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Article

Effect of Drainage Practice on the Emission of Two Carbon-Based Greenhouse Gases (CO₂ and CH₄) from Paddy System in South Korea: Field Pilot Study

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Abstract: In this field pot study, effect of drainage method (e.g., intermittent drainage (ID) and continuous flooding (CF)) on greenhouse gas (GHGs: CO₂ and CH₄) emission was determined from three Korean paddies (BG, MG, and JS series), varying soil properties such as soil texture, labile carbon, and mineral types. Emission of GHGs was evidently influenced by the irrigation, to a different extent, depending on paddy's redox (Eh) shift upon flooding events. The Eh decline upon flooding was slower in JS pot, where pore-water concentration of ferric and sulfate ions is the highest (~ up to 3-fold) among three paddies. MG pot was 2- to 3-fold percolative than others and the Eh drop during flooding period was the smallest (staying above -50 mV). In ID treatment, CH₄ emission (t CO₂-eq ha⁻¹ yr⁻¹) was reduced in a wide range by 5.6 for JS pot, 2.08 for BG pot, and 0.29 for MG pot relative to CF, whereas CO₂ emissions (t CO₂-eq ha⁻¹ yr⁻¹) was increased by 1.25 for JS pot, 1.07 for BG pot, and 0.48 for MG pot due to the enhanced oxidation of labile carbon. Grain yield and aboveground biomass production from ID were no less than those from CF (p < 0.05). Consequently, gain of global warming potential (S GWP) by ID varied as the order of JS (37%) > BG (14%) > MG (~0 %) pots, and negligible effect observed for MG pot is due to the equivalent trade-off between CO₂ and CH₄. Our findings suggest that the efficacy of ID practice on GHGs emission can be further improved by the consideration of redox response of paddy system.

Keywords: Paddy soil; Intermittent drainage; Greenhouse gas; Carbon dioxide; Methane

1. Introduction

The Intergovernmental Panel on Climatic Change (IPCC) reported that rice paddy is recognized as a source of considerable greenhouse gases (GHGs) emission. Rice (*Oryza sativa* L.) is one of the most important staple foods in Asian countries [1]. In particular, rice cultivation field accounts for approximately 51% of the agricultural cropland area and 27% of the GHGs emission in Korean agricultural lands [2,3]. The common practice of rice cultivation involves maintaining a flooded environment by irrigation treatment from rice planting to harvest season [4,5].

The flooding event comprises anoxic environments as the biochemical activity reduces redox potential (Eh) of paddies [4]. A sufficiently low Eh of paddy water is required to invoke the formation of methane (CH₄), since methanogenic bacteria can metabolize only in strictly anoxic environments. Consequently, irrigation treatment has been recognized to significantly affect CH₄ emissions from paddy soils [5]. The drainage practice has been widely recognized to suppress CH₄ emissions by increasing Eh level of paddy [6–9]. For an example, implementation of intermittent drainage during the rice-growing season was found to reduce about 48.5% of CH₄ emissions relative to continuous flooding in Korean paddy.

Meanwhile, carbon dioxide (CO₂) emission from agricultural land has not been widely recognized as GHG according to IPCC guidelines, because agricultural soils are generally regarded as a carbon sink [1]. However, CO₂ emissions from Korean paddy field can be significant, because

more than 50% of the aboveground rice biomass is not returned back to the field after harvesting, but is used for other industries (e.g., animal husbandry) [2].

Soil wetness is one of the most important environmental factors that controls the degree of soil microbial respiration, the method of irrigation practice in rice paddies can significantly affect soil basal respiration rates [10]. The general consensus from previous studies is that drainage increases atmospheric oxygen (O_2) diffusion into soils, thereby enhancing aerobic decomposition and promoting CO_2 production, while at the same time suppressing CH_4 emissions [5]. Thus, in order to precisely assess the benefit of intermittent drainage practice on GHGs emission, the trade-off between the reduced CH_4 emissions and the increased CO_2 emissions must be properly accounted.

Paddy soils are subject to changes from oxic to anoxic conditions under flooding treatment, leading to decreasing soil redox (Eh) conditions and the sequential reduction of terminal electron acceptors, such as nitrate (NO_3^-), manganese (Mn^{4+}), ferric (Fe^{3+}), and sulfate (SO_4^{2-}), according to their energy release and availability [4]. For example, when O_2 is depleted and Eh drops, the reduction of NO_3^- to nitrogen gas occurs before Mn^{4+} (in MnO_2) is reduced to Mn^{2+} . Then, Fe^{3+} (in $Fe(OH)_3$) is transformed to Fe^{2+} in the range of $200\text{ mV} < Eh < -100\text{ mV}$, after which SO_4^{2-} becomes the preferred terminal electron acceptors in highly reduced condition (e.g., -100 mV to -180 mV) [4,11]. If Eh value drops as low as -180 mV , methanogenesis occurs and the remaining CO_2 is reduced with soil organic carbon (SOC) (e.g., acetic acid) to CH_4 by methanogens [4,5]. Therefore, abundance of electron acceptors in paddy water that can be supplied from the soil minerals is known to slow down the rate of Eh reduction, resulting in suppressed CH_4 flux [12,13].

Percolation (or internal drainage) is the process by which water moves downward through the soil under gravitational forces [14]. The rate of percolation is controlled by soil particle sizes, and it measures how promptly paddy soil becomes unsaturated and oxic condition during drainage event. The effect of drainage practice on the migration of GHGs emission should markedly vary with the textural class of paddy field. For an example, Yagi et al. [15] observed an approximately 2.8-fold decrease in seasonal CH_4 fluxes from a loamy paddy field, as compared to a silty clay loam paddy field, due to about 3-fold higher percolation rate of the former (2.5 cm day^{-1} vs. 7.7 cm day^{-1}). The reduced CH_4 emission from the loamy field was explained by the occurrence of the prompt and wider Eh elevation upon draining paddy water. Therefore, CH_4 production could be suppressed in highly percolative paddy by repeated drainage events as the soil continuously formed in oxic condition [5,14,15].

