Study on ponding water management by intermittent irrigation to reduce methane emission from paddy fields

2022

Soken Matsuda

Contents

List of Figures

List of Tables

Chapter 1

General introduction

1.1 Food production and global warming

The world's population, currently estimated at 7.6 billion people, is predicted to increase to approximately 8.6 billion by 2030, 9.8 billion by 2050, and 11.2 billion by 2100 (UN, 2017), making it imperative to increase food production to feed this growing population. However, it is widely known that greenhouse gases are emitted as a consequence of agricultural practices. The global average annual temperature has risen significantly due to the effects of greenhouse gases, and it is predicted that the temperature will increase by up to 5.7°C by the end of this century (IPCC, 2021). Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), water vapor, ozone, and chlorofluorocarbons are among the substances that contribute to global warming. These substances absorb heat and increase the temperature of the atmosphere, the consequences of which include floods, typhoons, and droughts. The global warming potential of CH_4 and N_2O is 28 and 273, respectively, and when these emissions are converted to CO_2, the contribution of CO_2, CH_4, and N_2O to total anthropogenic emissions is 76%, 16%, and 6.2%, respectively (IPCC, 2013). Most of the CH_4 and N_2O emissions are of agricultural origin (IPCC, 2021).

Rice is a globally important crop as it is the staple food of more than half of the world's population and, in 2019, the global area of paddy fields was estimated at 162 million ha, accounting for approximately 11% of the world's arable land (FAOSTAT, 2019). It is widely known that paddy fields are a source of greenhouse gas emissions, especially CH_4 (Schütz et al., 1989; Minami, 1994; Cao et al., 1996). Of the world's three major cereal crops, rice cultivation emits more CH_4 per ha compared to that of wheat and maize (Linquist et al., 2012) and accounts for approximately 11% of the global CH_4 emissions from anthropogenic activities (Runkle et al., 2019). Thus, as global warming is expected to continue in the future, it is necessary to implement countermeasures against global warming in the agricultural sector, particularly in relation to rice production. There are two main types of agricultural policies with regard to global warming: *adaptation strategies* and *mitigation strategies*. As the air temperature rises and the amount and timing of precipitation changes due to global warming, it is highly likely that rice yields will decrease because growth will be hindered if rice is planted in the same way as before (Tripathi et al., 2016). Examples of rice cultivation adaptation strategies that could be implemented in response to possible future changes in rainfall patterns and average temperatures include: (1) using rice varieties with a later cropping season to avoid high temperatures during the ripening period, thus preventing quality deterioration; (2) cultivating varieties that can be harvested in a shorter period to reduce the possibility of exposure to drought and high temperatures; and (3) appropriately managing the amount of water supplied to paddy fields because it may become difficult to secure irrigation water when the timing of snowmelt or precipitation changes due to climate change. In addition, because rice paddies are one of the major sources of greenhouse gas emissions, mitigation strategies to reduce greenhouse gas emissions are also required. According to the Fifth Assessment Report of the IPCC (2014), mitigation strategies implemented in the agriculture, forestry, and other land use sectors are cost-effective and provide economic, social, and adaptive co-benefits. Therefore, efforts to reduce CH_4 emissions from rice paddies for productive and sustainable rice cultivation are expected to contribute significantly to mitigating the impacts of climate change.

1.2 Mitigation of CH_4 emissions by water management

Greenhouse gas emissions from rice paddy soils are controlled by redox reactions mediated by several soil microorganisms. Unlike the production of CO_2 and N_2O, which can occur under both aerobic and anaerobic conditions, CH_4 production proceeds only in anaerobic environments (Yagi and Minami, 1990). When paddy fields are flooded, water covers the soil and prevents air from entering it. As a result, oxygen, which was abundant in the soil before flooding, decreases in availability, and the environment eventually shifts to one suitable for CH_4 production. Thus, the amount of oxygen or the amount of soil moisture has a key influence on the redox state of the soil. Therefore, irrigation plays an important role in the control of greenhouse gas emissions.

It is an old practice in Japan that many farmers try to dry their fields for approximately a week (mid-term drainage) and irrigate them intermittently after that (Kanno et al., 1997). The purpose of this practice is to increase yield (1) by aeration of the roots to increase root vigor, and facilitate root penetration into the subsoil to prevent toppling and increase weather resistance; (2) by suppression of the supply of ammonia nitrogen to prevent excessive tillering; and (3) by hardening the soil, thus improving workability for top-dressing and harvesting (Leon et al., 2015). As a result, this water management practice has been shown to reduce CH_4 emissions (Yagi et al., 1996). However, in rice cultivation in Southeast Asian countries, continuous-flooding water management is customary, and tends to lead to the development of soils in a strong reducing state, which supports CH_4 production. Therefore, draining water more than once during the rice cropping season to create an oxidized soil state is expected to result in reduced CH_4 emissions (Yagi et al., 1996; Wassmann et al., 2000). To this end, an intermittent irrigation method termed alternate wetting and drying (AWD; Lampayan et al., 2015a) has attracted much attention in recent years (see Chapter 2).

1.3 Efforts in Vietnam

Vietnam, one of the countries where rice is a staple food, is the fifth largest rice producer in the world, accounting for approximately 6% of the total production (FAOSTAT, 2019). Coarse water management may affect water and air quality through water pollution caused by fertilizer, pesticide runoff, and greenhouse gas emissions. Regarding greenhouse gases, Vietnam is reported to account for approximately 5% of the CH_4 emitted from rice paddies worldwide (FAO, 2017). In Vietnam, rice cultivation accounts for up to 51% of agricultural and 16% of total anthropogenic greenhouse gas emissions; of these, CH_4 is a major contributor, raising concerns about CH_4 emissions from rice paddies and promoting social demands for the implementation of agricultural mitigation strategies (MONRE, 2014). The rice paddy area in the Red River Delta is one of the major rice-growing regions in Vietnam, and substantial efforts are being made to implement mitigation strategies in the agricultural sector in this region (UNFCCC, 2015). As rice cultivation is conducted two to three times a year in Southeast Asian countries, including in the Red River Delta region in Vietnam, the practice of *environmentally friendly management* in paddy areas is important and has become the focus of research.

Most farmers in Vietnam’s Red River Delta region are small-scale farmers with less than 0.5 ha of farmland and high labor input for cultivation (Tuan and Satoh, 1998). A major problem in these farmlands is the lack of water supply in most downstream plots due to inadequate coordination between water management organizations and farmers, and the lack of adequate secondary and tertiary canals despite the availability of primary irrigation facilities. To provide sufficient water to each field, farmers are forced to use additional labor inputs or, more recently, use portable pumps to obtain water from adjacent canals. In this context, it is essential to improve irrigation and drainage systems to increase land and labor productivity (Tuan and Satoh, 1998). Thus, the improvement of irrigation systems in rice paddies in Vietnam will benefit rice production in this country, and the study of environmentally friendly and water-saving management practices is expected to provide useful knowledge not only applicable to rice production in Vietnam but also in neighboring countries at similar stages of development.

1.4 Research problems

Alternate wetting and drying has been researched for its potential to reduce CH_4 emissions; it has also attracted attention as a water-saving irrigation method to effectively utilize limited water resources. However, past studies on AWD have been conducted on a relatively small scale, such as in pot tests and test plots, and few studies have applied AWD to actual farmland to promote this practice in general. This is because AWD does not provide any direct benefits to farmers, such as increased yields. In the paddy field regions of Southeast Asia, which account for 27% of the world's paddy field area, there is a need to implement environmentally friendly water management using AWD over a wide area and to quantitatively evaluate the effect of AWD on reducing greenhouse gas emissions.

1.5 Research objectives

This study aimed to formalize ponding management by intermittent irrigation to reduce CH_4 emissions from rice paddies as a global warming mitigation strategy in the agricultural sector. The research was conducted in the field (Red River Delta, Vietnam) and in laboratory tests, and the specific objectives were to:

1. Study the feasibility of organized AWD water management at the district level in the rice paddies of the Red River Delta in Vietnam and to establish a system that enables organized water management by water management organizations given that it is difficult to ask individual farmers to manage water in an environmentally friendly way.
2. Determine the effects of organized AWD water management by water management organizations on ponding depth, greenhouse gas emissions, and rice yield.
3. Draft a concrete ponding water management schedule for mitigation of CH_4 emissions considering the CH_4 production mechanism based on the ponding depth, soil redox potential, and CH_4 flux data obtained from the experimental plots.
4. Estimate the CH_4 emission mitigation effect and water-saving effect of the draft ponding water management schedule.
5. Investigate the effect of the infiltration rate, which is considered to affect the schedule, on CH_4 emission and redox condition in the soil during AWD application through rice cultivation in pots under different infiltration rates.

1.6 Outline of the thesis

This thesis consists of six chapters: a general introduction, a review of previous studies, three main chapters, and a summary. A brief description of the contents of each chapter is provided below.

Chapter 1 describes the background, research problems, and objectives of the study. Chapter 2 contains a review of previous studies, with a focus on the mechanisms that underly the production of CH_4 in paddy soils and its emission from these soil to the atmosphere, the approaches that exist to mitigate CH_4 emissions, and the nature of AWD water management. Chapter 3 reports that district-level organized AWD water management is feasible in rice paddy areas in the Red River Delta of Vietnam, and clarifies the effects of this organized water management on ponding depth, CH_4 and N_2O emissions, and rice yield. In Chapter 4, the importance of providing farmers and water managers with a concrete ponding management schedule for sustainable organized water management is discussed. Draft ponding management schedules to mitigate CH_4 emissions considering the CH_4 production mechanism, and based on the field observation data (ponding depth, soil redox potential [Eh], and CH_4 flux), are described. In addition, estimates of the effect of the schedules on the suppression of CH_4 emissions and the effect of water conservation are presented. Chapter 5 reports on the effects of infiltration rate on the soil redox conditions and associated CH_4 emissions to the atmosphere, which are considered to be factors that affect the schedules. These effects were investigated by pot cultivation tests on rice plants because the formulated ponding management schedules are area specific. Chapter 6 provides a summary of the study, with a focus on what has been found so far and the issues that require clarification in future research.

Chapter 2

Literature review

2.1 Paddy soil CH_4 emissions

2.1.1 Mechanisms of CH_4 production in paddy soil

Rice paddies are a non-negligible source of CH_4, a greenhouse gas (Conrad, 2002). Asia accounts for approximately 88% of global CH_4 emissions from rice paddies (FAO, 2017), making the control of rice paddy CH_4 emissions an important issue for Asian countries. To address this issue, there has been a substantial increase in the number of studies measuring CH_4 fluxes in paddy fields under different conditions, in different regions, and at different times of the year. In publications of previous field and laboratory studies, the researchers have speculated about the major factors that affect CH_4 emissions, with the most important factors considered to be *soil type*, *rice variety*, *temperature*, *soil redox potential (Eh)*, *water management*, and *organic carbon and nitrogen fertilization* (Conrad, 2002).

Methane-producing bacteria (methanogens) in paddy soil are obligate anaerobes, that are activated under strong reducing conditions in the soil. After flooding, the amount of molecular oxygen in the soil decreases due to the metabolic activity of aerobic bacteria, and the Eh decreases accordingly. Thereafter, the reduction of NO_3^- to N_2 or N_2O by denitrifying bacteria (denitrification) becomes the dominant process. With a further decrease in Eh, iron-reducing and sulfate-reducing bacteria begin to compete with the methanogens for hydrogen (H_2), and the amount of H_2 increases again once the ferric ions (Fe^{3+}) and sulfate (SO_4^{2-}) are depleted. The formation of CH_4 begins when the Eh reaches −150 to −200 mV (Wang et al., 1993; Yagi and Minami, 1993). Thus, all these reactions are mediated by soil microorganisms. Subsequently, the rate of CH_4 production becomes temporarily constant as the amount of substrate H_2/CO_2 and acetic acid decreases, and CH_4 production is eventually suppressed (Conrad, 2002). The presence of high amounts of readily degradable organic substrates (including acetate, formate, methanol, and methylamine) and low amounts of NO_3^-, Mn^{4+}, Fe^{3+}, and SO_4^{2-} (electron acceptors) in the soil results in high CH_4 production (Wassmann and Aulakh, 2000).

