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Investigating the relationship between temperature and soil CO_2 emission according to paddy water condition**

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A b s t r a c t. The soil CO_2 emissions from rice paddy fields have a significant influence on net CO_2 fluxes throughout the year. Unlike other agroecosystems, rice paddy fields are flooded for most of the growing season. Over the course of this study, soil CO_2 emissions in rice paddy fields were observed under fallow, flooded, and drainage conditions using a closed-system portable chamber. It was found that the dried and bare soil in fallow paddy systems emit a significant amount of CO_2. On the other hand, the CO_2 released from the soil during flooding periods was suppressed by the water layer. In drainage conditions, the exponential curve of the relationship between soil CO_2 emissions and soil temperature was particularly evident. These results suggest that soil CO_2 emissions during fallow and drainage periods can exceed the level of CO_2 emissions that is suppressed under flooded conditions. However, immediately after draining or the occurrence of a rainfall event, the suppression of soil CO_2 emission by residual paddy water will provide valuable insights in the interpretation of agricultural carbon cycle models.

K e y w o r d s: paddy, soil CO_2 emission, fallow, flooded, drainage, temperature

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1. INTRODUCTION

Rice paddy fields are for the most part distributed in monsoon Asia (Haque *et al.*, 2015) and have multiple functions concerning the environment such as atmospheric cooling, flood alleviation, the prevention of soil erosion, and biodiversity conservation (Kim *et al.*, 2006; Bouman *et al.*, 2007). Furthermore, paddy ecosystems are associated with greenhouse gas emissions in agriculture to a significant extent (Min and Rulík, 2020).

The carbon exchange system between farmland and the atmosphere is greatly influenced by anthropogenic activities (*e.g.*, water management, manure input, and ploughing) (Smith *et al.*, 2014; Ahmed *et al.*, 2022). Unlike other agroecosystems, rice paddy fields are flooded for most of their growing season. Thus, most previous studies focused on assessing methane emissions from submerged paddies in anaerobic conditions (Cai *et al.*, 2007). However, carbon dioxide (CO_2) emissions occur in both aerobic and anaerobic soil conditions. In addition, while fallow paddy soil is dry or covered with other crops, soils can be submerged or drained during rice cultivation (Gwon *et al.*, 2019). Indeed, assessing soil CO_2 emissions is critical to understanding the carbon cycle in paddy ecosystems (Valentini *et al.*, 2000). However, it has rarely been investigated (Nishimura *et al.*, 2015).

Soil CO_2 emissions are a major source of carbon fluxes in agroecosystems (Zou *et al.*, 2007). Even though atmospheric CO_2 is sequestered by rice plants in paddy fields during the growing season, the soil affects carbon balance throughout all four seasons of the year. Soil organic matter is decomposed by soil microorganisms, this results in the emission of large amounts of CO_2 through both aerobic and anaerobic respiration (Lal, 2004). Such soil CO_2 emissions in paddies varies daily, seasonally, and annually (Valentini *et al.*, 2000), with the intensity of the emissions being governed by environmental factors such as soil temperature, water/moisture, pH, oxygen conditions, and soil organic matter (Luo and Zhou, 2010; Bond-Lamberty and Thomson, 2010; Kögel-Knabner *et al.*, 2010). Indeed, the estimation of soil CO_2 emission is generally calculated using soil temperature because of the substantial relationship between them (Fang and Moncrieff, 2001). The empirical relationship between soil CO_2 emissions and soil temperature will be useful in developing soil carbon modelling and in quantifying the amount of soil CO_2 emissions from rice paddy fields.

According to previous observation studies, both flooded and drainage/fallow conditions play critical roles in CO_2 emissions, particularly in paddies (Valentini *et al.*, 2000). Nishimura *et al.* (2015) showed that CO_2 emissions from paddy soil were suppressed during the submerged period but enhanced during the following drained period. Miyata *et al.* (2000) reported approximately 46% more CO_2 emissions from intermittent drainage than from continuous flooding. Similarly, others have reported about 24.84-32.39% (Tang *et al.*, 2018) and 47% (Haque *et al.*, 2016) higher CO_2 emissions under intermittent drainage conditions in paddy fields. However, the different responses of soil CO_2 emissions as they relate to soil temperature under flooded, drained, and dry soil conditions are still not fully understood (Liu *et al.*, 2013).