Global warming potential (GWP) was widely adopted to provide an understanding of agricultural impacts on radiative forcing [1]. This concept allows for direct comparisons of the overall impacts induced by GHGs. Another concept, greenhouse gas intensity (GHGI) which is calculated by dividing the GWP by the crop production, was also introduced to simultaneously assess GHGs emission and rice production in the paddy soils [16]. Existing literature shows that the emission of GHGs from paddy field can be substantially reduced by adopting intermittent drainage practice [6–9], but no relationship between GWP and grain production has been delineated in combination with different soil physicochemical characteristics and irrigation methods. In addition, only a few studies have simultaneously examined the emission dynamics of GHGs (CO_2 and CH_4) from rice paddies and their trade-offs by intermittent drainage [8,9].

So far, a good deal of laboratory and field studies reported that GHG emission from rice paddy fields is greatly reduced by introducing intermittent drainage during conventional flooding practice. However, the effect of the intermittent drainage on mitigation of GHG emission from Korean rice paddies has not been well examined. Therefore, the primary goal of this study was to quantify the flux of GHGs (e.g., CO_2 and CH_4) as affected by irrigation method (e.g., continuous flooding vs. intermittent drainage) from three different Korean paddies over the duration of rice cultivation (from transplanting to harvest). Seasonal variation of GHGs flux was interpreted by analyzing the temporal condition of three paddy soils such as redox couple, redox potential, etc. By coupling rice grain yield and global warming potential, the benefit of the intermittent drainage practice was also addressed.

2. Materials and Methods

2.1. Experimental Settings

2.1.1. Rice Pot Design

Paddy soils of three different rice fields (e.g., Bugog (BG), Meagog (MG), and Jisan (JS) series) were collected near Korea University Farm (KU farm hereafter) in Gyeonggi Province, Korea. These soils have been used for rice cultivation for a couple of decades. Collected samples were air-dried in KU farm. Pot experiment was set up in a paddy field (L = 35 m, W = 25 m) in KU farm (37°35'01"N, 127°14'16"E).

Eighteen holes with a depth of 30 cm were dug at a spacing 2 m × 3 m and the pallet and non-woven mat were laid on the bottom of each hole [17] in order to eliminate the influence of the underlying soil condition (moisture status, groundwater table, etc.) (Figure S1). A cylindrical rubber pot (68 cm diameter and 46 cm height) was placed in each hole and was filled with the soil; approximately 132 kg for BG pot, 131 kg for MG pot, and 141 kg for JS pot, close to their bulk density in the field (1.21 g cm⁻³ for BG pot, 1.20 g cm⁻³ for MG pot, and 1.29 g cm⁻³ for JS pot). Six weepholes with 5 cm diameter were installed in the bottom of the cylindrical rubber pots (Figure S1) to facilitate drainage according to the percolation properties of each pot. The pot experiment was conducted from May to Sep. in 2019. This region belongs to temperate monsoon climate zone with an annual mean temperature of 12.0 ± 0.4 °C and a mean annual precipitation of 1408 ± 256 mm over the past 20 years. Intensive rainfall occurs between Jun. and Aug. (Figure S2).

2.1.2. Soil Characterization

Selected properties of the paddy soils were characterized as followings; pH at a soil mass to solution volume ratio of 1:5 (g:mL), particle size distribution using the pipette method, percolation rate using air-entry permeameter method, total organic carbon by K₂Cr₂O₇ oxidation, and labile carbon by KMnO₄ oxidation, and Fe-oxide content by oxalate extraction (pH 3) and dithionite–citrate–bicarbonate (DCB) extractions [18,19]. Mineralogical compositions of clay particles (< 2 μm) were identified using X-ray diffraction (XRD) with Cu Ka radiation at 45 kV and 40 mA (D/max 2500v/pc, Rigaku, Japan). All patterns were collected at a scanning speed of 1.2° min⁻¹ over the 2θ range of 5–70°. Highscore Plus data analysis program (Malvern Panalytical, UK) which includes the standards of the International Centre for Diffraction Data was used to identify the observed digital diffraction pattern [20].

2.1.3. Farming Method

In paddy pot, urea was applied as a N source (i.e., 70 kg ha⁻¹) and approximately 2 cm-depth of water was supplied before transplanting on May 12th. Four to five hills of 25-days-grown rice seedlings (*Oryza sativa* L., maturity 124 days) were manually transplanted on May 16th at a planting density of 0.15 m × 0.15 m. Paddy pots were initially flooded with 1 – 2 cm water until the rice growth attains the three-leaf stage on May 30th. To conduct continuous flooding (CF) treatment, 5 – 7 cm depth of paddy water was maintained during irrigation period (May 31st – Aug. 10th). For intermittent drainage (ID) method, the pots were intentionally drained three times (e.g., May 31 to Jun. 4, Jun. 16 to Jun. 23, and Jul. 6 and Jul. 28). The number of drainages was designed not to affect the rice yield based on our preliminary test. Water depth was measured daily during the irrigation period, and then deficit water was supplied to maintain the target water depth for each irrigation schedule, as shown in Table S1. For both irrigation methods, all paddy pots were permanently drained through the drain valve (Figure S1) on Aug. 10th, and rice was harvested on Sep.17th which is 38 days laps after the final draining event. Agronomic practices conducted for rice pot experiment are summarized in Table S1. Paddy pots were triplicate.

2.2. Measurement and Data Collection

For 125 days after rice transplanting, the greenhouse gas, paddy water, and soil volume wetness data were collected on the same day at average intervals of 4 days. Details for the data collection and analysis method are following.

2.2.1. Greenhouse Gas Emission

The flux of two GHGs (CO₂ and CH₄) was measured using the closed chamber method [17]. The system consists of a closed chamber with a measurement unit in which a moisture filter, direct current (DC) pump, flow meter, gas detector module, and data logger are sequentially connected (Figure S1). An opaque acrylic cylinder, which had a diameter of 30 cm and 40 cm in height (or 100 cm in height depending on rice growth), was anchored into the soil surface to collect gas emitted from the soil. The chamber was wrapped with an aluminum foil to minimize air temperature changes inside the chamber during the period of sampling. The chamber was able to cover the four rice plants transplanted in each pot without air exchange with the outside. A DC pump (Motorbank, Korea) and an air flow meter (Dwyer, USA) were installed to maintain a constant flow rate (≈ 1 L min⁻¹) of air between the chamber and the detector, thereby forming a continuous air circulation system. The concentration of CO₂ and CH₄ were directly determined using a CO₂ sensor (Soha-Tech, Korea) and CH₄ sensor (Axetris, Switzerland) incorporated within the measuring device.