Soil temperature also affects greenhouse gas emissions from the soil. However, under actual field conditions, the effects of water content and temperature are so complex that it is difficult to evaluate their effects in isolation (Fang and Moncrieff, 2001). As soil temperature increases, microbial metabolism increases, and as a result, the production and emission of CH_4 and N_2O also increase (Butterbach-Bahl et al., 2013). The effect of temperature change on the amount of gas emitted from the soil has been evaluated using the temperature coefficient (Q_{10}). This represents the number of times the reaction rate increases when the temperature increases by 10°C (Meyer et al., 2018). Dunfield et al. (1993) studied CH_4 production under anaerobic conditions in a slurry of peat samples at different temperatures (0−35°C) and pH values (pH 3.5−8). According to their experiments, CH_4 production is negligible in the 0−10°C range, the optimum temperature is approximately 25°C, and the Q_{10} value of CH_4 production is 5.3−16.

2.1.2 Methanogens

Methane production can be attributed to microbial or geothermal decomposition of organic matter. In the context of the three domain classification system of organism (*Bacteria*, *Archaea*, and *Eukarya*), methanogens fall into the domain *Archaea*. *Archaea* are unicellular organisms with a cell size of approximately 1 µm, which are indistinguishable from *Bacteria* in terms of their cell shape and size. Although *Archaea* are prokaryotes without nuclei, their biochemical properties are more similar to *Eukarya* than to *Bacteria*. Methanogen habitats range from extreme environments such as hydrothermal vents in the ocean to places close to our living environments such as marine sediments, soils, rice paddies, digestive tracts of ruminants and termites, wetlands, and lake sediments. Most methanogens are mesophilic and can produce CH_4 at temperatures ranging from 20 to 40°C (Dubey, 2005). Methanogens can be divided into those that use only H_2 and CO_2, those that use only acetic acid, those that use methyl compounds such as methanol and methyl diamine, and those that use lower alcohols such as ethanol. Of these, hydrogenotrophic methanogens that use only hydrogen and carbon dioxide (some can use formic acid), and aceticlastic methanogens that use acetic acid, play a particularly important role in the production of CH_4 from organic matter (Conrad, 1999), accounting for approximately 20% and 80% of methanogens, respectively (Malyan et al., 2016). The decomposition of organic matter to gas in the CH_4 production process proceeds in three stages (Shigematsu et al., 2009). In the first stage of the acid production process (liquefaction process), complex organic matter is transformed by the action of acid-producing bacteria into small molecular weight substances such as monosaccharides and amino acids, followed by acetic acid and lower fatty acids such as propionic acid and butyric acid, and then lactic acid and ethanol. In the second stage, lower fatty acids other than acetic acid, lactic acid, and ethanol are converted into hydrogen and acetic acid by hydrogen-producing bacteria, and in the third step, they are decomposed into CH_4 and CO_2 by methanogens with strong substrate specificity. Two pathways are considered for CH_4 production from acetic acid: (1) a reaction by acetic acid-utilizing methanogens (**Table 2.1 [reaction 1]**, **Fig. 2.1**), and (2) a thermodynamic symbiosis between acetic acid-oxidizing bacteria and hydrogen-utilizing methanogens (**Table 2.1 [reaction 4]**). The order Methanosarcinales is reported to contain acetate-utilizing methanogens capable of performing reaction 1 (**Table 2.1**) (Yuan et al., 2018). In contrast, the decomposition of propionic acid to acetic acid proceeds via a thermodynamic symbiosis reaction between propionate-oxidizing bacteria and hydrogen-utilizing methanogens (**Table 2.1 [reaction 6]**).

Table 2.1 Degradation reactions of acetate and propionate under methanogenic conditions (Shigematsu et al., 2009)

(1) Aceticlastic methanogens	$CH_3COO^- + H_2O \rightarrow CH_4 + HCO_3^-$
(2) Acetate-oxidizing bacteria	$CH_3COO^- + 4H_2O \rightarrow 2HCO_3^- + 4H_2 + H^+$
(3) Hydrogenotrophic methanogens	$4H_2 + HCO_3^- + H^+ \rightarrow CH_4 + 3H_2O$
(4) Reaction (2) + (3)	$CH_3COO^- + H_2O \rightarrow CH_4 + HCO_3^-$
(5) Propionate-oxidizing bacteria	$CH_3CH_2COO^- + 3H_2O$ $\rightarrow CH_3COO^- + HCO_3^- + 3H_2 + H^+$
(6) Reaction (3) × 3 + (5) × 4	$4CH_3CH_2COO^- + 3H_2O$ $\rightarrow 4CH_3COO^- + 3CH_4 + HCO_3^- + H^+$
(7) Reaction (6) + (1) × 4	$4CH_3CH_2COO^- + 7H_2O \rightarrow 7CH_4 + 5HCO_3^- + H^+$

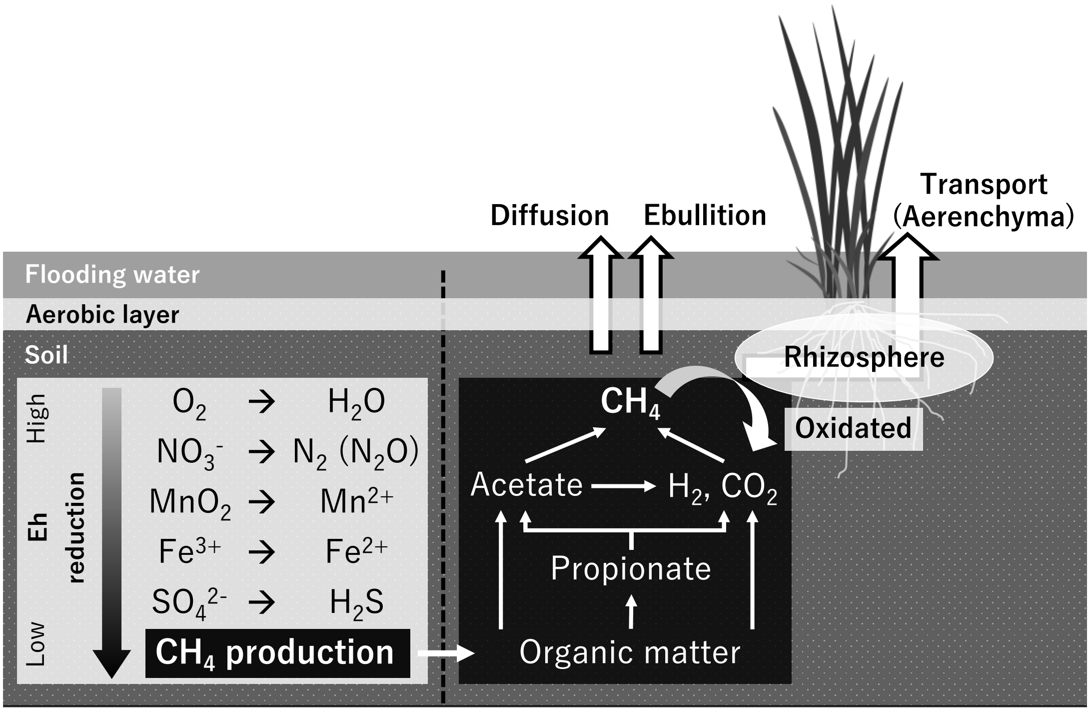

Fig. 2.1 Reduction reaction and flow of CH_4 produced in flooded paddy soil

The orders Methanocellales, Methanomicrobiales, and Methanobacteriales are reported to contain hydrogen-utilizing methanogens (Yuan et al., 2018).

A method used to quantify the presence of methanogens in soil involves the measurement of the amount of the mcrA gene, which is unique to methanogens. Watanabe et al. (2010) investigated the number of mcrA genes in the depth direction in soil and observed that the distribution of methanogens was similar to that of rice roots. Ma et al. (2012) studied the relative amounts of mcrA genes and mcrA transcripts in soil over time by growing rice plants in continuously flooded and intermittently irrigated pots. Their results showed that the relative amounts of the mcrA gene in the soil are not affected by water management; however, the amount of transcripts is reduced by drainage. This biological approach to determining soil methanogen content also indicates that drainage inhibits CH_4-producing activity in the soil.

2.1.3 Oxidation and emission of CH_4 and the effect of rice plants

The amount of CH_4 emitted into the atmosphere is the difference between the amount of CH_4 produced in the soil and the amount oxidized (Satpathy et al., 1997). Methane-utilizing bacteria (methanotrophs) generally use CH_4 or methanol as an energy source (Semrau et al., 2010). Because O_2 is also required for the oxidation of CH_4, these bacteria proliferate and are active at the aerobic-anaerobic interface where both CH_4 and O_2 are present. In rice paddies, this environment is generally found in the rhizosphere and in a thin layer of topsoil (Liesack et al., 2000). Up to 80% of the CH_4 produced in the soil is oxidized before being emitted to the atmosphere (Malyan et al., 2016). Methane is more easily oxidized in soils planted with rice than in soils without rice plants, because O_2 is supplied to the roots through the rice plant body (Wassmann and Aulakh, 2000).

Methane is present in gaseous or dissolved forms in paddy soils (Tokida et al., 2005). However, because CH_4 is not in ionic form, its solubility is as low as 17 mg in 1 L of water at 35°C (Malyan et al., 2016), and it is thought to exist mostly as a gas. Methane is emitted from rice paddy soil to the atmosphere in three ways: ebullition, diffusion, and transport within the rice plant (**Fig. 2.1**).

Diffusion and ebullition are both physical processes; however, diffusion is slower than ebullition and contributes less to CH_4 emission from soil because of the lower solubility of CH_4 in water (Malyan et al., 2016). Ebullition involves the emission of CH_4 as bubbles (Green, 2013), and is observed particularly during the early stages of rice growth (Wassmann et al., 1996). Seasonal variation in the amount of ebullition generally follows a bimodal pattern throughout the cropping season. In the middle stage of growth, CH_4 transport through the aerenchyma of the rice plants increases and the amount of CH_4 trapped in the soil decreases, resulting in a decrease in the amount of ebullition; however, in the late growth stage, CH_4 production shows high activity due to the supply of organic matter from the plant (Wassmann and Aulakh, 2000), resulting in an increase in the amount of trapped CH_4 and an associated increase in ebullition (Wassmann et al., 1996).

The transport of CH_4 within rice plants is a biological process, which occurs via the aerenchyma. The main function of the aerenchyma is to deliver O_2 to the roots; however, CH_4 also moves through the cells of this tissue but in the opposite direction to O_2 (Nouchi et al., 1990). Approximately 90% of the CH_4 emitted from rice paddies during the cropping season is transported within the rice plants (Schütz et al., 1989; Setyanto et al., 2004). During the process of CH_4 transportation from the roots to the aboveground zone, CH_4 dissolved in soil water in the rhizosphere first diffuses into the cells of the root cortex along a concentration gradient. Cracks at the junction of the main root and root hairs are the main entry points for CH_4 (Wassmann and Aulakh, 2000). After entering the plant, CH_4 is gasified in the root cortex and transported to the aboveground zone via the aerenchyma. Finally, CH_4 is emitted into the atmosphere from various parts of the rice plant (Nouchi et al., 1990).

