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Estimating Surface CO_2 Flux Based on Soil Concentration Profile

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Authors' contributions

This work was carried out in collaboration between all authors. First author performed the measurement at the field, data analysis and drafted the manuscript. Second author checked the consistency of the data, proofread, and managed the flow of the drafted manuscript. The third author helped in setting experimental and field work. All authors have read and approved the final manuscript.

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ABSTRACT

Aims: To estimate the surface CO_2 flux derived from CO_2 concentration profiles and to validate the results by previous data of surface CO_2 flux obtained from the measurements using close-chamber method.
Study Design: The measurement of soil CO_2 concentration profile, soil properties, and soil temperature was carried out to estimate surface CO_2 flux using the derived model of mass balance equation. The results were subsequently compared with measurements of surface CO_2 flux using close-chamber method.
Place and Duration of Study: INAS field located in Ito Campus of Kyushu University (Japan) from November 2015 to March 2016.
Methodology: CO_2 gas was sampled in four different depths to analyze its concentration within the soil layer. Soil temperature was monitored throughout the measurement and soil properties such as density, porosity and moisture content were measured as well to estimate the diffusion rate. Derived from mass balance equation, the surface CO_2 flux was estimated. It was validated using the previous measurement data of surface CO_2 flux using close-chamber method that had been conducted formerly at the same location.
Results: A total of seven measurements of soil CO_2 concentration profile showed that the CO_2 concentration increased with soil depth and it was fitted with logarithmic trend (R^2 = 0.981 in average). A range of CO_2 concentration values was measured at each depth, i.e., 1300 to 8700 ppm at 0.1 m depth; 2500 to 10800 ppm at 0.2 m depth; 4200 to 13200 ppm at 0.3 m depth; and

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5800 to 16500 ppm at 1.0 m depth. High CO_2 concentration in 0.1 m soil depth indicated high surface CO_2 flux.

Conclusions: Soil CO_2 concentration in INAS field increased following a logarithmic trend. Based upon this trend, an equation to estimate the surface CO_2 flux was proposed using derived model from mass balance equation and gas diffusion model. The estimated surface CO_2 flux was compared and showed a good agreement with measured one. The equation presented herein is potentially suitable to estimate the surface CO_2 flux.

Keywords: CO_2 concentration profile; logarithmic trend; surface CO_2 flux; close-chamber method; INAS field.

1. INTRODUCTION

Carbon dioxide (CO_2) emission from soils is one of the important parameters contribute to the carbon cycle on the Earth because soil is the biggest carbon pool in terrestrial land [1]. It contributes around three-quarters of the CO_2 total ecosystem respiration [2]. Emitted CO_2 can be estimated by measuring its flux on the soil surface or in this paper defined as surface CO_2 flux. CO_2 flux from the soil is determined by two major processes [3] including the generation of CO_2 within the soil, and its transport in the soil and the emission to the atmosphere. The source of the soil CO_2 production is primarily originated from root respiration, decomposition of organic matter, atmospheric infiltration, magmatic degassing, or the metamorphosis or dissolution of carbonate [4]. On the other hand, its transport to the surface is controlled by several factors such as physical properties of the transport media (soil), climate conditions (temperature, rainfall, wind speed, etc), and many other factors. Nevertheless, both the soil temperature and soil water content are reported to be the key factors acting upon surface CO_2 flux [3,5]. The former parameter is the interest of this work.

Some studies have shown that soil CO_2 concentration increases with depth [7-10]. Turcu et al. (2005) carried out a laboratory experiment and showed that the CO_2 concentration increased linearly with depth. Tang et al. (2003) continuously measured the CO_2 gas concentration at an oak-grass savanna and found that it linearly increased with the depth, up to 16 cm. An experimental study of snowpack by also showed the same trend [11]. In this case, the concentration profile increased linearly up to 1.0-m depth. Davidson et al. (2006) showed that CO_2 gas concentration exponentially increased with depth, having varying trends, depending on seasonally sensitive parameters such as soil temperature and moisture content [12]. The different fitting trends observed in the soil gas concentrations with depth affects the governed models used to estimate the surface CO_2 flux. Therefore, in this work, we measured soil CO_2 concentration profiles in order to estimate surface CO_2 flux using derived model based on mass balance equation.