The measurement was conducted twice on a given day (e.g., between 8–11 am and between 3–6 pm) and results were averaged for daily emissions based on sampling protocols [21]. The amount of gas emission (gas flux, F , mg m⁻² hr⁻¹) was calculated using Eq. (1) [22].

$$F = \rho \cdot \left[\frac{V}{A} \right] \cdot \left[\frac{\Delta C}{\Delta t} \right] \cdot \left[\frac{273}{(T + 273)} \right] \quad (1)$$

where ρ is the density of gas (mg m⁻³), V is the volume of the chamber (m³), A is the bottom area of the chamber (m²), $\Delta C/\Delta t$ is the average rate of concentration change (ppmV h⁻¹), and T is the average temperature in the chamber (°C).

2.2.2. Chemical Analysis of Paddy Water and Paddy Soil

Paddy water sample was filtered through a 0.45 μ m membrane filter prior to chemical analysis. The concentration of Fe³⁺ and Fe²⁺ was determined at 510 nm using a UV-Vis spectrophotometer (UV-1800, Shimadzu, Japan) using 1,10-phenanthroline [19]. The concentration of SO₄²⁻ was determined by ion chromatography (ICS-2000, Dionex, USA) with anion-exchange column (IonPac AS18, 250 mm \times 4 mm). Temporal change of two redox elements (Fe and S) was assumed to be due to the result of redox potential of paddy pots.

On each day when GHGs flux was measured, pH and Eh were measured for pore water at a 5 cm-depth from soil-water interface using a portable pH/Eh meter (Pro Plus, YSI, USA). The volume wetness (v/v, %) of paddy soils at 5 cm and 15 cm depth was also measured using a soil moisture sensor (HydraProbe, Stevens, USA).

2.2.3. Rice Grain and Biomass

Rice plant samples were taken from three sample areas of 0.36 m² in each plot where the grain yields were determined at maturity stage (Sep. 17th). At the same time, three hills of straw at each plot were randomly sampled and oven-dried at 85 °C to a constant weight to obtain the aboveground biomass. The rice grain was adjusted to the standard moisture content of 0.14 g H₂O g⁻¹ (fresh weight) to obtain the grain production [9]. The production of grain and aboveground biomass were expressed as the unit of t ha⁻¹ considering the pot surface area.

2.3. Data Analysis

2.3.1. GWP, Cumulative GHGs Emissions, and GHGI Estimates

The GWP (kg CO₂-eq ha⁻¹) based on the CO₂ and CH₄ emissions were used to account for the climatic impact of among three soils under different irrigation methods. The GWP coefficient is 34 for CH₄ when the GWP value for CO₂ is taken as one [1].

The cumulative emissions of CH₄ and CO₂ (t CO₂-eq ha⁻¹) were calculated for each plot according to the following equation, as described by Eq. (2) [9].

$$\text{Cumulative emission} = \Sigma[(F_i + F_{i+1})/2 \times d] \quad (2)$$

where F_i and F_{i+1} are the measured fluxes of two consecutive sampling days (t CO₂-eq ha⁻¹), and d is the number of days between two sampling days.

The term GHGI ($t \text{ CO}_2\text{-eq ha}^{-1}$) relates the sum of GWP production to grain yield ($t \text{ ha}^{-1}$) for each paddy pot and was calculated by Eq. (3) [16].

$$\text{GHGI} = \text{GWP}/\text{grain production} \quad (3)$$

2.3.2. Statistical Analysis

Statistical differences (*t*-test) were determined at the significance level of $p < 0.05$ for between CF and ID method using SAS 9.4 (SAS Institute Inc., USA).

3. Results and Discussions

3.1. Soil Characteristics

Selected properties of paddy soils used in this study are presented in Table 1. All soils exhibited near natural pH (6.6 - 7.0). The labile carbon content (g kg^{-1}) of three soils varied as following; JS (10.6 ± 1.27) > BG (8.42 ± 0.44) > MG (5.48 ± 0.55). Because of high sand content, MG pot showed the highest percolation rate (cm d^{-1}) as 8.51 ± 1.06 , more than twice of others (BG pot = 2.84 ± 0.53 and JS pot = 3.90 ± 0.55). The soluble concentration of Fe^{3+} (mg L^{-1}) had a similar range (0.11 - 0.16) across the three pots. JS pot showed over 2.6-fold higher SO_4^{2-} concentration ($66.5 \pm 2.7 \text{ mg L}^{-1}$) than BG and MG pots (25.6 ± 0.3 and $22.7 \pm 0.6 \text{ mg L}^{-1}$, respectively). Result of XRD analysis of clay fraction showed that JS soil is mainly composed of quartz (SiO_2), ferrihydrite ($\text{Fe}(\text{OH})_3$), and langite ($\text{Cu}_4(\text{SO}_4)(\text{OH})_6 \cdot 2\text{H}_2\text{O}$) while both BG and MG mainly contains quartz (SiO_2) and magnetite (Fe_3O_4). Note that ferrihydrite is amorphous whereas magnetite is crystalline [23]. Likewise, the content of Ox-Fe was higher in JS soil ($12.8 \pm 0.32 \text{ g kg}^{-1}$) in comparison with BG and MG soils.

Table 1. Physical and chemical properties of three Korean paddy soils.

