from other collars for both days. Usually, greater efflux is related to higher soil temperature and/or higher soil moisture content. However, a careful examination of Fig. 4 indicated that this was not the case here. Firstly, at collar No. 3, both days showed markedly higher effluxes than other neighboring days although both soil temperature and moisture content did not show any significant difference. It was also worth noting that effluxes on 20 September was much greater than those on 26 September whereas both soil temperature and moisture content were higher on 26 September. Secondly, at collar No. 8, both days released soil CO_2 at the highest rates among all 11 collars. However, both soil temperature and moisture content at this collar were no different from those from other collars except moisture content on 20 September. Furthermore, despite much lower soil temperature and moisture content on 26 September, effluxes on this day were quite comparable to those on 20 September. Uncertainties in our measurements could have caused such confounding results. However, relatively small values of CV (~20%) again suggest that factors other than soil temperature or moisture might have played a role here.

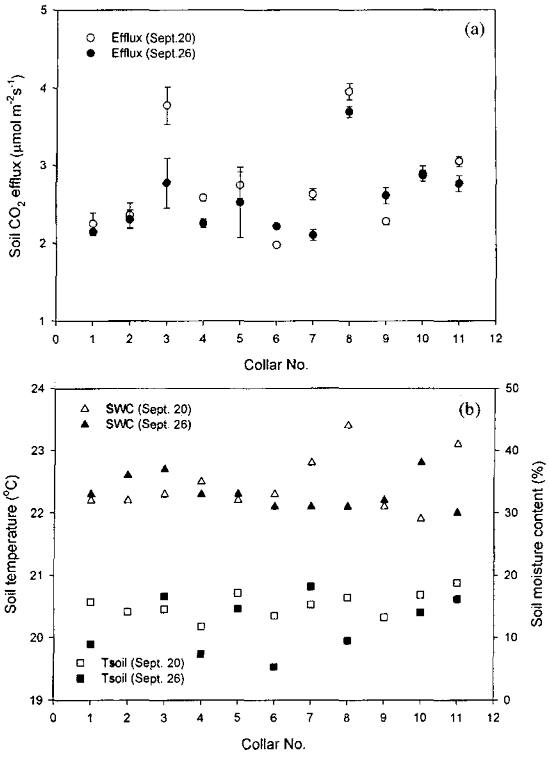

Fig. 4. Soil CO_2 efflux (a), soil temperature and soil moisture content (b) for each sampling point in rice paddy, Sept. 20 and 26.

3.3. Farm land

On 31 July 2002, we inter-compared three closed dynamic chamber systems (i.e., one LI6400 and two SRC-1) in a farmland in Haenam, Korea. During this field inter-comparison, five sampling locations were selected on bare soil surface and the CO_2 efflux was measured along with soil temperature. Unfortunately, collars were not used in this experiment. Despite several shortcomings of this field experimental design, the comparison results revealed some interesting insights. Among five locations, only one location (i.e., #3) showed good agreement in soil CO_2 emission among the three systems (Fig. 5). On average (using all the data from five locations), soil CO_2 efflux from SRC-1(1), SRC-1(2) and LI6400 were 2.8, 3.3, and 4.3 μmol

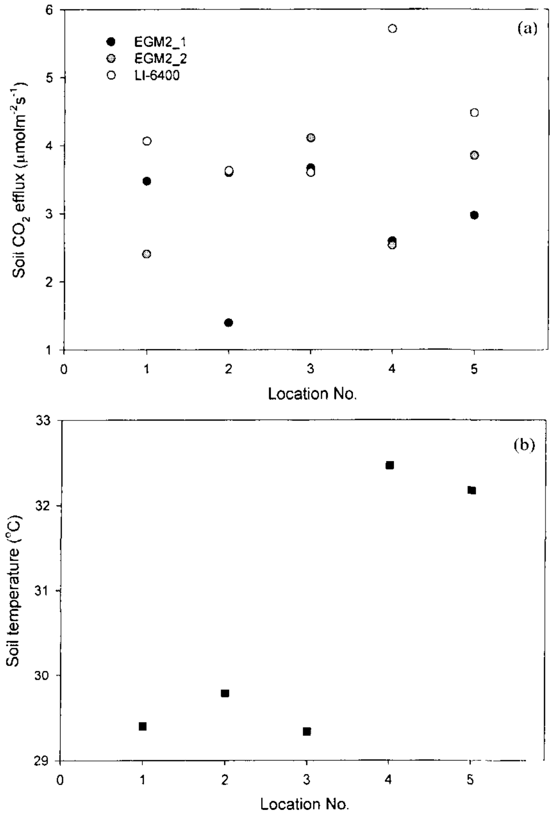

Fig. 5. Inter-comparison of three closed dynamic chamber systems (LI6400 and two SRC-1(EGM-2)) (a) soil temperature (b) for bare soil, July 31.

m^{-2} s^{-1}, respectively for averaged soil temperature of 31°C. The two SRC-1 systems agreed well only at location #4 but showed differences of 20% to 300% at other locations. Furthermore, the patterns and magnitudes of disagreement between the two were inconsistent. Other feature worth noting is the temperature responses of the measured effluxes from the three systems. Both SRC-1 systems were insensitive to changes in soil temperature of up to 6°C, whereas LI6400 system well reflected such changes in the measured soil CO_2 efflux.

IV. Summary

Measurements of soil CO_2 efflux were made with a closed dynamic chamber connected to infrared gas analyzers at forests, rice paddy and farmland, along with concomitant measurements of controlling variables such as soil temperature and moisture content. Despite the short measurement period, soil CO_2 efflux from each ecosystem was diverse with a range of 1 to 6 μmol m^{-2}s^{-1}. Even within the same ecosystem, changes in soil CO_2 efflux from different collars were difficult to explain in terms of concurrent changes in major controlling variables. Two types of chamber systems currently used in KoFlux sites were intercompared and the results showed both potential instrumental bias between the systems and large uncertainties in fluxes associated with spatial variability of plants and soil at the sites. To estimate spatially representative soil CO_2 efflux, systematic approach (integrating models, geographic and remote sensing information) is required along with laboratory experiment on field soil samples to better understand the exchange mechanism.

적 요

토양으로부터의 CO_2 방출은 생태계의 탄소 순환에 중요한 위치를 차지한다. 주요 생태계의 순 CO_2 교환과 일차 생산량 등을 정확히 산출하려면 군락 CO_2 플럭스와 더불어 토양 CO_2 플럭스의 관측이 함께 이루어져야 한다. 본 논문에서는 닫힌 역학 챔버 시스템을 활용한 토양 이산화탄소 플럭스의 관측 방법을 간략히 검토하고, 한반도 주요 생태계에 구축된 한국 타워 플럭스 관측 지역망(KoFlux)의 거점 관측소에서 예비 관측된 결과와 서로 다른 관측 시스템간의 상호 비교 결과를 보고하고자 한다.

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