2. STUDY LOCATION AND MEASUREMENT METHODS

2.1 Field Location

The field measurements of CO_2 concentration profiles were carried out at INAS test field (Fig. 1). This is located on the west side of the Ito Campus of Kyushu University. It has an altitude of 74 m above sea level. It is currently covered by grass, having no trees around. The soil layer is up to 3.0 m thick [13].

The official website of the Japan Meteorological Agency (JMA) provides historical weather data. Weather data from 2000 to 2016 show that the annual mean temperature was 17.4°C, while the maximum and minimum monthly temperatures were around 32.6°C in August and 3.7°C in January, respectively. The monthly average temperature in 2015 ranged from 7.6°C in February to 27.4°C in August with an annual mean temperature of 17.3°C. Fig. 2 shows that the daily maximum and minimum temperatures measured during the eight days undertaken during this study, as well their values recorded at the Fukuoka Station (World Meteorological Observation Station ID:47807; 33°34'9"N, 130°22'5"E). The highest and lowest monthly precipitation amounts were 319.5 mm in August and 42.5 mm in February, respectively. Total precipitation was 1867.5 mm year-1 throughout the year, including slight snowfall.

At the INAS test field, two boreholes of 113 m and 100.5 m in depth were drilled in 2010, as well as three holes of 19.5 m in depth to monitor CO_2 release [14]. The soil CO_2 concentration ranged from around 400 ppm at the surface to thousands of ppm in the shallow soil layer. The location selected for monitoring in this study was about 2 m in the distance from the 100.5-m wells.

Fig. 1. Location of INAS field. (a) a map showing the context of the INAS field location on Kyushu Island, Japan; (b) location of the INAS field on Ito Campus of Kyushu University (red circle); (c) field condition and boreholes location at the INAS field (red circle); and (d) image showing CO_2 sampling using an air pump and gas bag

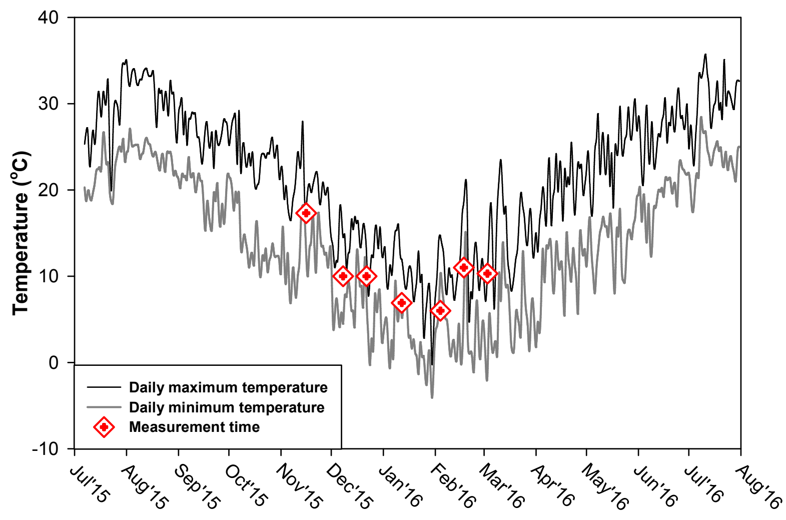

Fig. 2. Seven days of field measurements of CO_2 concentration profiles at the INAS test field, along with daily maximum and minimum temperature

2.2 Field Measurement of Soil CO_2 Concentration Profile

Soil CO_2 gas concentration and its flux are required to quantify CO_2 emissions from the ground surface to the atmosphere. CO_2 concentration profiles in the soil were measured at the INAS test field. A borehole, 10 cm in diameter was drilled to carry out the measurements of the soil CO_2. A vertical casing pipe was fitted within the well and four vinyl tubes, 10 mm in diameter, were connected to the sampling holes, perpendicular to the inner wall of the pipe at depths of 0.1, 0.2, 0.3 and 1.0 m from the surface (Fig. 3). Soil gases were sampled into a 1.0 l gas bag at these four levels using an air pump having a low suction speed of less than 1 cc s^{-1} to prevent convection flow within the soil. The soil gases were analyzed in the laboratory using a CO_2 gas analyzer (LI-840A; Li-Cor, Lincoln, NE, USA). In this study, we assumed that the CO_2 concentration from the gas bag was treated as the average value of soil gas at each depth.