The rice crop itself also influences CH_4 production to varying degrees depending on its growth stage. Rice plants not only enhance soil anaerobiosis by consuming O_2 in the rhizosphere via respiration, but also influence the soil Eh and CH_4 production by supplying carbon and energy sources to rhizosphere microorganisms as organic compounds (electron donors) from readily degradable organic substrates in the root exudates and shed root tissues (Wassmann and Aulakh, 2000). In general, the secretion of root exudates is maximal during the vegetative stage of the rice crop, and peak CH_4 production is observed to coincide with the vegetative stage (Suryavanshi et al., 2013).

2.2 Methods to control CH_4 emissions

Fertilizer management, soil organic matter management, rice variety selection, rice planting methods, and water management are some of the techniques used to mitigate CH_4 emissions from rice paddies. However, the implementation of each of these mitigation measures must take cognizance of the following: It is noted that farmers' consent is important when considering the field application of new technologies such as those listed above, and in some cases, obtaining this consent may be a constraint (Sánchez et al., 2016). Each farmer has a customary way of cultivating rice, and new techniques that are not yet widespread may be perceived as not good (Sanz-Cobena et al., 2017). In addition, if the management practices are difficult, misuse may further reduce yields, which would exacerbate negative impressions about the new technology. Therefore, it is important to develop technologies from the perspective of who will be using them.

2.2.1 Methods other than water management

2.2.1.1 Fertilizer management

Fertilizers added to the soil are not always effective for supporting crop growth, and proper management of the amount and type of fertilizer application is important for reducing the impact of greenhouse gases emitted from paddy fields (Hussain et al., 2015). For example, Cai et al. (1997) have shown that the application of ammonium sulfate (100 and 300 kg N ha^{-1}) in paddy fields under intermittent irrigation reduces CH_4 emissions by 42%−60% compared to the control (0 kg N ha^{-1}), a finding attributed to substrate competition between sulfate-reducing and methanogenic bacteria (Denier van der Gon et al., 2002). In addition, Dong et al. (2011) have reported that the addition of ammonia-based non-sulfate fertilizers 150 kg N ha^{-1} (base fertilizer and one additional fertilizer) and 250 kg N ha^{-1} (base fertilizer and two additional fertilizers) to rice soils reduces CH_4 emissions by 38%−49%. Nitrogen fertilizer activates methanotrophs, which results in higher CH_4 oxidation in paddy soils (Banger et al., 2012). It has been noted that the application of N fertilizer may increase N_2O emissions instead of decreasing CH_4 emissions (Pittelkow et al., 2013), and this trade-off between the production of CH_4 and N_2O must be taken into account.

To address this trade-off, studies have been conducted to investigate the reduction of both CH_4 and N_2O emissions from paddy fields by adding nitrification inhibitors or slow-acting N fertilizers. Nitrification inhibitors reduce N_2O emissions by decreasing the amount of nitrification and the amount of nitric acid required for denitrification (Hussain et al., 2015). Xu et al. (2002) showed that the combined addition of hydroquinone, which inhibits the action of urease in hydrolyzing urea to CO_2 and ammonia, and dicyandiamide, a nitrification inhibitor, reduces N_2O and CH_4 emissions. They stated that Eh values in the rhizosphere of rice plants increase in the presence of dicyandiamide, resulting in a decrease in CH_4 emissions.

2.2.1.2 Soil organic matter management

As CH_4 production in paddy soil requires organic matter as a substrate for methanogens, CH_4 emissions can be controlled by managing the amount of organic matter in the soil. According to Wassmann et al. (2002), when comparing the emission of CH_4 associated with the same cultivar grown with and without rice straw addition, the average CH_4 emission increased by 3.8 times under conditions where rice straw was added at a rate of 5 t ha^{-1} during the wet season, and by 3.6 times under conditions where rice straw was added at a rate of 3 t ha^{-1} during the dry season. Therefore, removal of post-harvest residues of the previous crop or addition of organic matter after pre-cultivation composting could reduce CH_4 emissions. However, it has been pointed out that removing post-harvest residues after each crop may reduce soil organic matter in the long term, which may have a significant impact on soil fertility, or at the same time reduce the carbon sequestration potential of the soil and cause net emissions of CO_2 to the atmosphere (Yagi et al., 2020).

Biochar, which is carbonized organic matter such as agricultural and forestry wastes, waste wood, and food wastes, has attracted attention as a technology for reducing greenhouse gas emissions (Feng et al., 2012; Ly et al., 2014). As there are various types of biochar, further research is needed to understand the greenhouse gas reduction effects of different biochar qualities (related to the raw materials and preparation methods), utilization methods, and decomposition rates (Yagi et al., 2020). Biochar is generally expected to increase soil fertility and improve rice growth and yield because of its high porosity and capacity to retain water and nutrients (Bhattacharjya et al., 2016). However, care should be taken regarding the type of organic matter used and the amount applied because many experiments have shown that the field application of compost without sufficient composting can increase the release of CH_4.

2.2.1.3 Rice variety selection

Mitigation strategies have also been proposed using a breeding approach. The CO_2 absorbed by the rice leaves and stems is converted into sugars through photosynthesis. These sugars are used to produce starch in the shoots, roots, and seeds. In general, the higher the photosynthetic activity, the higher the biomass production, and the greater the allocation of products to each part of the plant (i.e., shoots, roots, and seeds): thus, biomass production and the associated emission of excess carbon to the soil and CH_4 production are proportional to the amount of solar radiation that the plant receives (Sass and Cicerone, 2002). However, following the report that higher CH_4 emissions are observed in the wet season, when solar radiation is lower than in the dry season (Corton et al., 2000), Denier van der Gon et al. (2002) showed that cutting rice spikelets at various rates to reduce their capacity to store photosynthetically fixed carbon in the grain results in lower grain yields and redistribution of some of the carbon that would have been transferred to the grain for CH_4 production. They stated that these results suggest that CH_4 emissions can be reduced by optimizing rice productivity. In other words, larger rice grains and higher starch content mean that less carbon is transported to the soil and converted to CH_4.

Su et al. (2015) developed SUSIBA2 rice by introducing a single transcription factor gene, barley SUSIBA2, into rice. This has resulted in rice plants that show a greater distribution of photosynthates to the above-ground biomass (reflected as increased starch content) than to the roots. Field tests conducted over a three-year period in China showed that SUSIBA2 rice cultivation results in a significant reduction in CH_4 emissions and a decrease in methanogenic bacterial levels in the rhizosphere. The development of rice varieties, such as SUSIBA2 rice, that show a combination of high productivity and low CH_4 emissions may increase in the future.

2.2.1.4 Rice planting methods

Direct seeding of rice is the practice of growing rice by sowing seeds in the field, rather than transplanting seedlings grown in a nursery into the field. There are three methods of direct rice seeding: dry seeding (sowing dry seeds into dry soil), wet seeding (sowing pre-germinated seeds on wet puddled soils), and water seeding (sowing seeds into standing water) (Farooq et al., 2011). The reason why CH_4 emission can be suppressed by direct seeding is because the soil is in an oxidized state due to the absence of flooding, especially during the early crop growth stages (Kumar and Ladha, 2011). Dry seeding has been the dominant method used in developing countries since the 1950s (Pandey and Velasco, 2005), and requires less labor than transplanting cultivation because it does not require watering or transplanting seedlings into the paddy fields. Therefore, direct seeding cultivation is appropriate when wages are high and the amount of available irrigation is insufficient; conversely, transplanting cultivation is appropriate when wages are low and sufficient water exists. There are some disadvantages of direct seeding cultivation which may result in lower yields, including weeds that tend to thrive and are costly to control (Rao et al., 2007), uneven nitrogen fertilization, and deficiencies of micronutrients such as Zn and Fe caused by high infiltration rates (Saleque and Kirk, 1995; Gao et al., 2006).

In most parts of the world, direct seeding was replaced by transplanting in the 1970s (Kumar and Ladha, 2011); however, there are reported cases where CH_4 emission is suppressed by adopting direct seeding cultivation. For example, in a field experiment in the Philippines

(Corton et al., 2000), the emission of CH_4 was compared among the treatments: direct seeding and transplanting under dry and wet seasons, and under water management conditions of continuous flooding and mid-term drainage, and the results showed that direct seeding reduces emissions by 12%–49%, where direct seeding with mid-term drainage in the wet season has the highest reduction. Susilawati et al. (2019) also compared the effects of direct seeding and transplanting cultivation on CH_4 and N_2O emissions in an experimental field in Indonesia during the wet season, and found that CH_4 emissions are 47% lower under direct seeding cultivation. In rice paddy soils, there is a trade-off between N_2O and CH_4 production, and whereas the possibility of increased N_2O emissions due to lower water usage during initial cropping under direct sowing cultivation occurs, no significant differences were found in this experiment. Li et al. (2019) showed that higher planting densities under direct seeding cultivation result in higher rice production, which in turn increases the emission of CH_4.

2.2.2 Water management methods

2.2.2.1 Paddy water management in Japan

Paddy water management methods include shallow flooding, deep flooding, intermittent irrigation, and mid-term drainage, and their expected effects are shown in **Table 2.2** (NARO, 2021). Deep flooding is used when the priority is to maintain the temperature of the rice, and intermittent irrigation is used to maintain the vitality of the roots by supplying oxygen. Therefore, water management is an important technology for controlling rice growth, and it is necessary to select a water management method that is appropriate for the growth conditions and growth environment of rice. The general rice paddy water management system implemented in Japan is illustrated in **Fig. 2.2** and described as follows (NARO, 2021).

Table 2.2 Rice paddy water management approaches and their effects on growth and the growing environment (NARO, 2021)

Water management	Heat keeping	Promoting tillering	Nutrient uptake	Oxygen supply
Shallow flooding	Medium	High	High	None−Low
Deep flooding	High	None−Low	Medium	Low
Intermittent irrigation	Low	Medium	Medium	Medium
Mid-term drainage	None−Low	None−Low	None−Low	High

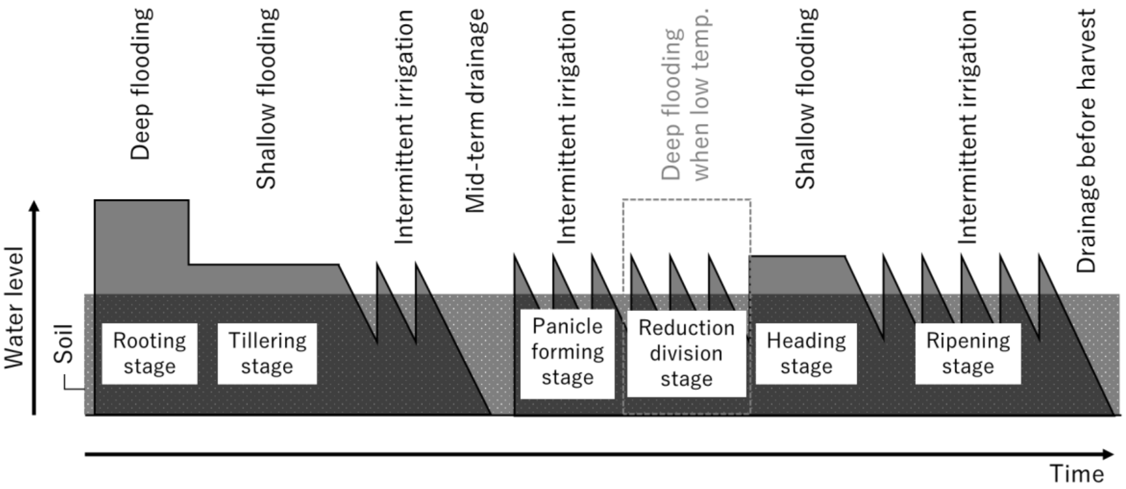

Fig. 2.2 General rice paddy water management system in Japan (NARO, 2021)

Rooting stage

The optimum temperature for rice plant rooting is 25−30°C. To hasten rooting under low-temperature conditions, it is important to keep the water temperature as high as possible by ponding depth management. The ponding depth should be kept shallow (3−4 cm) during the day to raise the water temperature, and should be increased to approximately 5 cm at night. During the rooting stage, low temperatures and wind not only delay rooting, but also cause plant damage due to forced evapotranspiration and physical damage to the seedlings, and in severe cases, the seedlings die. Under such conditions, as a protective measure, the ponding water should be deep enough to cover three-quarters of the height of the seedlings.