The aim of this study is to investigate the relationship between paddy soil CO_2 emissions and soil temperature with reference to dry conditions for the fallow period and flooded and drained conditions for the rice-growing period. Thus, this study observed the CO_2 emissions in rice paddy fields under various land conditions using a closed-system portable chamber for one year.

2. MATERIALS AND METHODS

This study was conducted in the rice paddy fields of the Jeollanamdo Agricultural Research and Extension Services (JARES), Naju City, South Jeolla Province, Republic of Korea in 2021 (35º 01′ 36.93″ N, 126º 49′ 18.92″ E; 21 m above sea level) (Fig. 1). The study site has a temperate monsoon climate, and receives hot and humid air from the sea in the summer and cold and dry air from the continent in the winter. The 30-year average annual, maximum, and minimum air temperature and precipitation were 13.6, 19.8, 8.6°C, and 1 310.4 mm, respectively; these data came from the Korean Meteorological Administration and represent the period between 1991 and 2020.

In 2021, the properties of the soil before rice cultivation were as follows: available phosphates: 43 mg kg^{-1}; total organic carbon: 39 g kg^{-1}; total potassium: 0.39 g kg^{-1}; pH: 5.56; and electrical conductivity: 0.94 dS m^{-1}.

The rice (*Oryza sativa* L.) which was sown 1 month previously, was transplanted to flooded paddy fields on the 8th of June 2021. After about 30 days, the intermittent drainage of the paddies was performed during the 2 weeks from 7-20 July. The final drainage was performed from mid-September until the harvest period on the 20th of October. However, a rainfall event occurred during the final drainage in 2021. After the harvest was completed, the fallow paddy was maintained during the winter and spring seasons.

Soil CO_2 emissions were measured using a closed chamber (LI-6400-09, LI-COR Inc., Lincoln, NE, USA), this was connected to a portable infrared gas analyser with a pressure relief vent (LI-6400, LI-COR Inc.). Polyvinyl

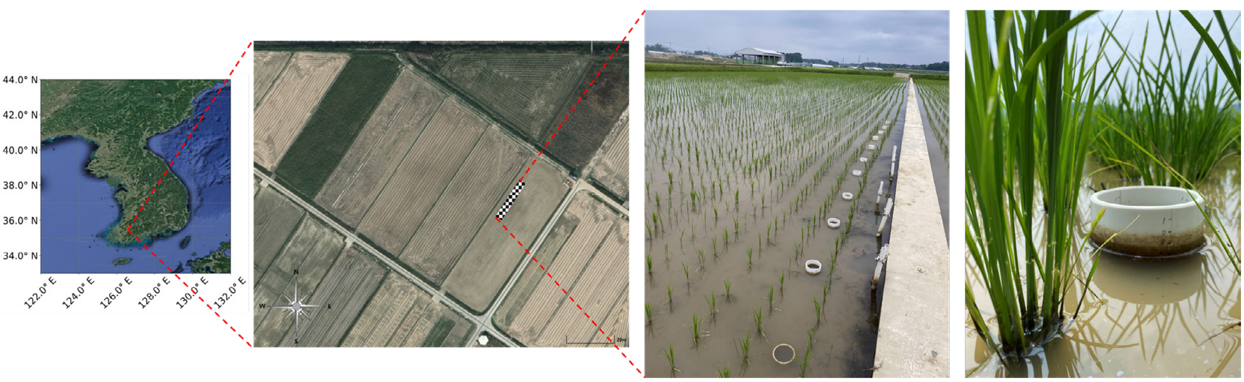

Fig. 1. Location of study site and installation of chamber collars to measure soil CO_2 emissions.