2.3 Models of Surface CO_2 Flux and CO_2 Diffusion Coefficient of the Soil

CO_2 concentration in a given soil layer is dependent the mass balance between the CO_2 produced within the layer and the CO_2 diffused into it from other layers. If we assume C_s (mol m^{-3}) is the soil CO_2 gas concentration at time t (h) and depth z (m), S (mol m^{-3} h^{-1}) is the CO_2 production in the soil and F (mol m^{-2} h^{-1}) is the soil CO_2 flux, then a 1-dimensional CO_2 mass balance can be expressed as Eq. (1).

$$\frac{\partial C_s}{\partial t} = \frac{\partial F(z)}{\partial z} + S(z) \quad (1)$$

where $\frac{\partial C_s}{\partial t}$ is the unsteady term for CO_2 concentration in the soil. In this study, a steady state situation was assumed. Soil depth (z) is defined as positive, in a downward from the surface.

$$\frac{\partial F(z)}{\partial z} = -D_s \frac{\partial^2 C_s}{\partial z^2} \quad (2)$$

D_s (m^2 h^{-1}) is the gas diffusion coefficient in the soil, which is a function of the soil properties, and is expressed in terms of the effective gas diffusion coefficient, η (-), given in Eq. (3), and its variation with temperature and pressure, as defined in Eq. (4) [15].

$$D_s = \eta D_a \quad (3)$$

$$D_a = D_{a0} \left(\frac{T_s}{T_0}\right)^{1.75} \left(\frac{P_0}{P}\right) \quad (4)$$

Thus, D_a ($m^2.h^{-1}$) is the diffusion coefficient in free air and D_{a0} is the value under standard conditions, 5.004 ẋ 10^{-2} m^2 h^{-1} for CO_2 at standard temperature and pressure (T_0 = 273.15 K; P_0 = 101.3kPa). T_s (K) is soil temperature, while P is assumed to be equivalent to P_0, until 1 m soil depth.

The CO_2 diffusion coefficient is one of the major parameters used to estimate the gas flux in the soil. It is determined by the physical properties of the soil, such as its dry density, porosity, water-filled porosity and gas-filled porosity. In this study, we estimated the diffusion coefficient using Moldrup et al., (1997), as written below. This model of diffusion rate was the best fitted with measurement results compared to other models [16].

$$\eta = 0.66(\phi - \theta)\left(\frac{\phi - \theta}{\phi}\right)^{\frac{12-m^*}{3}} \quad (5)$$

*m = 3 for undisturbed soil and m = 6 for disturbed soil

where ϕ (m^3 m^{-3}) is soil porosity and θ (m^3 m^{-3}) is the volumetric water content.

This model of diffusion rate was found to suit best our measurement results comparatively to other available models [16]. With the knowledge that the porosity refers to the void pores in the soil capable of being filled with water (and/or gas), it can be conjectured that a high porosity medium with lower moisture content will result in high gas diffusivity compared to higher moisture content with same porosity or lower porosity medium with same moisture content condition (Fig. 4).

2.4 Soil Physical Properties of the Field

In the field, soils were sampled from the surface as well as from within boreholes to determine their density, moisture content, and porosity. Moisture content was measured by heating the soils in an oven at 105°C for 24 hours. Dry density was calculated based on dry weight and soil volume. Soil porosity was estimated from the dry density using Eq. (6).

$$\phi = 1 - \frac{\rho_d}{\rho_p} \quad (6)$$

where ϕ (m^3 m^{-3}) is soil porosity and is evaluated using dry density, ρ_d (kg m^{-3}) and the particle density for a mineral soil (ρ_p = 2560 kg m^{-3}).