Tillering stage

One of the key objectives of water management during the tillering stage is to secure early vigorous tillering from the second to the fifth nodes, which have high productivity. To meet this objective, shallow water management is implemented and a depth of approximately 3 cm is maintained to promote tillering, as well as to cause an increase in water temperature during the day and a decrease at night to increase the daily temperature difference. However, since shallow water management promotes the reduction of paddy soil, intermittent irrigation should be applied on warm days in rice fields where there is continuous use of rice straw or poor drainage.

Tillering stage to panicle formation stage

During the tillering to panicle formation stages, control of ineffective tillering is important to strengthen disease resistance and lodging resistance in order to improve rice growth by suppressing excessive nitrogen absorption. Therefore, when the target number of tillers is reached, the soil should be dried (mid-term drainage). The mid-term drainage not only has the effect of improving rice growth, but also increases the soil bearing capacity and improves the efficiency of mechanical work. The degree of drying is based on the extent to which small cracks of 1 cm or less in width appear on the surface of the field; however, drying should be intensified in straw-fertilized fields or fields with excessive growth, and shortened in fields with poor growth. After drying, intermittent irrigation is implemented to supply water and oxygen alternately to avoid reducing the vitality of the rice plants. Because the reduction division stage is the most susceptible to sterility damage caused by low temperatures, when low temperatures are expected, the panicles should be protected by deep flooding.

Heading stage

Immediately after emergence, ears are susceptible to physical damage, and disturbances in the physiology of water in the rice plant body can also affect flowering and fertilization. Therefore, sufficient flooding should be maintained during the heading stage.

Ripening stage

After flowering, the rice crop is irrigated intermittently to promote the development and elongation of branching roots and to maintain root vigor. Drainage before harvesting should be performed approximately 30 days after heading to enable machines to enter the fields. However, the later the field is drained, the better the yield and quality improvement, and the timing of drainage should be determined by the harvest date and soil moisture conditions.

2.2.2.2 Alternate wetting and drying

Alternate wetting and drying is an intermittent irrigation method developed for water conservation, and is a water management technique that involves repeated flooding and non-flooding (Lampayan et al., 2015a). This method has been reported to reduce irrigation water requirements (Oo et al., 2018a), reduce surface water drainage, and control runoff of fertilizer components by surface water drainage without reducing yield (Liang et al., 2013). The International Rice Research Institute (IRRI) has promoted AWD as a water-saving technology for rice cultivation via its national agricultural research in Bangladesh, the Philippines, and Vietnam.

When implementing AWD, a polyvinyl chloride pipe with holes drilled into the wall is often inserted into the field to facilitate water depth checking. The holes in the pipe wall enable water to enter the pipe from the surrounding area to indicate the water level above and below the ground surface. When the water level reaches 15−20 cm below the surface, irrigation is applied, and the field is flooded to a depth of approximately 5 cm. Drying before and after the heading stage lowers the rate of rice ripening and significantly reduces the yield (Matsushima, 1962). To control weed growth, intermittent irrigation should be started 1−2 weeks after transplanting. Therefore it is important to avoid drying the soil during these periods.

The process of AWD periodically oxidizes paddy soils and has been reported to have many benefits with regard to the reduction of CH_4 emissions (Begum et al., 2019; Fertitta-Roberts et al., 2019; LaHue et al., 2016; Setyanto et al., 2018; Tirol-Padre et al., 2018). Runkle et al. (2019) conducted a 3-year experiment in rice fields in central Indonesia to investigate the feasibility of AWD during both wet and dry seasons. Their results showed no significant difference in rice yield between the AWD and continuous flooding treatments during both the wet and dry seasons. However, AWD significantly reduced the total CH_4 emission to 35%−38% of that associated with continuous flooding. This study showed that the AWD system is effective even in the wet season because the study area is located on an upland and well-drained plateau.

There are several reports on the water-saving effects of AWD, and related studies have been conducted not only in Asian countries such as Vietnam, India, China, Thailand, and the Philippines, but also in Europe, South America, and Africa (Carracelas et al., 2019; Jalindar et al., 2019; Lagomarsino et al., 2016; Lampayan et al., 2015b; Liang et al., 2016; Shaibu et al., 2015; Son et al., 2008). The water-saving effect of AWD varies by region and season (high or low precipitation); for example, 4.5% in Thailand under full water level control (Sriphirom et al., 2019) and 79.8% (Oo et al., 2018b) in India during the monsoon season.

To implement mitigation strategies using water management practices, certain irrigation and drainage systems must be in place. Less than half of the paddy fields in Southeast Asia are irrigated (approximately 42%; Redfern et al., 2012), of which Malaysia has the highest percentage (75%), whereas Lao PDR has the lowest percentage (11%), and Vietnam has a higher than average percentage (65%). In the future, it will be important to increase irrigation and drainage installations to mitigate global warming by practicing environmentally friendly water management.

2.2.2.3 Organizational water management

It is difficult to promote the use of mitigation strategies based on water management unless there are direct benefits for each of the farmers who manage the paddy fields. Therefore, the implementation of a water management system that operates on an organizational, rather than on a farmer-by-farmer basis, can be expected to be more effective at reducing the emissions of greenhouse gases.

Examples of organizational water management systems that are currently operating effectively are termed *subak* organizations in Bali, Indonesia, *muang fai* groups in northern Thailand, and *land improvement districts* in Japan (MAFF, 2003). A subak is a water users' community organization, and the name is derived from the word *seuwak*, which means *distribution of running water*. Each subak organization determines policies such as the start of cropping, sets the dates of rituals, and also takes responsibility for the repair of irrigation facilities (Saptom et al., 2015; Jansing et al., 2020). The area of paddy managed by one organization ranges from 2−500 ha, and there are approximately 1,600 subak organizations throughout Bali. Muang fai groups are responsible for water allocation, maintenance of irrigation facilities, and mediation of water use disputes, and there is an organization for each small river in northern Thailand (Ounvichit et al., 2006). The muang fai system functions on fairness, based on a code called *sanya*. In Japan, irrigated rice cultivation has been practiced for a long time, and irrigation was managed by water users' associations based in village communities until after World War II (Tanaka and Sato, 2005). At this time, there were various conflicts over irrigation water among the water users' associations due to unequal water allocation, that is, differences in the amount of irrigation water available upstream and downstream. However, with the enactment of the *Land Improvement Act* in 1949, land improvement districts were established, and the rights of irrigation management were transferred from each water users' association to the land improvement district. Currently, the land improvement districts initiative is regarded as an example of a successful farmer participatory water management system (Tanaka and Sato, 2005).

According to the definition of the Land Improvement Act, a land improvement district is an organization established for the purpose of undertaking land improvement projects, including the construction, improvement, and management of irrigation and drainage facilities, and the integration of agricultural lands within a district. The requirements for establishing a land improvement district are: (1) participation by a minimum of 15 farmers; (2) the consent of at least two-thirds of the farmers affected by the project; and (3) after establishment of the land improvement district, sharing of the total cost of the project by the interested farmers (National Federation of Land Improvement Association, 1986). These water management organizations are established for the purpose of equitable water distribution and maintenance of irrigation facilities, but there are also examples of where they have been useful for environmental conservation. To preserve the water quality of Lake Biwa, the largest and most important water resource in Japan, a group of water users take the lead in water management and control the operation of pumps and gates in a recirculating irrigation system connected to this lake. Here, drainage water is reused for irrigation to reduce the load of suspended solids (Hama et al. 2010) and nitrogen (Hama et al. 2011).

2.3 Conclusions

When paddy soil is strongly reduced, CH_4 is produced by the activity of methanogens. Globally, a number of measures have been taken to control the emission of CH_4 from paddy fields to the atmosphere. To control the amount of available substrate for soil microorganisms, we can change the amount and type of fertilizer applied, control the amount of organic matter in the soil, and breed rice varieties that reduce subsurface carbon transfer. To suppress the activities of soil microorganisms, we can maintain the soil redox potential in a highly oxidized state by devising rice planting and water management methods that facilitate this soil condition. Among these global warming mitigation strategies, this thesis focuses on the control of CH_4 emissions from paddy soils by water management. In the following chapters, it is discussed how to improve the sustainability of organized water management by adopting an organizational water management approach rather than one based on water management by individual farmers. I also consider the disadvantages of the lack of short-term and direct benefits to farmers, and take into account the mechanisms of influence of water management on CH_4 production, release, or suppression.

Chapter 3

Effect of organizational paddy water management by a water user group on methane and nitrous oxide emissions and rice yield in the Red River Delta, Vietnam

---

Quang L.X., Nakamura K., Hung T., Tinh N.V., Matsuda S. et al. (2019) *Agric. Water Manag.* 217, 179−192. DOI: 10.1016/j.agwat.2019.02.015

3.1 Introduction

Water-saving management has been recognized as an important issue, especially for agricultural sustainability and development (Bouman and Tuong, 2001). In addition, atmospheric environments can be affected by inappropriate water management, such as the emission of greenhouse gases (GHGs). Because rice is cultivated twice or three times a year in Southern Asian countries, the practice of eco-friendly and water-saving management in paddy areas has become important and a topic of research focus.

For sustainable rice cultivation, it is essential that water is managed appropriately through the introduction of irrigation systems. If irrigation systems do not function adequately in terms of both hardware and software, water may be unequally allocated across paddy fields, resulting in water shortage, and thus decreased yield, in some sections.

Paddy water management influences rice yield. For example, Matsushima (1962) conducted various experiments to examine the effects of drought and flooding at different growth stages and the effect of different ponding depths in the growing season on rice yield, and showed that drought at the reduction division stage in pollen mother cells and around the heading (ear emergence) stage reduced the percentage of ripened grains and seriously damaged rice yield. This remarkable reduction in yield was caused by the whole plant submergence treatment, and rice yields obtained were in this order: ponding depth 5 cm above the soil surface > 15 cm above the soil surface > 30 cm above the soil surface > 0 cm > 5 cm below the soil surface > 15 cm below the soil surface. Nugroho et al. (2018) showed that rice yields increased with intermittent irrigation, in which the water depth was very shallow (ca. 2 cm) from 0 to 40 days after transplanting, and was associated with an increased number of panicles, which resulted from enhanced tiller development under shallow water during the vegetative stage. Hence, flooding during the periods after transplanting and around the ear emergence stage is important for securing rice yield physiologically. On the other hand, the effects of paddy water management on emissions of methane (CH_4) and nitrous oxide (N_2O), which have much higher greenhouse warming potential than carbon dioxide (CO_2) is also something to be considered. There is an inverse relationship between CH_4 and N_2O emissions with changes in soil redox potential and the recommended range of soil redox potential for water management is around −100 to +200 mV to prevent CH_4 production and encourage N_2O reduction (Hou et al., 2000). Ratering and Conrad (1998) showed that drainage for 48 h resulted in drastically decreased CH_4 emission rates while longer drainage and aeration resulted in a short-term increase of N_2O

production. Appropriate water management should be considered by paying attention to the trade-off relationship between CH_4 and N_2O emissions when controlling soil water regimes.