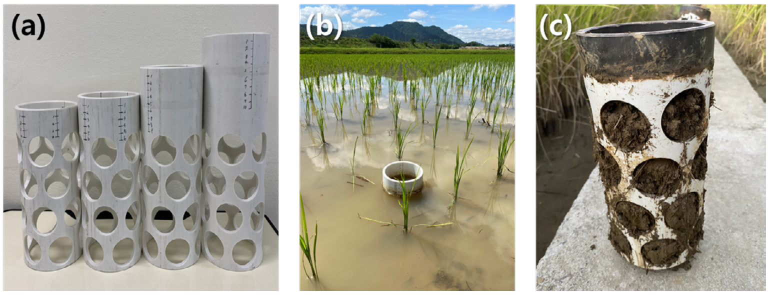

Fig. 2. Soil collars inserted into the paddy soil: a) 4 different heights of collars, b) soil collars inserted around rice, and c) roots inside the collar removed just before harvest.

chloride (PVC, KS M 3404, VG1) collars, which assist with the insertion of the chamber into the soil, were installed for the entirety of the rice cultivation and fallow periods. The colour of the collar is opaque white in order to prevent the problematic growth of algae in the paddy water inside the collar. The part of the collar that was buried in the soil had holes (4.5 cm in diameter) to allow the surrounding roots and water to enter the collars inside (Fig. 2). This ensures that the effect of the roots on soil CO_2 emissions is not excluded from the chamber observation.

Given that air circulates inside the chamber, the total inner volume of the chamber (diameter: 9.5 cm; volume: 991 cm^3) when the PVC collar lid (diameter: 10 cm) is attached should be reduced to avoid underestimation due to insufficient air mixing. However, this inner volume changes with paddy water height. Therefore, five collars for each of the four different heights (24, 26, 30, and 34 cm) were fixed in the soil at a depth of about 20 cm and at 100 cm intervals. The collar that was the least exposed above the water surface without being fully submerged was then selected for all measurements (Fig. 2). The application of this technique not only reduced the degree of uncertainty arising from a lower level of air mixing due to a larger chamber volume but also ensured uniformity in all data values. However, the fact that the collars were installed at the edge of the rice field to make use of a large number of collars ($5 \times 4 = 20$) may be viewed as a weakness in representing the entire rice field.

For the five collars selected, each chamber measurement was repeated once, and the mean value was used for data analysis. The measurement was taken over a short duration (3 to 5 min) to avoid large variations in temperature in the chamber. Soil CO_2 emissions were measured and calculated according to the LI-COR Instrument Manual (LI-COR, 1997):

$$F_c = \frac{\mathrm{k}PV}{S(T_c + 273)}\left(\frac{\partial C}{\partial t} + \frac{C}{(1000 - W)}\frac{\partial W}{\partial t}\right),$$

where: F_c is the soil CO_2 emissions (μmol CO_2 m^{-2} s^{-1}), k is a constant value for unit conversion (10/8.314 = 1.2028) from the ideal gas constant (8.314 J K^{-1} mol^{-1}), P is the atmospheric pressure (kPa), V is the total system volume (cm^3), S is the enclosed soil area (cm^2), T_c is the air temperature (°C) within the chamber, C is the CO_2 concentration (μmol CO_2 mol^{-1}), and W is the H_2O concentration (mmol H_2O mol^{-1}). After connecting the collar and chamber, the period data exhibiting a near-linear rise in was utilized to calculate F_c using equation.

Five time periods were observed at an interval of 2 weeks during the fallow period (Table 1). During the growing period, measurements were taken 18 times at an interval of approximately one week. All measurements were conducted from the morning to the afternoon.

Meteorological data were recorded every 10 min using a data-logger (CR1000; Campbell Scientific Inc., USA). Rainfall was measured using a tipping bucket (WDR-205; Wedaen Co., Seoul, South Korea) located on the roof of a building about 600 m away from the study site. A pressure transducer with a stainless-steel case (CS451; Campbell Scientific Inc.) which was installed on the bottom surface of paddies was used to measure the water depth. The air temperature and relative humidity were measured using a probe (HMP60; Vaisala Inc., Vantaa, Finland). Solar radiation was measured using a net radiometer (CNR4; Kipp and Zonen B.V., Delft, the Netherlands). Soil temperature was measured using a portable probe at a 5 cm soil depth (TPI-367; Summit, South Korea). The time series of meteorological data during the observation period is shown in Fig. 3.