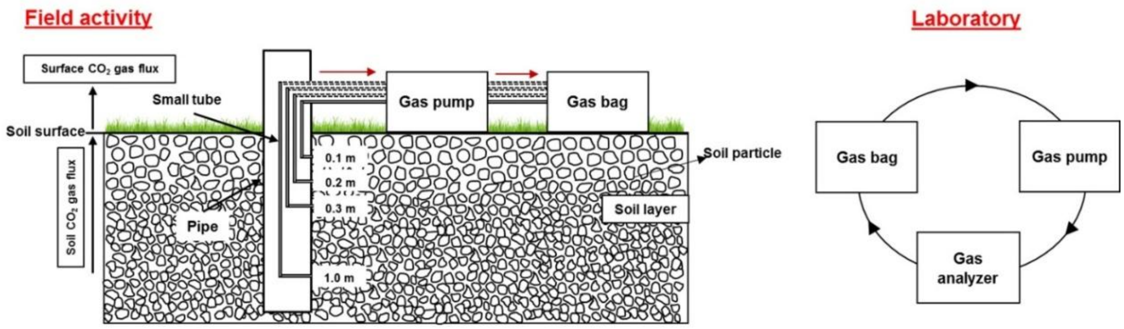

Fig. 3. Field measurement method of soil CO_2 concentration profiles using a gas pump and gas bag at INAS test field, and laboratory measurements with a CO_2 analyzer

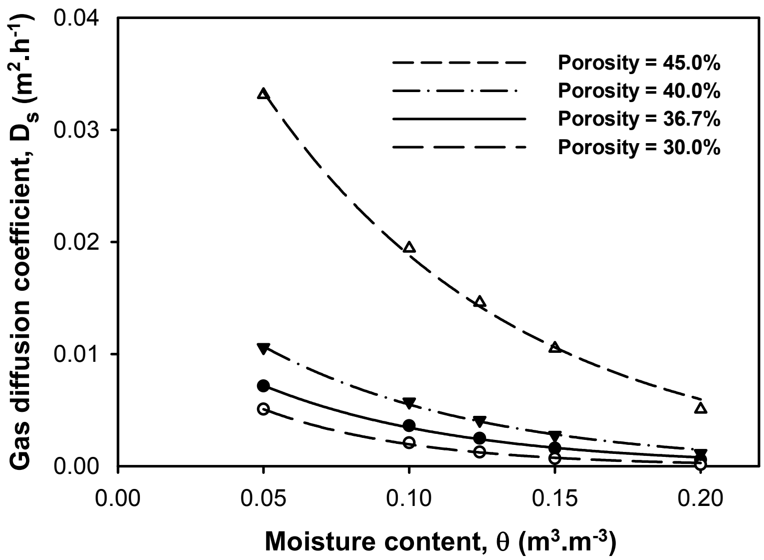

Fig. 4. The effects of moisture content and soil porosity on the gas diffusion coefficient, as calculated by the models of Moldrup et al. (1997)

Table 1. Physical properties of the soil at INAS field during measurements

Parameter	Symbol	Unit	Soil*
Dry density	ρ_d	Kg m^{-3}	1530 – 1695 (1620)
Moisture content	θ	m^3 m^{-3}	0.092 – 0.157 (0.124)
Porosity	ϕ	m^3 m^{-3}	0.338 – 0.402 (0.367)

**range (average value)*

3. RESULTS AND DISCUSSION

In the field, measurements of soil CO_2 concentration were carried out from November 2015 to March 2016 (Fig. 2). The CO_2 concentration profile up to 1.0 m depth followed a logarithmic trend with R^2 = 0.981 on average (Table 2) and was generalized in Eq.7. A range of values was measured at each depth, i.e., from 1300 to 8700 ppm at 0.1 m depth; 2500 to 10800 ppm at 0.2 m depth; 4200 to 13200 ppm at 0.3 m depth; and 5800 to 16500 ppm at 1.0 m depth.

$$C_s(z) = y_o + a\ln(z - z_0) \tag{7}$$

where a, y_0 and z_0 were coefficients estimated by the logarithmic regression. Based on Eq. 2, the surface CO_2 flux could be estimated using Eq. 8,

$$F_0 = -D_s a \frac{1}{z_0} \quad (8)$$

CO_2 concentration profiles for the INAS field are shown in Fig. 5. The soil respiration changed seasonally as a function of the soil temperature, affecting thereby the CO_2 concentration profile [17,18]. High CO_2 concentration in the near surface (up to 0.3 m depth) was observed in November 2015, when soil temperature was still high (17°C on average), and also in March 2016, when the growing season began [19]. The lowest CO_2 concentration was recorded in February, presumably because of the decrease in the microbial activity or root respiration, as soil temperature was minimal (daily mean temperature was 7.4°C on average in February, while daily total precipitation was at its lowest, about 3.0 mm on average). Evidently, the high CO_2 concentration hints at a higher gas production concurrently with a low diffusion rate [20, 21].