Recently, many studies have investigated alternate wetting and drying (AWD) as an eco-friendly and water-saving management technique in paddy fields (e.g., Li et al., 2018; Carrijo et al., 2018; Mote et al., 2018; Islam et al., 2018; Darzi-Naftchali et al., 2018; Tirol-Padre et al., 2018). AWD is an intermittent irrigation technique that repeats flooding and recession periods in paddy systems instead of the traditional continuous flooding. Experiments by Kima et al. (2015) in Taiwan showed that the optimal ponding depth in the AWD technique (i.e., that did not affect yield) was 3 cm. Zhao et al. (2011) showed that the system of rice intensification including AWD was effective in decreasing the amount of irrigation water used and in increasing water-use efficiency. Regarding GHGs, increased N_2O emissions under AWD are associated with enhanced nitrification in the upper soil layers during plant establishment and are, thus, related to basal nitrogen fertilization and mineralization of native soil nitrogen (Verhoeven et al., 2018). Iida et al. (2007) showed CH_4 and N_2O emissions cyclically fluctuated during intermittent irrigation. Such studies have shown that CH_4 emission-controlling and water-saving management is possible through water management that involves intermittent irrigation. However, most of the previous experiments were conducted on small paddy plots (several meters squared) or test pots, e.g., Pascual and Wang (2017) conducted experiments in $6\,m^2$ plots to estimate the effect of water management, Oo et al. (2018a) used 7 × 5 m experimental plots, and Minamikawa and Sakai (2005) used pot experiments to estimate the effect of soil redox potential control on rice yield and CH_4 emission compared to conventional management methods (continuous flooding, midseason drainage, and midseason drainage plus intermittent irrigation). Verhoeven et al. (2018) conducted experiments using two paddies, 20 × 80 m, however, the paddies were located in the Italian Rice Research Center where the water management was controlled by specialists. Practical and direct experiments of on-farm level water management by farmers or water management organizations have rarely been conducted.

This lack of practical examples is a consequence of eco-friendly and water-saving management techniques not having a direct benefit for each farmer who serves as the water manager of each paddy plot; there is, therefore, a lack of motivation to implement such eco-friendly and water-saving management. Under scenarios that irrigation water is not allocated fairly in the district and water supply is not stable, such water-saving irrigation will be unacceptable to farmers. Therefore, organizational water management of on-farm level, i.e., water managed by an organization (referred to as a water user group), rather than by each farmer is expected to be an effective eco-friendly and water-saving management structure.

In this study, the feasibility of on-farm level, organizational, eco-friendly, and water-saving management in the lowland paddy area of the Red River Delta, Vietnam was examined. This was achieved by introducing new water division works and sluice gates along the water channels in the district (covering an area of 44.24 ha), which were used by a water user group to control the irrigation, and by clarifying the influence of intermittent irrigation on the ponding depth, CH_4 and N_2O emissions, and rice yield.

3.2 Materials and methods

3.2.1 Experimental site and water management design

Experiments were conducted in the rice paddy fields in the Phu Thinh commune, which is located on the Red River Delta in the Kim Dong district, Hung Yen province, Vietnam (21°25’ N, 105°46’ E) (**Fig. 3.1**). The experimental paddy area was 44.24 ha (**Fig. 3.1**) and the topography was mostly flat. The paddy soil was clay with a hydraulic conductivity of 6.1×10^{-3}, 4.2×10^{-5}, and 2.6×10^{-4} cm s^{-1} near the soil surface (upper), at 30 cm depth (middle), and at 50 cm depth (lower), respectively. The carbon content of air-dried paddy soil was 2.3%, 1.5%, and 0.4%; the nitrogen content was 0.24%, 0.15%, and 0.05%; and the C/N ratio was 10.0, 10.1, and 9.1 in the upper, middle, and lower soil layers, respectively.

The experimental site was irrigated using two pumps (discharge amounts: 1000 and 1400 m^3 h^{-1}) in the pump station, which used water from a main canal that was sourced from the Red River. The water channels in the site were dual-purpose (irrigation and drainage). Two water division works were constructed along the channel that were directly connected to the pumps just before initiation of the experiments. The water division works consisted of three manual sluice gates. Gates 1–3 and 5–7 were attached to the water division works (see **Fig. 3.1**). Gates 4 and 8–11 were constructed or repaired to reduce water loss from the district and were usually closed but could be opened when needed. Water managers operated the pumps and gates and recorded their operation times and dates. Water managers were appointed by the agricultural cooperative that plays the role of the water user group in the district.

The experimental site was divided into three experimental blocks: the conventional (C), weak-dry (W), and strong-dry (S) blocks (**Fig. 3.1**), with areas of 26.73, 8.11, and 9.40 ha,

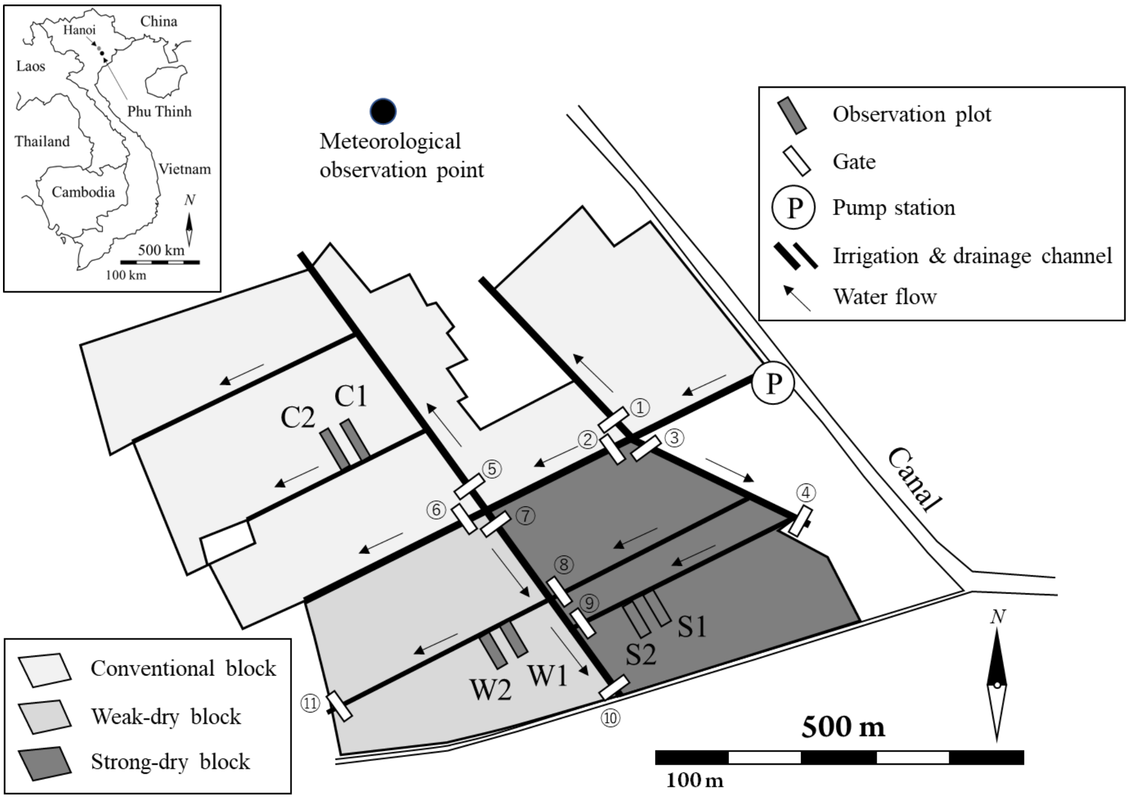

Fig. 3.1 Experimental site location in Phu Thinh district and experimental site layout in Phu Thinh district. The experimental site was divided into three experimental blocks with two observation plots in each: conventional (C1, C2), weak-dry (W1, W2), and strong-dry (S1, S2)

respectively. The target ponding water depth of paddy plots in the C block was traditional: ponding was maintained except for the midseason drainage. The W and S blocks contained the experimental AWD water management paddy plots. The target ponding depth was maintained at around 3 cm for one month after transplanting, after which the water managers practiced intermittent irrigation until the midseason drainage. Ponding was targeted to be maintained from the end of the midseason drainage to the ear emergence period for about 35 days in the W block and for about 20 days, including the ear emergence period, in the S block because the period from 20 days before ear emergence to 10 days after ear emergence is sensitive to drought due to reduction in the percentage of ripened grains (Matsushima, 1962). The successive intermittent irrigation was implemented thereafter. During the intermittent irrigation period, water was irrigated by the operation of pumps and gates. Water managers monitored the water level in pipes (20 cm in diameter) that had holes in the pipe wall and had been buried in paddy plots near to the water division works, i.e., to a depth of 5 cm under the soil surface (hereafter referred to as −5 cm) in the W block and to a depth of 15 cm (hereafter referred to as −15 cm) in the S block. Ideally, gates for delivering water to the W or S block were closed when the ponding was not necessary and were opened only when the ponding depth was lower than −5 cm in the W block and −15 cm in the S block. In this way, the AWD water management was expected to have been implemented by the systematic operation of pumps and gates by the water user group without requiring each farmer to manage the AWD. Furthermore, irrigation water had previously been distributed throughout the district, however, because water was allocated to only parts of the district by the operation of the gates of the water division works. In this study, the number of paddy plots that received irrigation increased and the AWD water management and irrigation system used were expected to relieve the water shortage in the district.

3.2.2 Crop management

In the study region, rice was produced twice a year: during the winter-spring season (WS, from February or March to June) and the summer-autumn season (SA, from June to September). Some vegetables are cultivated from the harvest of the SA season to the start of the WS season. Experiments were conducted for both seasons in 2015, 2016, and 2017. **Table 3.1** shows the transplanting and harvest dates, growing period, rice variety, and the standard rice planting density. Fertilizers were applied three times during the growing season. The first and basal fertilizer included nitrogen and phosphorous and was applied 1 or 2 days before the transplanting. The second and top-dressing fertilizer included nitrogen and was applied 5 or 7 days after the transplanting. The third fertilizer included nitrogen, phosphorous, and potassium, and was applied about 35 days after transplanting.

Table 3.1 Rice crop management in the paddy experimental site

	2015		2016		2017	
	WS	SA	WS	SA	WS	SA
Transplanting	Feb. 3	June 26	Feb. 19-22	July 2-4	Feb. 15-17	July 5
Harvesting	June 4	Sep. 22	June 15	Sep. 20	June 20	Sep. 25
Growing period (d)	122	89	118	81	126	83
Variety	Bac thom	Thien uu 8	TBR225	N25	Thien uu 8	Thien uu 8

Note: WS, the winter-spring season (February or March to June); and SA, the summer-autumn season (June to September). Experiments were conducted for both seasons in 2015, 2016, and 2017.

3.2.3 Meteorological conditions

Meteorological variables were measured from the rooftop of a house situated near to the experimental site, at a height of 10 m above the ground. A rain gauge (ECRN-100, Decagon Devices, Inc.); a solar radiation sensor (PYR, Decagon Devices, Inc.); and vapor pressure, humidity, and temperature sensor (VP-3, Decagon Devices, Inc.) were installed. Data were collected every 10 min using a data logger (Em50, Decagon Devices, Inc.). Daily potential evapotranspiration was calculated from the meteorological data using the Penman equation (Penman, 1948; Chang, 1970).