3. RESULTS AND DISCUSSION

The relationship between soil temperature at a 5 cm soil depth and soil CO_2 emissions during the fallow period is shown in Fig. 4a. From late winter to late spring, the soil temperature gradually increased, ranging from 4 to 35°C. Most of the previous studies employed an exponential relationship to reveal the influence of temperature on soil CO_2 emissions (Bond-Lamberty *et al*., 2010; Fang *et al*., 2001; Valentini *et al*., 2000). The fallow paddy soil CO_2 emissions are associated with increasing soil temperatures in the form of an exponential curve ($y = 2.8\ e^{0.06x}$, R = 0.81, n = 76) and ranged from 1.1 to 21.7 μmol m^{-2} s^{-1}. On the other hand, when a linear correlation was used, the resulting R value (0.81) was exactly the same as that obtained

Table 1. Observation schedule table for the soil CO_2 emission from fallow to rice growing period in 2021

Periods		Date	Number of observations in a day			Remarks
			Morning	Afternoon	Total	
Fallow period		23 Feb.	4	11	15	Dry soil
		9 Mar.	5	13	18	
		25 Mar.	3	11	14	
		29 Apr.	5	10	15	
		13 May	5	9	14	
Rice growing period	Flooded condition	9 Jun.	0	5	5	After transplanting
		17 Jun.	5	8	13	
		30 Jun.	5	10	15	
		7 Jul.	0	5	5	Tillering stage
	Drainage condition	14 Jul.	3	3	6	
	Flooded condition	21 Jul.	2	6	8	Panicle initiation stage
		27 Jul.	5	12	17	
		4 Aug.	4	12	16	
		10 Aug.	2	11	13	Booting stage
		17 Aug.	3	6	9	
		2 Sep.	2	0	2	Heading stage
	Drainage condition	14 Sep.	5	15	20	Ripening stage
		23 Sep.	4	6	10	
		28 Sep.	0	13	13	
		5 Oct.	5	8	13	
		7 Oct.	4	4	8	
		12 Oct.	0	5	5	
		14 Oct.	3	1	4	Before harvest

using the exponential approach. This indicates that, within the temperature range of 4 to 35°C during the fallow period, the quantity of soil CO_2 emissions under relatively high-temperature conditions was lower than might be expected given the typical exponential curve associated with a specific land type. The relatively dry soil moisture conditions in the fallow paddy may not significantly enhance soil CO_2 emissions, even under high-temperature conditions (Curiel Yuste *et al*, 2007; Orchard and Cook, 1983). Nevertheless, during the fallow period the paddy acted as a carbon source as much as the amount of soil CO_2 emission without no CO_2 uptake of rice plant.

However, the exponentially fitted model of soil emissions and temperature during the fallow period had a relatively large root-mean-square error (RMSE) (3.08 μmol m^{-2} s^{-1}), thereby indicating that soil emissions cannot be fully explained using soil temperature alone. It is possible that soil moisture, soil organic matter, and other significant factors in determining soil respiration, varied spatially (Hendrix *et al*., 1988; Li *et al*., 2022).

In drained rice paddies during the growing period, soil CO_2 emissions ranged from 0.08 to 27.3 μmol m^{-2} s^{-1}, this corresponded with the 19 to 30°C range in soil temperature (Fig. 4b). The relationship between soil temperature