Properties	Soils ^a		
	BG	MG	JS
Order/Subgroup ^b	Ultisols/Typic Fragiudults	Inceptisols/Anthraquic Eutrudepts	Alfisols/Typic Endoaqualfs
pH ^c	6.6±0.1	6.8±0.1	7.0±0.1
Sand ^d	27.4±2.1	54.5±0.3	41.4±0.5
Clay ^d	33.9±0.4	18.6±1.0	24.8±0.3
Percolation rate ^e	2.84±0.53	8.51±1.06	3.90±0.55
TOC ^f	14.4±0.40	14.9±0.39	21.2±0.46
Labile C ^g	8.42±0.44	5.48±0.55	10.6±1.27
Soluble ferric ^h	0.16±0.03	0.11±0.03	0.15±0.02
Soluble sulfate ⁱ	25.6±0.3	22.7±0.6	66.5±2.7
DCB-Fe ^j	38.7±0.33	32.3±0.73	29.3±0.22
Ox-Fe ^k	6.62±0.26	5.84±0.05	12.8±0.32
Major Minerals	Quartz (SiO_2), Magnesioferrite (MgFe_2O_4), Magnetite (Fe_2O_4)	Quartz (SiO_2), Gupeite (SiFe_3), Magnetite (Fe_2O_4)	Quartz (SiO_2), Ferrihydrite ($\text{Fe}_2\text{O}_3 \cdot 0.5\text{H}_2\text{O}$), Langite ($\text{Cu}_4(\text{SO}_4)(\text{OH})_6 \cdot 2\text{H}_2\text{O}$)

^a Three paddy soils were named by their respective series. ^b Soil classification of order and subgroup by soil taxonomy. ^c Aqueous soil pH measured at 1:5. ^d Percent (%) of sand and clay with particle sizes less than 2 mm and 2 μm , respectively. ^e Percolation rate (cm day^{-1}). ^f Total organic carbon (g kg^{-1}). ^g Labile carbon (g kg^{-1}). ^h Water soluble ferric (Fe^{3+}) measured at 1:5 (mg L^{-1}). ⁱ Water soluble sulfate (SO_4^{2-}) measured at 1:5 (mg L^{-1}). ^j Dithionite–citrate–bicarbonate extractable iron (g kg^{-1}). ^k Oxalate (pH 3) extractable iron (g kg^{-1}).

3.2. Weather Conditions of Experimental Site

Data of precipitation and air temperature during pot experiment (May - Sep.) are provided in Figure S2. The mean temperature over the given period was $23.6 \pm 2.1 \text{ }^\circ\text{C}$, with the highest temperature between Jul. and Aug. The cumulated precipitation was $731 \pm 45 \text{ mm}$, and most of the rainfall occurred between Aug. and Sep. (Figure S2). Typical temperate monsoon climate was observed during the experimental period.

3.3. Impact of Irrigation Methods on Paddy Water

The concentration (mg L^{-1}) of Fe^{2+} and SO_4^{2-} , and Eh (mV) for the paddy water of three paddy pots (BG, MG, and JS) under two irrigation methods (CF and ID) are displayed as a function of time in Figure 1. Note that the CF pot is continuously submerged during irrigation period (May 12th - Aug. 10th) while the ID pots are intentionally drained and re-flooded three-times during the given period. Both CF and ID pots were permanently drained after Aug. 10th. The gray area in Figure 1 indicates the duration of (re)flooding in ID method.

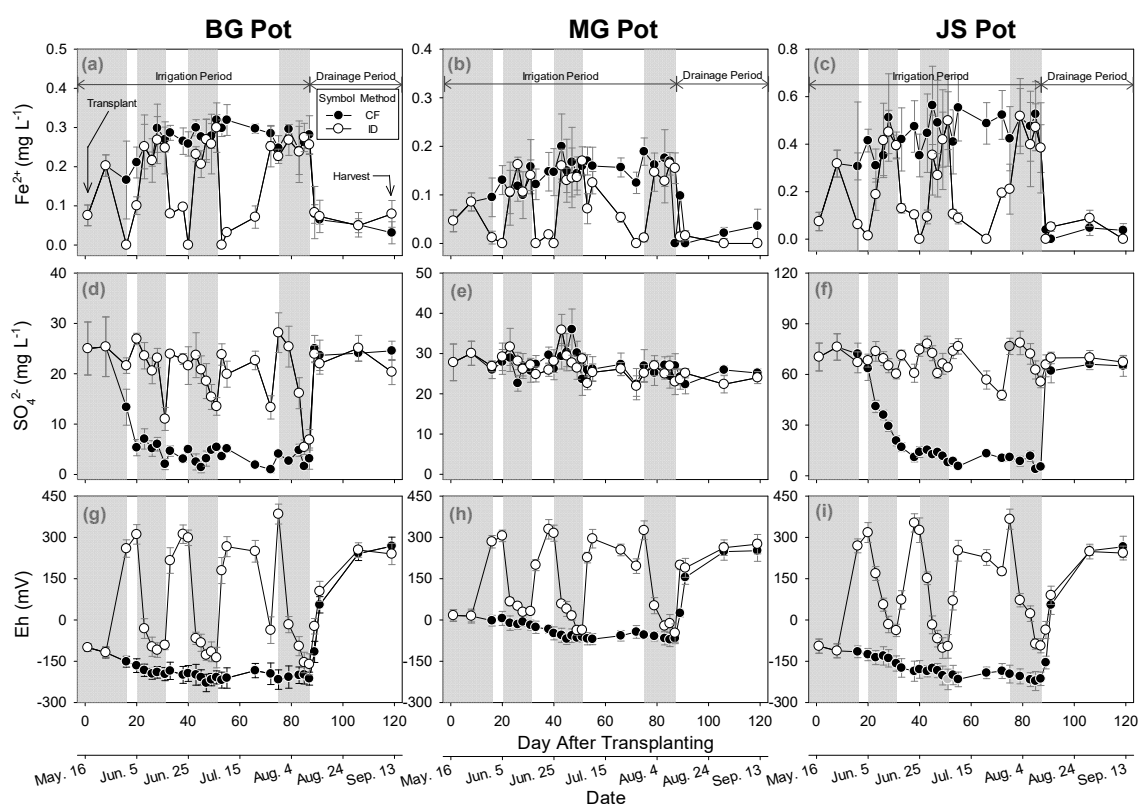


Figure 1. Concentration (mg L^{-1}) of Fe^{2+} (a – c) and SO_4^{2-} (d – f) and the magnitude (mV) of Eh (g – i) in paddy water of BG, MG, and JS pots under the method of continuous flooding (CF) and intermittent drainage (ID). White and gray columns represent drained and flooded periods of ID method, respectively. All pots were permanently drained on Aug. 10th. The duration of the irrigation (May 12th – Aug. 10th) and the timings of transplant (May 16th) and harvest (Sep. 17th) are also shown.