Figure 3.2 shows monthly rainfall, monthly average air temperature, monthly solar radiation, and rainfall (R) minus potential evapotranspiration (ET_p) in 2015, 2016, and 2017. Annual rainfall was calculated from the data from one 12-month period and ranged between 1480 mm and 1797 mm (average: 1651 mm). The rainfall amount was highest from June to August and the monthly rainfall varied from year to year. For example, the monthly rainfalls in April and in July and August of 2015 were small compared to 2016 and 2017. The annual average air temperature was about 25 °C and differed only slightly between years. The monthly solar radiation in 2015 was high compared to 2016 and 2017. The annual potential evapotranspiration ranged from 668 mm to 763 mm (average: 731 mm). Differences between monthly rainfall and evapotranspiration were smaller in the WS season than in the SA season. There was an abundance of rainfall compared to evapotranspiration in August 2016 and July 2017.

3.2.4 Measurement

Two observation plots were set up in each water management block: C1 and C2 in the C block, W1 and W2 in the W block, and S1 and S2 in the S block (**Fig. 3.1** and **Table 3.2**). In each observation plot, temporal changes in the ponding depth were monitored at 10 min intervals at three points (**Fig. 3.3**) using water level sensors (WT-HR, Intech Instruments Ltd.). The average value of the three points was assumed to be representative of the data for each plot.

To estimate the emission fluxes of GHGs, gas sampling was conducted at around 7-day intervals using a chamber-based method. One base of the chamber was installed in each plot in 2015 and 2016 and two bases were installed in 2017 (**Fig. 3.3**). The rectangular acrylic chamber was gently placed on the base during gas sampling. The height of the base was 20 cm and the chamber dimensions were 60 × 60 × 100 cm (length × width × height). Ten to seventeen rice

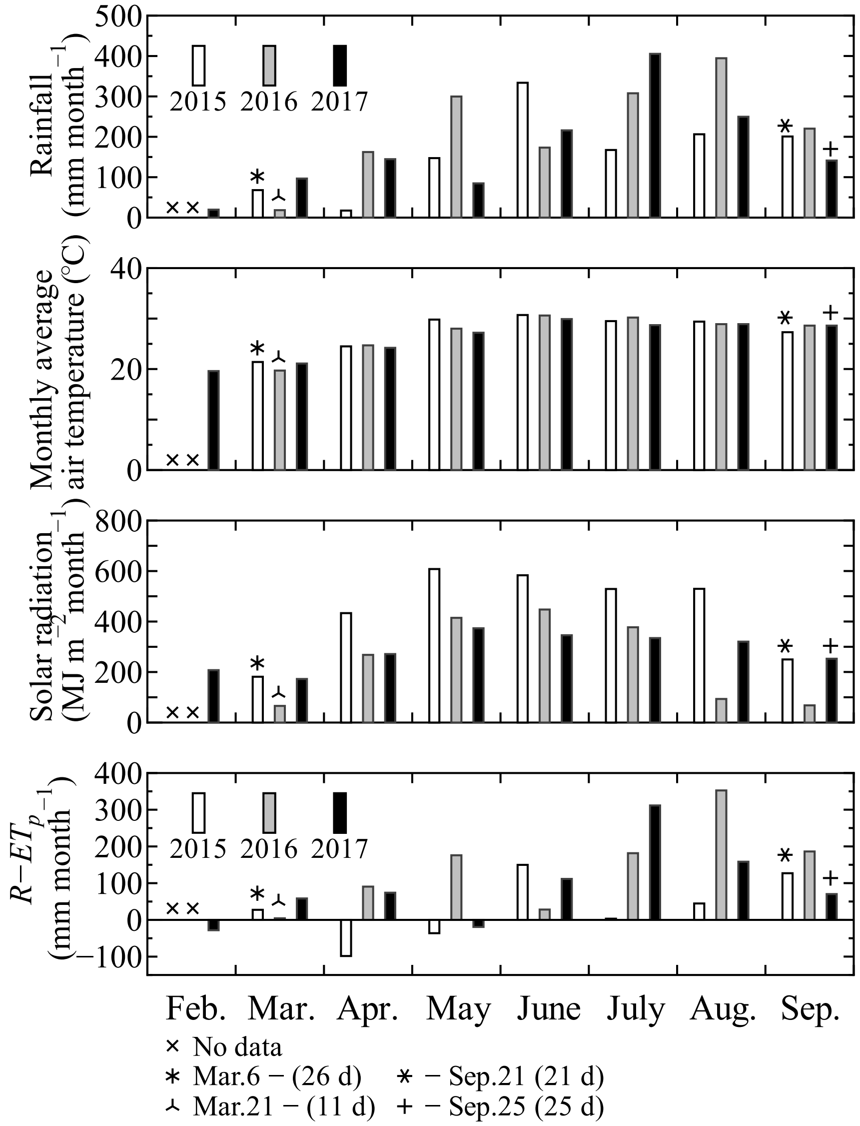

Fig. 3.2 Monthly rainfall, average air temperature, solar radiation, and rainfall (*R*) minus potential evapotranspiration (ET_p) in the rice paddy experimental site in 2015, 2016, and 2017

Table 3.2 Properties of observation paddy plots

	C1	C2	W1	W2	S1	S2
Area (m^2)	1152.0	1152.0	872.5	718.8	902.1	788.2
Elevation (m)	5.03	5.05	5.04	5.04	5.02	5.04

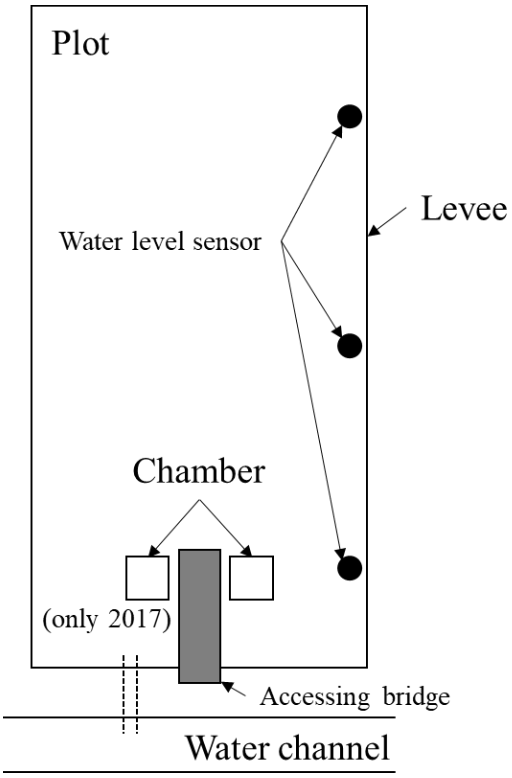

Fig. 3.3 Schematic diagram of each observation plot

stubbles were included within each chamber. Gas was collected using a 15 mL plastic syringe and the chamber air temperature was measured 1, 10, and 20 min after installing the chamber. The samples were immediately transferred to evacuated injection vials. Almost all samplings were conducted in the morning (8:30–11:30 a.m.). The number of replicates for GHGs for each plot numbered one in 2015 and 2016 and two in 2017. Replicates for each water management block (C, W, and S) numbered two in 2015 and 2016 and four in 2017.

CH_4 and N_2O concentrations were measured using gas chromatographs equipped with flame ionization detectors and electron capture detectors, respectively (Itoh et al., 2011). Gas emission flux was calculated based on the temporal change in gas concentration in the headspace of the chamber using the following equation:

$$f = \frac{dc}{dt} \cdot M \cdot \frac{273}{22.4} \cdot \frac{1}{T + 273} \cdot \frac{V}{A} \qquad (1)$$

where, *f* is the gas flux (mg m^{-2} min^{-1}), *c* is the gas concentration (ppm), *t* is the time (min), *M* is the molecular weight (g mol^{-1}), *T* is the air temperature in the chamber (°C), *V* is the volume of the headspace in the chamber (m^3), and *A* is the cross sectional area of the chamber (m^2).

Unhulled rice yield was estimated by the planting density (the number of rice stubbles per unit area) and the weight of ripened grains per one rice stubble. Ripened grains were selected using salt water with a density of 1.06 g cm^{-3}. The planting density was obtained by measuring the area planted with 121 (= 11 × 11) rice stubbles in each plot. The weight of ripened and unhulled grain was the average of four rice stubbles. In the process of estimating yields, the number of ears per stubble and the number of grains per ear were also measured. Rice yield measurements were conducted at two or three points in each plot.

3.3 Results

3.3.1 Paddy ponding depth and irrigation water management

Temporal changes in paddy ponding depths of the experimental plots are shown with daily rainfall amounts in **Fig. 3.4**. In the 2015 WS, ponding frequently decreased and it was inferred that the prolonged period of dry surface soil was due to the lower rainfall in April (**Fig. 3.2**). The ponding depths of all six plots showed similar temporal changes and no differences were observed among the treatments (C, W, and S blocks). Because frequent rainfall events in the latter half of the irrigation period dominated the temporal changes in ponding depths in all experimental plots, pump operation was not necessary and the ideal AWD water management (i.e., experiment) was not achieved. In the 2015 SA, similar temporal changes in the ponding depth were observed among the treatments. After the midseason drainage in the latter half of August, the ponding depths of all experimental plots corresponded to rainfall amounts and it was not possible to conduct the AWD water management.

In the 2016 WS, the difference in ponding depths in response to the operation of pumps and gates was observed in mid-April. According to a record log, a water manager operated the system to irrigate Block W on April 15 and 19 and Block S on April 15. Pumped water was expected to irrigate Block C on April 15, 16, and 19. The ponding depth of the C1 plot was maintained above 0 cm. The ponding depth of the W1 and W2 plots were temporarily at approximately −5 cm. The flooding receded in the S1 plot in mid-April and although the ponding depth of the C2 plot decreased, the high ponding depth of the S2 plot was maintained. The ponding depths of the W1, W2, and S1 plots decreased to almost −20 cm in mid-May, although this observation was independent from the operation of the pumps. In the 2016 SA, according to a record log, pumped water irrigated Block W on July 20 and August 20 and Block S on August 12. Block C was expected to have been irrigated on July 14, July 20, August 12, and August 20. The ponding depths of the C1 and C2 plots were almost above soil surface;