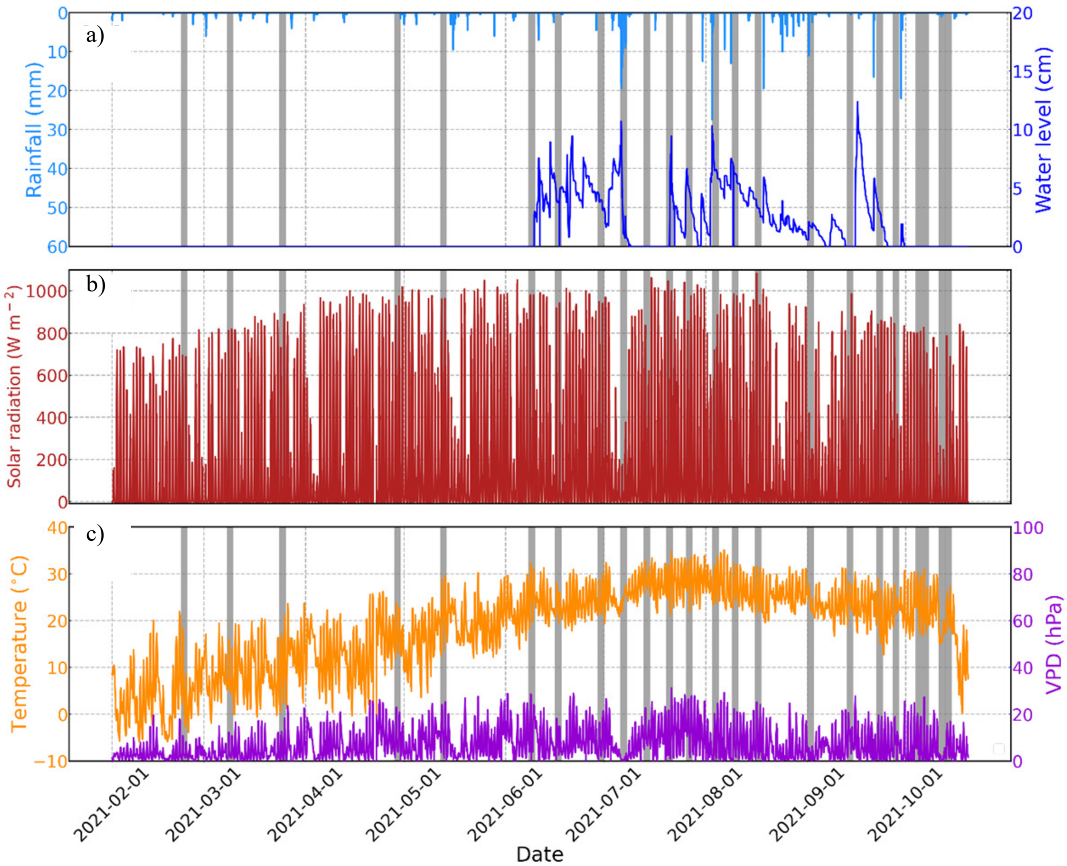

Fig. 3. Seasonal variations of meteorological variables at the study site from February to October 2021: a) 30 min sum of rainfall and average of water level, b) solar radiation, and c) air temperature and VPD. The grey vertical lines indicate the days when soil CO_2 efflux observations were conducted using the chamber method.