In CF pot, the concentration of Fe^{2+} gradually increased and remained relatively constant over the flooded period (May 12th – Aug. 10th) with an average of 0.27 ± 0.02 , 0.14 ± 0.02 , and 0.44 ± 0.05 mg L^{-1} for BG, MG, and JS pots, respectively (plots (a), (b), and (c) in Figure 1). The increase of Fe^{2+} can be assumed to be a result of reduction of Fe^{3+} ion in flooded paddies [24]. The highest Fe^{2+} concentration in JS pot can be explained by the different mineralogical compositions of three paddy soils [11]. Fe-oxides are the common source of iron in soils; thus, the Fe level in paddy water varies with the type of Fe oxides present in paddy soils. As shown in Table 1, ferrihydrite is a major Fe-oxide in JS soil and Ox-Fe content is almost twice greater than others, whereas magnetite is dominant in both BG and MG soils. Note that short-range ordered Fe-oxide (i.e., ferrihydrite) has lower thermodynamic stability than long-range ordered one (i.e., magnetite). For example, the solubility of Fe^{3+} maintained by ferrihydrite is 89 times greater than that maintained by magnetite [24] and the reduction potential of ferrihydrite ($\text{Eh} = 12$ mV at pH 7) is exceedingly higher than that of magnetite ($\text{Eh} = -310$ mV at pH 7) [25].

Meanwhile, the concentration (mg L^{-1}) of SO_4^{2-} in paddy water tended to decrease and the declining pattern was different among pots (plots (d), (e), and (f) in Figure 1). The initial SO_4^{2-} concentrations were 25.0 ± 5.3 , 27.8 ± 4.6 , and 70.3 ± 8.2 mg L^{-1} in BG, MG, and JS pots, respectively.

The concentration dropped to below near 10 mg L^{-1} after 20 days and 40 days for BG and JS pots, respectively. The Eh of respective pots also concurrently dropped to below -180 mV (plots (g) and (i) in Figure 1) by that time, supporting the conjecture that the depletion of SO_4^{2-} in paddy water is due to the reduction of SO_4^{2-} under the reducing condition. In general, the time required for paddy water to attain an extremely reduced condition (e.g., $< -180 \text{ mV}$; CO_2 reducing) depends on the availability SO_4^{2-} and the duration of aqueous SO_4^{2-} depletion in paddy water and the activity of SO_4^{2-} -reducing bacteria becomes predominated in the Eh range between -100 mV and -180 mV [11]. In this study, JS pot took approximately 20 days longer to attain the extremely reduced condition (e.g., -180 mV) than BG pot because of the initial 2.6-fold higher SO_4^{2-} concentration in JS pot ($70.3 \pm 8.2 \text{ mg L}^{-1}$) than BG pot ($25.0 \pm 5.3 \text{ mg L}^{-1}$). On the other hand, the depletion of SO_4^{2-} was not apparent in MG pot (plot (e) in Figure 1) as the Eh was persistently remained above -72 mV during the same period (plot (h) in Figure 1). Since MG pot is highly percolative (Table 1) frequent refurnishing of fresh water was needed to sustain the 5 - 7 cm of paddy water level. Consequently, weakly reduced condition was likely achieved in MG pot ($-72 \text{ mV} < \text{Eh} < 16 \text{ mV}$) through continuous O_2 influx by fresh irrigation water supply.

In ID pots, on the contrary, the concentrations of Fe^{2+} and SO_4^{2-} and Eh value were fluctuating in response to the occurrence of drainage and re-flooding events (Figure 1). For example, the concentration of Fe^{2+} promptly decreased (below 0.1 mg L^{-1}) whereas the concentration of SO_4^{2-} increased up to initial level by performing drainage. Simultaneously, the Eh rose up to 300 mV , indicating the development of oxic paddy condition in drained paddies. The Eh dropped quickly during the re-flooding periods but persisted above the Eh of CF pots.

To explain thermodynamic stability of Fe-oxides and SO_4^{2-} in paddy water, pH-Eh data collected from ID pots was plotted in the Pourbaix diagrams of Fe (solid line) and S (dashed line) species in Figure S3 [26]. Under pH-Eh range of this study, crystalline Fe-oxides present in BG and MG paddies (e.g., hematite and magnetite) are highly stable (plot (a) in Figure S3) while in JS paddy the dissimilatory iron release from amorphous Fe-oxide (e.g., ferrihydrite) is thermodynamically favorable (plot (b) in Figure S3). The pH-Eh sets of re-flooded paddies lie close to the border where SO_4^{2-} convert to its reduced forms (e.g., H_2S and HS^-). According to this theoretical reason, therefore, it can be reasonably speculated that 1) the highest concentration of Fe^{2+} in JS paddy is due to the reduction of iron released from amorphous Fe-oxide present in the JS paddy, and 2) the depletion of SO_4^{2-} in flooded paddies is most likely due to the reduction of sulfur in reduced condition. The presence of these electron acceptors is known to slow the rate of Eh decrease in flooded paddies [12,13].

3.4. Impact of Irrigation Methods on GHGs Emission

Temporal change of GHG flux ($\text{kg CO}_2\text{-eq ha}^{-1} \text{ day}^{-1}$) measured for three paddy pots (BG, MG, and JS) under two irrigation methods (CF and ID) are present in Figure 2. Volumetric soil wetness (v/v, %) determined at the depth of 5 and 15 cm is shown in Figure S4. All CF pots retained near saturated soil wetness ($\sim 40\%$) at both 5 and 15 cm depths over irrigation period (15 cm data not shown). The soil wetness of ID pots gradually decreased as low as 15 – 20% and the wetness at 5 cm depth was always lower than that at 15 cm during drainage periods. The wetness difference between two depths was minimal for MG pot due to its high percolation rate. Notice that the occurrence of Eh rise (Figure 1) is coincident to the timing of soil wetness decreases (Figure S4).