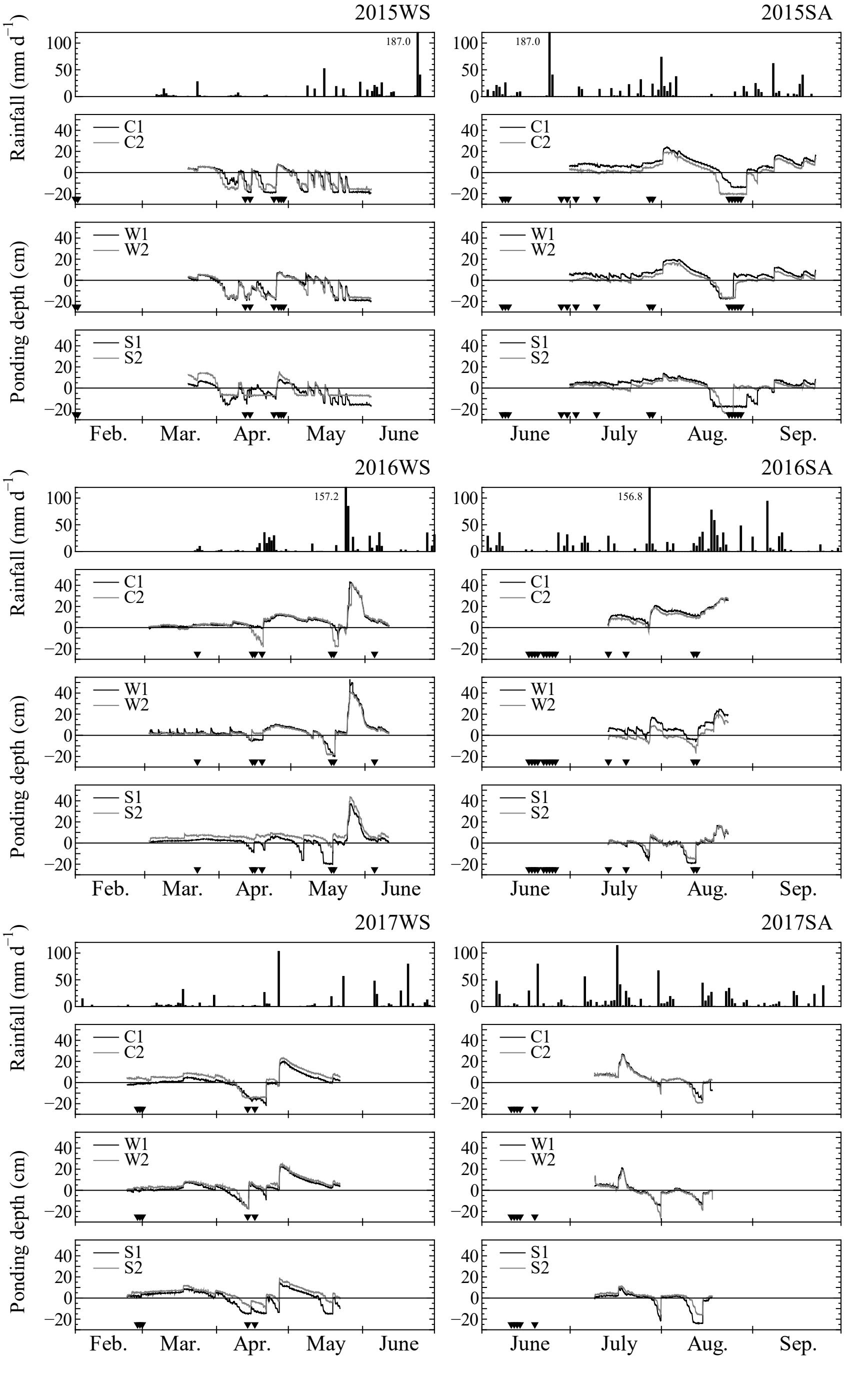

Fig. 3.4 Temporal changes in ponding water depths of the rice paddy observation plots with daily rainfall amounts. WS, the winter-spring season (February or March to June); and SA, the summer-autumn season (June to September). Experiments were conducted for both seasons in 2015, 2016, and 2017. The experimental site was divided into three experimental blocks with two observation plots in each: conventional (C1, C2), weak-dry (W1, W2), and strong-dry (S1, S2). Black triangles represent the operation of pumps according to the records logged by water managers

those of W1 and W2 plots decreased frequently to −5 cm and to −5 to −15 cm, respectively; and the ponding depths of the S1 and S2 plots reached −20 cm. A situation close to the ideal ponding depth was produced from July to August in 2016, despite the high rainfall in this season.

In the 2017 WS, the ponding depths of all plots decreased in mid-April. Although the ponding depths of the W1, W2, S1, and S2 plots increased on April 14 as a result of the operation of the pumps and gates, the ponding depths of the C1 and C2 plots continued to decrease. The ideal AWD water management was not achieved in this season. In the 2017 SA, the operation of pumps was not recorded in July and August. The ponding depths of the C1 and C2 plots were maintained above the soil surface longer than in the W1, W2, S1, and S2 plots, however, this was not as a result of water management (i.e., the use of the gates).

3.3.2 Drying index

To evaluate the degree of the period when the ponding depth was under the critical value, it was defined as the *drying index* that the ratio of the period when the ponding depth was under the critical value to the period when the ponding depth was observed. Three drying index values were estimated when the critical value was 0, −5, and −15 cm. A drying index of zero means the ponding depth was higher than the critical value, with flooding or wet soil conditions during the whole observation period. On the other hand, 1 in the index means the ponding depth was lower than the critical value, with non-flooding or dry soil conditions during the whole observation period. **Table 3.3** shows statistics on the drying index at 0 cm for each water management treatment (C, W, and S) in WS and SA seasons over the three years. The number of replicates was two for each treatment, so there were no significant differences for each treatment in all cropping seasons ($p > 0.05$) except in the 2017 SA based on the Tukey honest significant differences (Tukey HSD) test. There were no significant differences between each treatment at drying indexes for −5 and −15 cm. **Figure 3.5** represents the comparison of drying indexes for each cropping season and each plot. In the 2016 SA, the ideal water management for AWD was conducted as mentioned above and the intended differences for the drying indexes for 0, −5, and −15 cm of the critical value were approximately confirmed. In the 2017 SA, the drying indexes in the C1 and C2 plots were relatively lower than in the W and S plots and an especially extremely high drying index was observed in the W plots for the 0 cm critical value. The drying indexes for 0, −5, and −15 cm in the 2015 WS were higher than in the other seasons and years due to the lower rainfall. The average drying index was 0.65 in 2015 WS and 0.15–0.51 in other cropping seasons (**Table 3.3**). Also, smaller differences were observed between treatments,

Table 3.3 Drying index (<= 0 cm) for different water management block in the winter-spring season and the summer-autumn season in three years

	Sampling number for each treatment	Drying index (< = 0 cm)						Average for each year		Average for each season	
		C		W		S					
2015WS	2	0.64	a+	0.64	a+	0.68	a+	0.65	b*		
2016WS	2	0.10	a++	0.16	a++	0.18	a++	0.15	a*	0.34	a§
2017WS	2	0.29	a+++	0.13	a+++	0.25	a+++	0.22	a*		
Average for each treatment in WS		0.34	a#	0.31	a#	0.37	a#				
2015SA	2	0.18	a-	0.21	a-	0.25	a-	0.21	a**		
2016SA	2	0.01	a–	0.36	a–	0.43	a–	0.26	a**	0.33	a§
2017SA	2	0.27	a—	0.89	b—	0.38	a—	0.51	a**		
Average for each treatment in SA		0.15	a##	0.48	a##	0.35	a##				

Note: Letters (a and b) mean the results of Tukey HSD test for different groups of same symbols (+, ++, +++, #, *, -, --, ---, ##, and **). Welch' s test is for the average for each season (§). The *p*-value criterion is < 0.05 for both tests. WS, the winter-spring season (February or March to June); and SA, the summer-autumn season (June to September). Experiments were conducted for both seasons in 2015, 2016, and 2017. The experimental site was divided into three experimental blocks: conventional (C), weak-dry (W), and strong-dry (S).

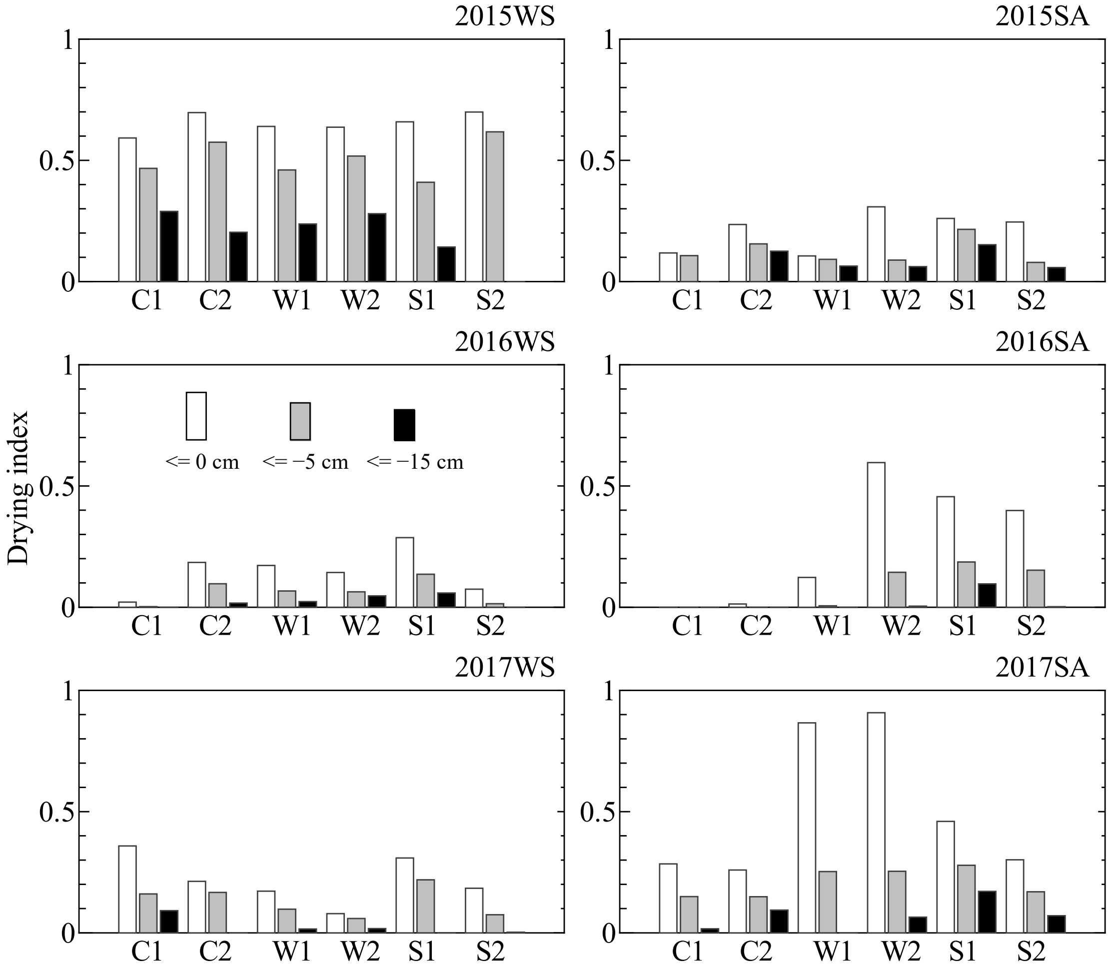

Fig. 3.5 Drying indexes when the critical ponding depth was 0, −5, -and −15 cm in the rice paddy observation plots. WS, the winter-spring season (February or March to June); and SA, the summer-autumn season (June to September). Experiments were conducted for both seasons in 2015, 2016, and 2017. The experimental site was divided into three experimental blocks with two observation plots in each: conventional (C1, C2), weak-dry (W1, W2), and strong-dry (S1, S2)

especially the drying indexes for 0 and −5 cm. Remarkable differences were not observed in the three drying indexes among blocks in the 2015 SA, 2016 WS, and 2017 WS.

3.3.3 Greenhouse gases emission

3.3.3.1 CH_4 emission

Figure 3.6 shows the temporal changes in CH_4 emission flux (mg m^{-2} min^{-1}) in each plot. The 2015 WS and the 2017 WS presented similar temporal patterns in CH_4 emission. CH_4 emissions were observed until early April and were almost negligible after mid-April, except in the W1, W2, and S2 plots on May 13 in 2017. Until early April (after the transplanting of rice), the ponding depths were maintained above the soil surface (**Fig. 3.4**) and this may have induced CH_4 emissions. Even though the ponding depths increased and became positive after the midseason drainage, CH_4 emission did not occur immediately. In the 2016 WS, the midseason drainage was insufficient in mid-April due to a rainfall event and the CH_4 emission continued, especially in the C and W plots. The drainage in mid-May may have decreased the CH_4 emission. The increase in ponding depths due to heavy rainfall at the end of May did not induce CH_4 emissions in the W and S plots.