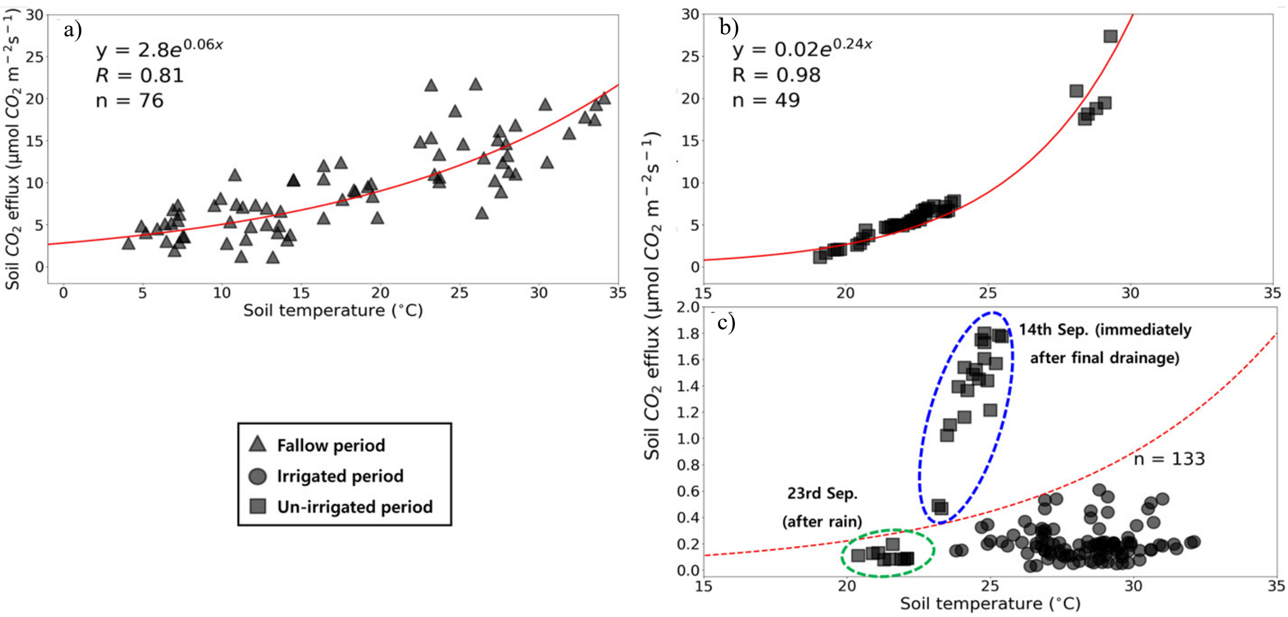

Fig. 4. Relationship between soil temperature (5 cm depth) and soil CO_2 emission during: a) fallow, b) drainage (un-irrigated), and c) flooded (irrigated) periods.

Table 2. Empirical correlation equations between soil temperature (Ts) and soil CO_2 emission (F_c) in the rice paddy field

Paddy condition	Number of data (n)	Correlation equation	Correlation coefficient (R)	RMSE (μmol m^{-2} s^{-1})
Fallow	76	$F_c = 2.8\ e^{0.06Ts}$	0.81	3.08
Drainage	49	$F_c = 0.02\ e^{0.24Ts}$	0.98	1.54

Table 3. Estimated paddy soil CO_2 emission (F_c) using the empirical equation (see Table 2)

Paddy condition	Period of estimation	Accumulated F_c estimation (mol m^{-2})		Daily F_c estimation (mol m^{-2} day^{-1})
Fallow	January 1 to June 7, 2021	72.77	99.17	0.46
	October 21 to December 31, 2021	26.40		0.37
Drainage	July 7 to 20, 2021	14.86	23.26	1.06
	September 26 to October 20, 2021	8.40		0.34

and soil CO_2 emissions under drainage conditions was fit to an exponential curve ($y = 0.02\ e^{0.24x}$, R = 0.98, n = 49). In addition, the RMSE was lower (1.54 μmol m^{-2} s^{-1}) than the value determined during the fallow period. This means that the temperature found in the drained rice paddies was the most significant factor across all periods of paddy field cultivation (Table 2).

According to a comparison of the slopes of the fitted models in fallow and drainage conditions, the CO_2 emissions determined during drainage periods are expected to be lower when the temperature is below the value of approximately 25°C. However, above that temperature, the drained paddy soils emit more CO_2. These results should be considered in paddy water management (Table 3).

The net CO_2 flux throughout the year in rice paddy fields is governed by soil CO_2 emissions because the annual amount of CO_2 uptake during the rice cultivation period does not fluctuate significantly (Iqbal *et al.*, 2009). However, soil CO_2 emissions vary substantially according to soil conditions and irrigation management practices. Even though this study documented the relationship between paddy soil CO_2 emissions and temperature during three periods, two more critical questions remain in order to understand net CO_2 flux in paddy fields. Firstly, the highly soluble CO_2 can be dissolved in paddy water and outgassed to the atmosphere, meaning that CO_2 can be released elsewhere as paddy water moves. Secondly, the sensitivity of soil CO_2 emissions to temperature have the potential to be changed by the application of organic fertilizer or practices such as soil tillage. Thus, the further observation of paddy soil CO_2 emissions under various conditions is required.

Soil CO_2 emissions under flooded conditions during the rice-growing period are shown as open circles in Fig. 4c. The relationship between soil CO_2 emissions and temperature was not readily apparent in flooded conditions. This finding is consistent with the results of previous studies conducted in paddy fields (Koizumi *et al.*, 2001; Li *et al.*, 2010; Nishimura *et al.*, 2015). However, anaerobic paddy soil can emit not only CH_4, but also CO_2 through organic matter decomposition by microorganisms, the oxidation of CH_4, and the atmospheric outgassing of dissolved CO_2 (Bridgham and Richardson, 1992; Casper *et al.*, 2000). All of these reactions are influenced to a substantial extent by temperature (Houshmandfar *et al.*, 2015). Thus, although temperature is not the most sensitive factor in soil CO_2 emissions in flooded paddies, the plots under flooded conditions can be represented as the boundary line (dotted red line in Fig. 4c) to temperature as an exponential function.