Based on Eq. 8 and the values of *a* and z_0 from logarithmic regression of soil CO_2 concentration profile, the estimated surface CO_2 flux was shown in Table 2. The surface CO_2 flux was found higher when soil concentration was higher as well, especially in 0.1m soil depth. High CO_2 concentration in 0.1 m soil depth indicated high surface CO_2 flux because most of the surface CO_2 gas flux was delivered from the shallow surface, 76.3% of it mostly from 0 to 15 cm soil depth [21] and more than 75% of it was originated from 20 cm soil depth [22].

We used measured surface CO_2 flux to validate the estimated one. Surface CO_2 flux at INAS field had been measured using close-chamber method (Fig. 6). A hemispherical chamber, 10 cm in radius, was placed on the soil surface to trap the CO_2 emitted. Before starting the measurement, the chamber was opened to the air for 4 minutes to clear it. Then, the chamber was placed on the soil surface for 5 minutes. The gas inside the chamber was pumped and circulated using a vinyl tube, 10 mm in diameter, connected to an air pump and a gas analyzer to measure the CO_2 concentration. The gas was allowed to flow back to the chamber to ensure the chamber's internal pressure remained constant and to prevent gas diffusion.

The surface CO_2 flux was calculated based on the rate of the CO_2 gas increase inside the chamber, having a volume of 2090 ml and a contact surface area of 314 cm^2, as defined in Eq. (9).

$$F_0 = \frac{V}{A} \times \frac{dC_c}{dt} \quad (9)$$

where, F_0 (mol m^{-2} h^{-1}) is the surface CO_2 flux, C_c (mol m^{-3}) is the CO_2 concentration in the chamber, V (m^3) is the volume of the chamber, A is the surface area (m^2) covered by the chamber, and t (h) is time.

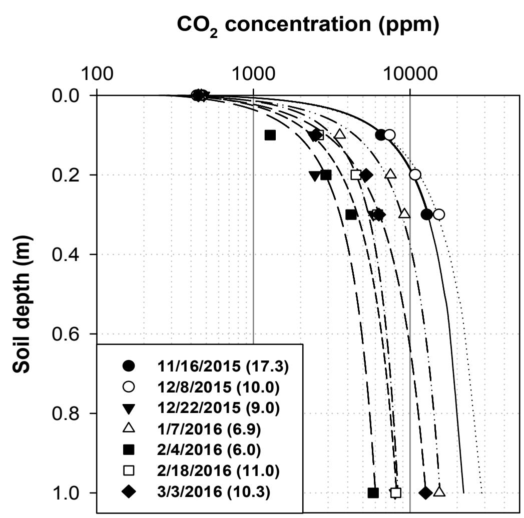

Fig. 5. Soil CO_2 concentration profiles at INAS test field. The measurement date and surface temperature are given in parentheses

Table 2. The values of *a*, z_0 and estimated surface CO_2 flux using Eq. 8

Measurement time	*a* (mol m^{-3})	z_0 (m)	Surface flux, F_0 (mol m^{-2} h^{-1})
16-Nov-15	0.395	-0.096	0.0101
8-Dec-15	0.699	-0.198	0.0087
22-Dec-15	0.170	-0.148	0.0028
7-Jan-16	0.302	-0.117	0.0064
4-Feb-16	0.108	-0.104	0.0026
18-Feb-16	0.120	-0.053	0.0055
3-Mar-16	0.336	-0.242	0.0034