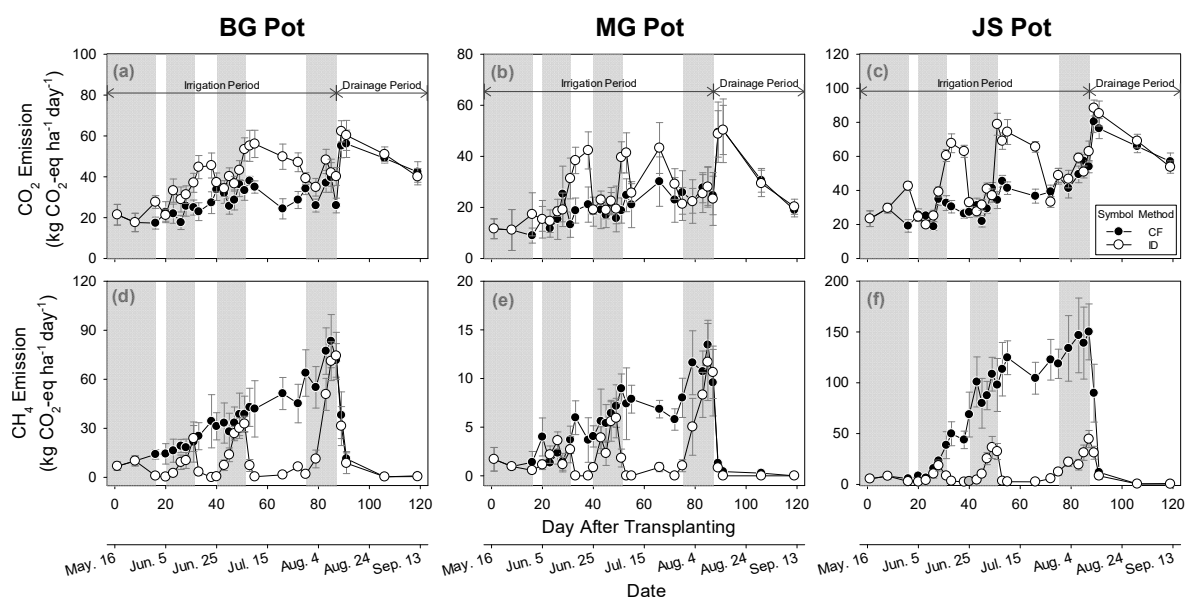


Figure 2. Emission ($\text{kg CO}_2\text{-eq ha}^{-1} \text{ day}^{-1}$) of CO_2 (a – c) and CH_4 (d – f) measured from BG, MG, and JS pots) under the method of continuous flooding (CF) and intermittent drainage (ID). White and gray columns represent drained and flooded periods of ID method, respectively. All pots were permanently drained on Aug. 10th.

3.4.1. Carbon Dioxide Emissions

The CO_2 flux was initially low until the three-leaf stage on May 30th and then peaked at the end of the irrigation period on Aug. 10th, after which it gradually declined until rice maturity (plots (d), (e), and (f) in Figure 2). The pattern of CO_2 release from agronomic soils is correlated with the life cycle of crop growth, likely because mature plants have more root exudates for soil microbes [27].

The two irrigation treatments showed distinctively different CO_2 dynamics upon starting flooding practice at the three-leaf stage on May 30th. Over cropping season, the CO_2 flux ($\text{kg CO}_2\text{-eq ha}^{-1} \text{ day}^{-1}$) under CF method ranged 17.3 – 39.7, 9.0 – 30.1, and 18.8 – 57.2 in BG, MG, and JS pots, respectively. The flux remained relatively low and then increased after permanent drainage starts, approximately five weeks before rice harvest. The CO_2 flux under ID method ranged 17.6 – 56.1, 11.2 – 43.3, and 19.8 – 78.9 in BG, MG, and JS pots, respectively, which present wider fluctuations than CF method as affected by the repetition of draining and re-flooding situation. The CO_2 emission appeared largest in JS paddy in which the content of labile carbon is highest among three paddies (Table 1) [10]. Compared between two irrigation methods, the CO_2 flux of drained paddy in ID method overwhelmingly exceeded that of flooded paddy in CF method (Figure 2). It is well understood that the rhizosphere system will be exposed to sufficient O_2 upon draining paddy water, which in turn facilitates the rhizospheric respiration and aerobic microbial SOC degradation; thus, leading to significant augmentation of CO_2 production [13,28], compared to flooded condition.

3.4.2. Methane Emissions

In CF method, the CH_4 flux gradually increased steadily with rice growth until the end of flooding period after which it declined rapidly (plots (g), (h), and (j) in Figure 2). The CH_4 flux ($\text{kg CO}_2\text{-eq ha}^{-1} \text{ day}^{-1}$) in CF methods was peaked as high as 83.3 ± 16.3 for BG pot, 13.5 ± 2.5 for MG pot, and 150.1 ± 27.5 for JS pot on mid-Aug., after rice heading. In ID method, the CH_4 flux was substantially declined in drained paddies as 2.5 – 74.3, 1.2 – 11.7, and 4.1 – 44.6 in BG, MG, and JS pots, respectively. This observation is well agreed with many previous results that intermittent drainage in rice growing season can reduce CH_4 emission from rice paddy fields by converting the redox potential to more oxic condition [6,9].

Meanwhile, it is also worthy to note that the CH_4 emission in JS pot was substantially lower in three re-flooded periods (Jun. 4 – Jun. 15, Jun. 24 – Jul. 5, and Jul. 29 – Aug. 10 in Figure 2) compared to given periods of CF method. During these periods, both the average (up to 76%) and peak (up to 70%) of CH_4 flux were greatly decreased in JS pot. Such decrease was not pronounced in other two

pots. The contrast between pots can be explained by the different availability of electron acceptors (Fe^{3+} and SO_4^{2-}), which regulates the pace of redox processes in rice paddies. Notice for JS pot that the rise of Eh in drained situation is the highest, whereas the drop of Eh is retarded in re-flooded situation (Figure 1). As previously mentioned for JS pot, the dissimilatory Fe release from amorphous Fe-oxides is more likely and the concentration of SO_4^{2-} is persistently highest (55.6 – 78.6 mg L^{-1}) among three paddy pots (plot (f) in Figure 1). Consequently, the abundance of these electron acceptors essentially was able to retard the abrupt drop of Eh in re-flooded JS paddy [11,12], thereby suppressing CH_4 production. For these three periods, log of CH_4 flux was well correlated with the Eh of paddy water (Figure 3). The variation of Eh in JS paddy was largest ranging between CO_2 -reducing condition and Fe^{3+} reducing condition, whereas the Eh of MG paddy was ranging only in Fe^{3+} reducing condition. This indicates that impact of drainage on the Eh rise is pronounced in JS pot, but negligible in MG pot; so is the CH_4 mitigation. The Eh of BG pot fell below the CO_2 -reducing condition (< -180 mV) when flooded, and it increased in the range of < 0 mV when drained.