Soil CO_2 emissions during the flooded period were relatively insignificant (mean: 0.21 μmol m^{-2} s^{-1}) and varied little, ranging from 0.03 to 0.61 μmol m^{-2} s^{-1} according to the soil temperature, which ranged from 23 to 32°C. Such a suppression of CO_2 emissions from paddy soil to the atmosphere under flooded conditions may be caused by the blocking of diffusion by the paddy water layer and the high degree of solubility of CO_2 gas. Despite the occurrence of a drainage period, the re-submerged condition as a consequence of rainfall or the remaining paddy water immediately after drainage (rectangles in Fig. 4c and picture in Fig. 5) also brought about the suppression of soil CO_2 emission.

4. CONCLUSIONS

1. This study found that fallow rice paddy soil emits a significant amount of CO_2 even at low temperatures, and as the temperature increases, CO_2 emissions continue to rise, despite the soil being dry. A similar result was achieved for CO_2 emissions from the soil of non-paddy fields in previous studies (*e.g.*, Hendrix *et al.*, 1988; Li *et al.*, 2022). Even if the fallow paddy soil CO_2 emission was linearly or

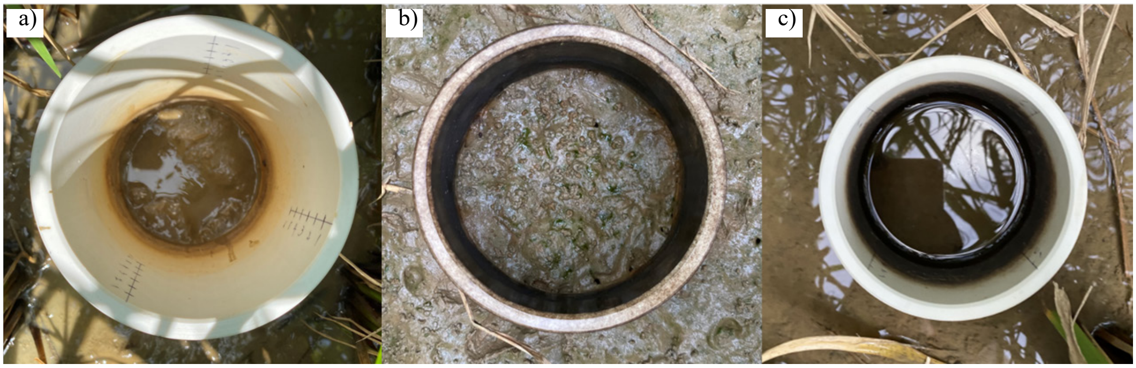

Fig. 5. Inside view of soil chamber collars: a) immediately after drainage (14 September), b) under drainage conditions, and c) re-submerged after rainfall (23 September).

exponentially related to temperature, that correlation varied spatially, this was probably due to differences in soil moisture and soil organic matter content.

2. In the rice paddy field, the CO_2 emissions which were suppressed during flooded periods and the markedly higher CO_2 emissions occurring in the drainage condition were identified as in previous studies (*e.g.*, Koizumi *et al.*, 2001; Li *et al.*, 2010; Nishimura *et al.*, 2015). During flooded periods, the measured CO_2 values were low and not dependent to a significant degree on temperature since the CO_2 released from the soil was blocked by the water layer.

3. Even if the rice paddy is drained, the water on the paddy soil surface may remain immediately after a draining or rainfall event. That residual water body on the paddy soil surface is found to effectively suppress soil CO_2 emission, irrespective of the depth of the paddy water. This phenomenon will provide valuable insights for interpreting the validation of carbon cycle models in the agricultural ecosystem.

4. In drained paddies, the exponential curve of the relationship between soil CO_2 emissions and soil temperature was found to be more distinct than that in the relationship present during the fallow period. In comparing fallow and drained paddies, it should be noted that fallow paddies are relatively longer in duration and cooler in temperature, also, drained paddies are more sensitive to temperature than they are during the fallow period, but this period has a shorter duration. This finding is likely to play a critical role in climate change mitigation and adaptation strategies in rice paddy farming.

Conflicts of Interest: The authors declare no conflict of interest.

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