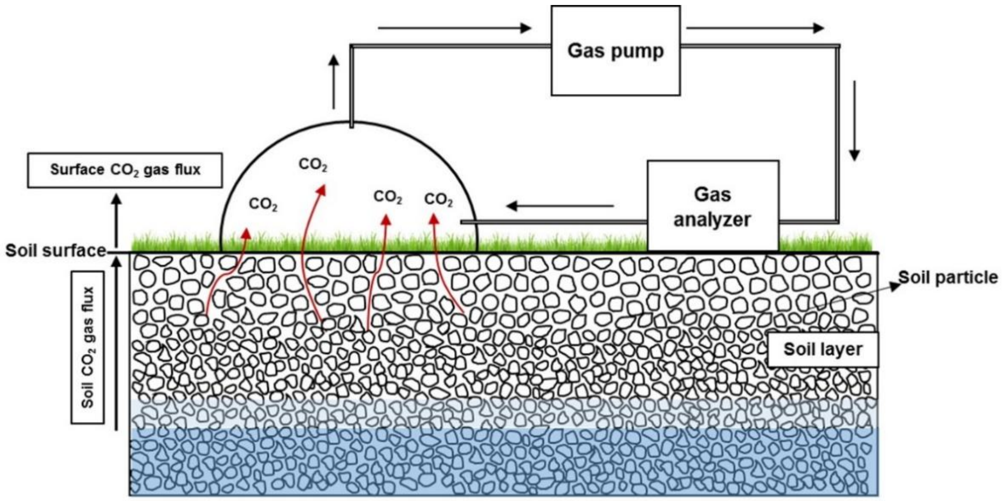

Fig. 6. Surface CO_2 flux measurement using the close-chamber method in the field

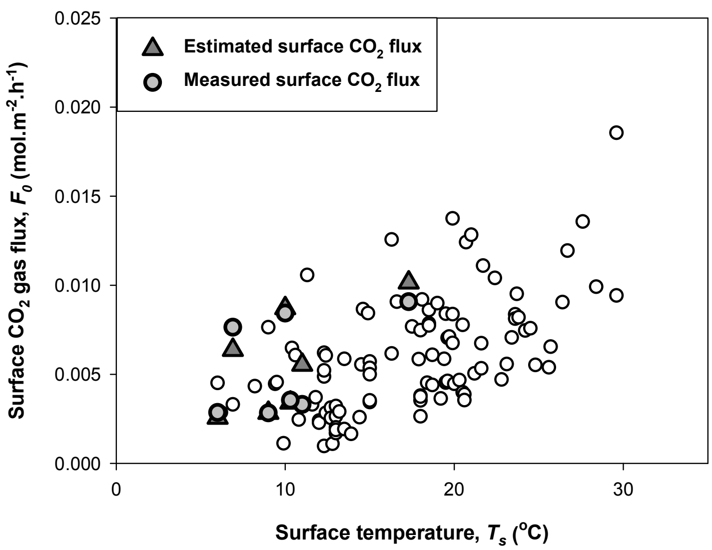

Fig. 7. Estimated and measured surface CO_2 flux with soil temperature (filled triangles are the estimated surface CO_2 flux derived from soil CO_2 concentration profile; open circles are the measured surface CO_2 flux while filled circles represent the one that measured with the same condition of soil CO_2 concentration profile)

From the 103 data measurement at the field using close-chamber method (Fig. 6). It was ranged from 0.00097 to 0.0186 mol m^{-2} h^{-1} with mean value of 0.006±0.0003 mol m^{-2} h^{-1} against increasing temperature from 6°C to 29.6°C (mean value of 17.4±0.5°C). These results showed a similar range in available literature [23]. In contrast, W. Kao & K.Chang (2009) and Pingintha et al. (2010) reported soil CO_2 flux having a lower value to ours [24,16].

Using the similar condition by considering soil temperature, we compared estimated surface CO_2 flux with measured one, as shown in Fig. 7. Our results concluded that estimated surface CO_2 flux using derived equation of logarithmic trend of soil CO_2 concentration profile, as written in Eq. 8, was acceptable in the INAS field.

4. CONCLUSIONS

Soil CO_2 concentration was measured in four different depths to estimate surface CO_2 flux in INAS field. The measurement results revealed that soil CO_2 concentration increased with soil depth following the logarithmic trend with R^2 =

0.981. Based on mass balance equation with some assumptions and using Moldrup et al., (1997) diffusion rate model to estimate the gas diffusion coefficient, an equation to estimate the surface CO_2 flux was proposed. Estimated surface CO_2 flux was compared and showed a good agreement with measurement results of surface CO_2 flux using close-chamber method. The equation presented herein is potentially suitable to estimate the surface CO_2 flux. Also, this work highlighted that high CO_2 concentration in soil, especially in 0.1 m depth, could indicate high surface CO_2 flux.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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