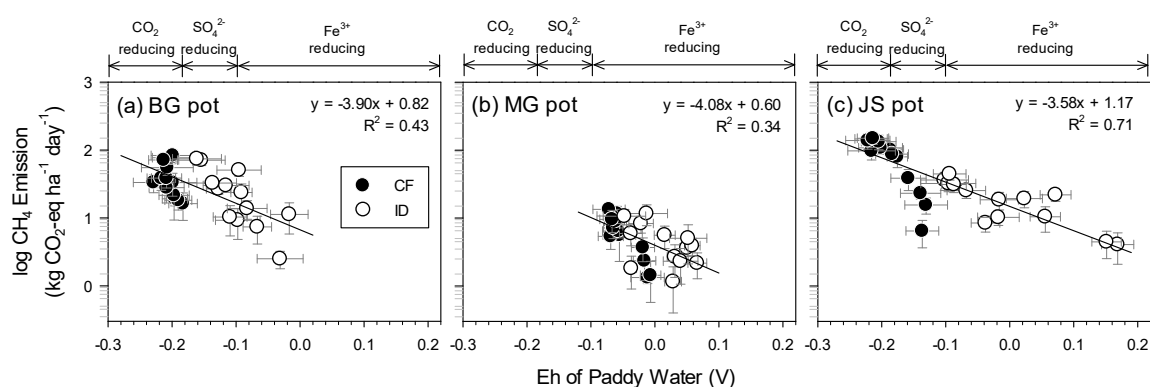


Figure 3. Correlation between the Eh in paddy water (V) and the log CH_4 emission ($\text{kg CO}_2\text{-eq ha}^{-1} \text{ day}^{-1}$) from flooded paddies of both continuous flooding (CF) and intermittent drainage (ID) method. Data point is the mean value of triplicates with the standard deviations shown as error bars. The solid line is regression fit and R^2 is the coefficient of determination.

3.5. Rice yield

The crop growth (rice grain yield and aboveground biomass) determined for all paddy pots are present in Table 2. The production of both grain and aboveground biomass in CF pots were in the following order: JS > BG > MG. The rice grain yield harvested in ID pots was slightly lower (approximately 10%) than CF pots, but the difference was not statistically significant. The growth data indicates that the drainage loss of the essential elements (e.g., N and C) in ID paddies is insufficient to inhibit the rice growth [29]. Similarly, Liu et al. [7] showed with meta-analysis data that the intermittent drainage has no effect on rice yield as long as the SOC level and N content (e.g., 50 kg N ha^{-1}) are sufficiently high, due to the enhanced decomposition of SOC in drained paddy. In general, the differences in crop production can be attributed to P availability in soils [4,30]. In this study, the concentration of available P determined for CF paddies (14.7 - 19.5 mg kg^{-1}) was higher than ID paddies (12.9 - 17.7 mg kg^{-1}), primarily due to the enhanced reductive dissolution of P-bearing minerals in flooded paddies [4,30]. However, the level of P in these paddies satisfies the required level (e.g., 13.5 mg kg^{-1}) for rice paddies recommend by Korea RDA. Even though it is apparent that the availability of nutrients (e.g., N and P) in paddies is influenced by drainage practice, its impact on rice production was not pronounced under the experimental settings of this study.

Table 2. Data^a of greenhouse gases (GHGs) emissions, rice production, and greenhouse gas intensity (GHGI) determined from the three different soils under two irrigation methods.

Paddy Pot	Irrigation Method ^b	GHGs Emission ($\text{t CO}_2\text{-eq ha}^{-1}$)			Rice Production (t ha^{-1})		GHGI ^d ($\text{t CO}_2\text{-eq t grain}^{-1}$)
		CO_2	CH_4	S GWP ^c	Grain	Aboveground Biomass	
BG	CF	3.87±0.12	3.24±0.22	7.11±0.25	7.09±1.08	15.35±2.06	1.00±0.19
	ID	4.94±0.15 (+28%)	1.16±0.09 (-64%)	6.10±0.17 (-14%)	6.23±0.96 (NS) ^e	13.42±2.35 (NS)	0.98±0.18 (NS)

MG	CF	2.77±0.21	0.48±0.03	3.26±0.21	5.82±0.86	12.68±1.78	0.56±0.12
	ID	3.25±0.19 (+17%)	0.19±0.02 (-61%)	3.44±0.19 (NS)	5.10±0.79 (NS)	12.35±1.87 (NS)	0.67±0.14 (NS)
JS	CF	5.05±0.12	6.62±0.33	11.67±0.35	7.79±0.55	16.04±1.55	1.50±0.15
	ID	6.30±0.13 (+25%)	1.02±0.06 (-85%)	7.32±0.14 (-37%)	6.98±1.19 (NS)	14.68±2.17 (NS)	1.05±0.20 (-30%)

^a An average value with standard deviation after \pm sign. ^b CF and ID denote continuous flooding and intermittent drainage, respectively. ^c Global warming potential (GWP) is the sum of CO₂ and CH₄ emissions as unit of CO₂-equivalents (kg CO₂-eq ha⁻¹). ^d The ratio between GHGs (CO₂ + CH₄) emission to rice grain production (kg CO₂-equivalents kg grain⁻¹). ^e Value in parentheses denotes the percentage reduction (-) or percentage increase (+) in rice production, GHGs emissions, and GHGI relative to the CF method. NS indicates not significant according to the *t*-test at the $p < 0.05$ level.

3.6. Efficiency of Intermittent Drainage on GHGs Reduction

Rice production (t ha⁻¹), the cumulative GHGs emission (t CO₂-eq ha⁻¹), and the associated index of GWP (t CO₂-eq ha⁻¹) and GHGI (t CO₂-eq t grain⁻¹) are present in Table 2. In CF method, the CO₂ and CH₄ emission over rice growing season was measured as 3.87 ± 0.12 and 3.24 ± 0.22 for BG pot, 2.77 ± 0.21 and 0.48 ± 0.03 for MG pot, and 5.05 ± 0.12 and 6.62 ± 0.33 for JS pot. The magnitude of two GHGs production (e.g., JS > BG > MG) was consistent with the order of labile carbon content in paddy pots (Table 1). Note that soil organic carbon is the primary source of electrons in soils [31] and the liable fraction of soil organic carbon is likely to act as preferential electron donors for soil microorganisms involved in GHGs forming reactions [10].

In ID method, the cumulative CH₄ emissions were greatly reduced as 64%, 61% and 85% of CF method in BG, MG and JS pots, respectively, mainly due to lower CH₄ production from drained oxic paddies (plots (g), (h), and (i) in Figure 2). Moreover, the CH₄ emission was also suppressed in re-flooding paddies of ID method as shown in Figure 2. In contrast, the cumulative CO₂ emissions increased by 28% and 25% in BG and JS pots, respectively, but the increment was insignificant in MG pot. Consequently, the reduction (%) of S GWP was significant (37%) only in JS pot. For both BG and MG pots, the decrease in CH₄ emission was quantitatively offset by the increase in CO₂ emission.

In terms of GWP budget, the above result suggest that the drainage practice is not an effective strategy for BG and MG pots. The BG pot showed a rapid transition to anoxic conditions (-161 mV < Eh < -17 mV) compared to other pots. In this case, it is recommended to apply amending materials with electron acceptors to retard abrupt drop of Eh value during re-flooding period [12], suppressing CH₄ emission when the paddy is re-flooded. For MG pot, the increase in CO₂ emission is well exceeding the decrease in CH₄ emission and S GWP is slightly greater in ID method. In this case, intermittent drainage may not be recommended for a strategy for mitigating GWP.

The greenhouse gas intensity (GHGI) was calculated by dividing S GWP by rice yield to estimate the magnitude of GHGs emission (t CO₂-eq ha⁻¹) per rice yield (t grain ha⁻¹) of a given rice cultivation (Table 2). The GHGI (t CO₂-eq t grain⁻¹) of three pots was in the order of JS (1.50 ± 0.15) > BG (1.00 ± 0.19) > MG (0.56 ± 0.12) in CF method and was JS (1.05 ± 0.20) > BG (0.98 ± 0.18) > MG (0.67 ± 0.14) in ID method. Consequently, JS pot exhibited the 30 % reduction of GHGI indicating that an introduction of ID practice can reduce 30 % of GWP without changing rice production. For both BG and MG pots, the difference in GHGI between two irrigation methods was not significant because the difference of both grain production and S GWP was not statistically different ($p = 0.05$).

Meanwhile, the emission of N₂O gas was not considered this study because we focused on the trade-off between CO₂ and CH₄ emissions by two irrigation methods. In literature, it was documented that the emission of N₂O is performed primarily by heterotrophic bacteria under transition condition from oxic to anoxic environments [32]. Extending the duration and increasing the drainage events elevates N₂O emission. Increasing the rate of N application also promotes N₂O emission [7,29]. For example, Xu et al. [9] observed 26% increase in N₂O emissions by implementing three drainage events at N application rate of 210 kg N ha⁻¹. In this study, three drainage events and 70 kg N ha⁻¹ of urea application were carried out. By reviewing the preceding results, it can be reasonably assumed that less than 26% increase of N₂O emission is expected to occur in ID pots, even though precise increment needs to be assessed by further work.

4. Conclusions

Results of this field pot study clearly demonstrate that the drainage practice can reduce the magnitude of GHGs emission, but the efficiency varied depending on the characteristics of paddy soils. The reduced CH₄ emission (%) by introducing drainage was enhanced by slow transition of the Eh to anoxic range in re-flooded paddy. This is the case of JS pot in which both Fe²⁺ and SO₄²⁻ dissolved in paddy water are consumed and the abrupt decline Eh value of paddy water is retarded. The benefit of CH₄ mitigation was largely counterbalanced by the increased amount of CO₂ emission from drained paddy. Therefore, the net benefit of S GWP by drainage practice was controlled by the balance of two GHGs emissions from given paddy. In this study, the mitigation of S GWP by intermittent drainage practice was apparent in BG and JS pots. However, when rice grain yield was combined together, the profit of drainage practice was only significant in JS pot, where CH₄ reductions were highest. Meanwhile, the intermittent drainage practice is not recommended for a paddy with low CH₄ emission, which is the case of MG pot in this study. Since the MG pot is highly percolative, irrigation water was frequently required to be refurnished and thus the decline of Eh and the emission of CH₄ were minimal. Therefore, it can be speculated that the practice of intermittent drainage cannot be a panacea for reducing GHGs in all types of paddy field. The strategies for applying intermittent drainage practice to mitigate GHGs should be precisely deployed by collecting local paddy characteristics, such as concentration of electron acceptors and percolation rate.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Table S1: Method and timing of a farming practices in the experiment field under continuous flooding and intermittent drainage; Figure S1: The components of the CO₂ and CH₄ flux measuring system (not to scale); Figure S2: Changes in air temperature and precipitations during the rice growing season; Figure S3: Pourbaix diagrams of Fe and S (25 °C) system (Davis and Ashenberg, 1989). The pH and Eh values measured in BG and MG pots containing magnetite are plotted in (a), and the pH and Eh values measured in JS pot containing ferrihydrite are plotted in (b) under the condition of intermittent drainage; Figure S4: Changes of soil wetness (v/v, %) measured at the depth of 5 cm from the soil surface. For the treatment of intermittent drainage, soil wetness at the 15 cm depth was also determined.

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