The CH_4 emission fluxes were larger in the SA than in the WS. In the 2015 SA, there were no CH_4 emissions during the midseason drainage at the end of August (**Fig. 3.4**) and they did not occur until the end of the irrigation period. In the 2016 SA, high rainfall and the associated increase in ponding depth (**Fig. 3.2**, **Fig. 3.4**) caused continuous CH_4 emissions in the C and W plots. Despite the missing ponding depth data in the 2017 SA, the midseason drainage also induced a decrease in the CH_4 emissions in the C1, W2, and S1 plots.

3.3.3.2 N_2O emission

Temporal changes in N_2O emission flux (mg m^{-2} min^{-1}) are shown in **Fig. 3.7**. Temporary N_2O emissions were observed after the nitrogen fertilizer applications. In WS, there were temporary N_2O emissions in March, which were inferred to be the result of the second nitrogen fertilizer application and an especially high N_2O emission was observed in early April in the 2016 WS. In the 2015 SA, 2016 SA, and 2017 SA, the N_2O emissions in mid- or late July from some plots occurred after the second fertilizer application. Although almost no N_2O emissions were observed where there was no ponding (**Fig. 3.4**), there was not a relationship between ponding depth and N_2O emission. Rainfall events did not affect the N_2O emissions. Additionally, there was no effect of water management on the N_2O emission in the mid-August in the 2016 SA. It could not be confirmed the relationship between water management and N_2O emission.

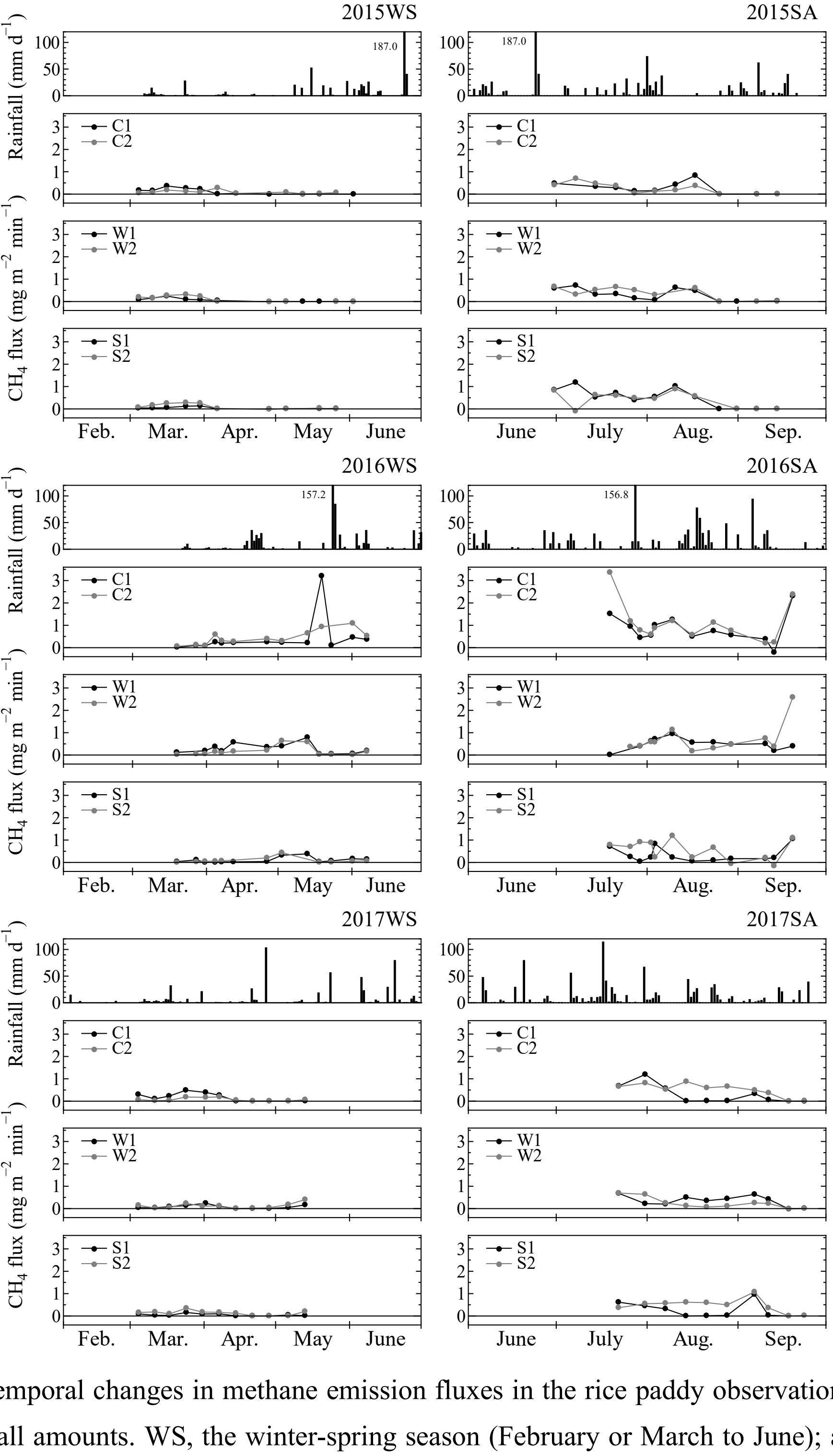

Fig. 3.6 Temporal changes in methane emission fluxes in the rice paddy observation plots with daily rainfall amounts. WS, the winter-spring season (February or March to June); and SA, the summer-autumn season (June to September). Experiments were conducted for both seasons in 2015, 2016, and 2017. The experimental site was divided into three experimental water management blocks with two observation plots in each block: conventional (C1, C2), weak-dry (W1, W2), and strong-dry (S1, S2)

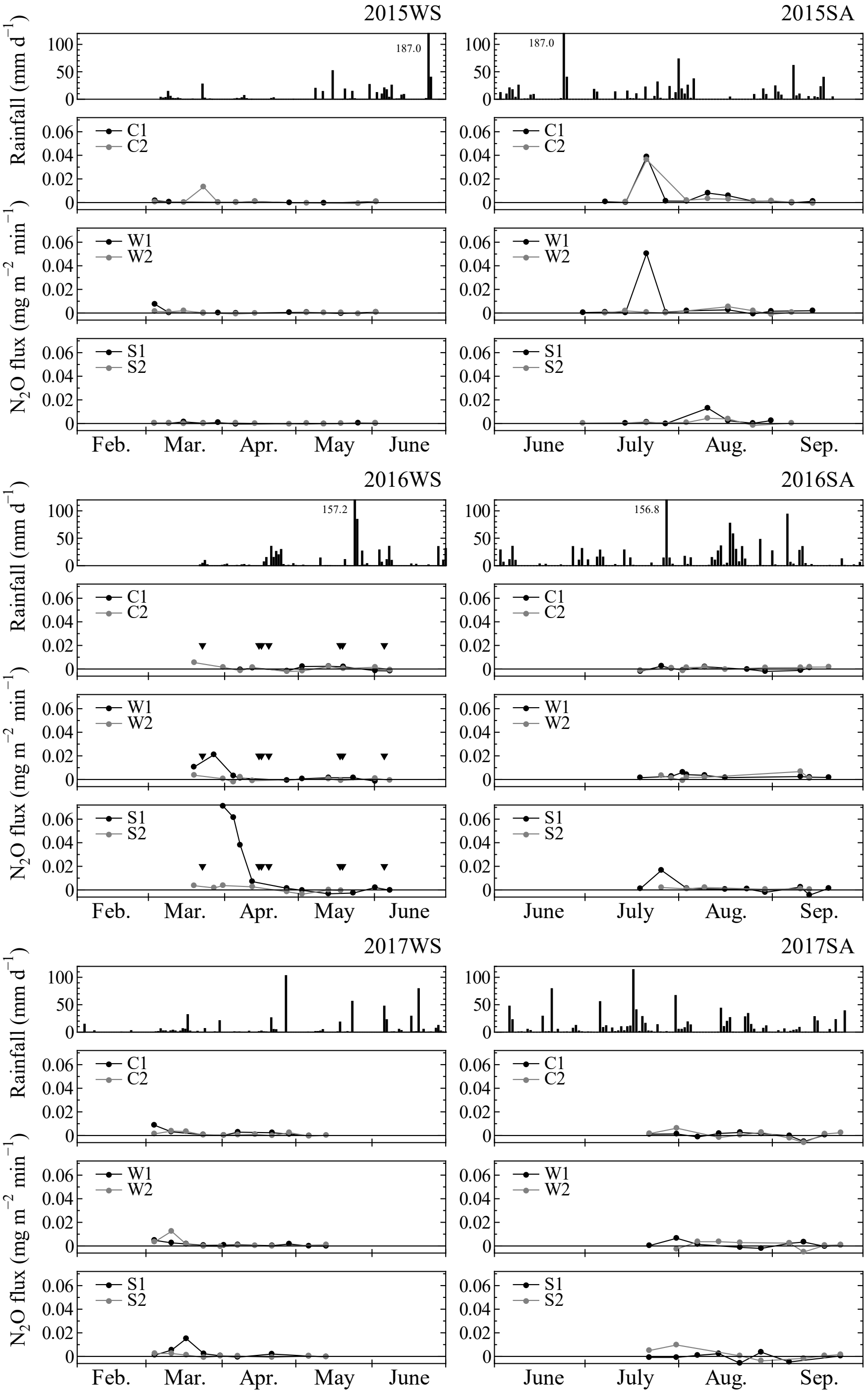

Fig. 3.7 Temporal changes in nitrous oxide emission fluxes in the observation plots with daily rainfall amounts. WS, the winter-spring season (February or March to June); and SA, the summer-autumn season (June to September). Experiments were conducted for both seasons in 2015, 2016, and 2017. The experimental site was divided into three experimental water management blocks with two observation plots in each block: conventional (C1, C2), weak-dry (W1, W2), and strong-dry (S1, S2)

3.3.3.3 Cumulative GHG emission amount

Daily average CH_4 and N_2O emission fluxes were calculated by dividing the cumulative gas emission amount by the observation period and were converted to CO_2 emission fluxes (g CO_2 m^{-2} d^{-1}) using the global warming potential values of 25 and 298 for CH_4 and N_2O, respectively (Solomon et al., 2007). The flux between the two observation dates was assumed to be constant and equal to the former one.

Table 3.4 shows statistics on the daily CH_4 emission flux for each water management treatment (C, W, and S) in WS and SA seasons over the three years. There were no significant differences by water management treatment for each cropping season except the 2016 WS and 2015 SA. Higher CH_4 emissions were observed in C plots than W and S plots in the 2016 WS, but the amount of CH_4 released was highest in S, followed by W then C plots in the 2015 SA. The average values of daily average CH_4 emission flux in all plots were 1.7, 9.6, and 3.5 g CO_2 m^{-2} d^{-1} for the 2015 WS, 2016 WS, and 2017 WS, respectively; and 11.5, 22.2, and 15.8 g CO_2 m^{-2} d^{-1} for the 2015 SA, 2016 SA, and 2017 SA, respectively. There was a large difference in CH_4 emission in relation to the cropping season and the cumulative CH_4 emission in WS was smaller than in SA. On the other hand, the CH_4 emissions were relatively higher in the C plots than in the W and S plots in the 2016 WS, 2016 SA, and 2017 SA, although the Tukey HSD test revealed that the differences among the three blocks were not significant ($p > 0.05$). **Table 3.5** shows the daily N_2O emission fluxes for each water management treatment in WS and SA seasons over the three years. There were no significant differences by water management treatment for each cropping season. The N_2O CO_2-equivalent emissions were less than CH_4; the average N_2O emission was 0.1 and 0.04 times that of CH_4 in WS and SA, respectively (**Table 3.4**, **Table 3.5**). **Figure 3.8** presents the daily average CH_4 and N_2O emission fluxes for each cropping season and each plot. There is no error bar for 2015 and 2016 because only one chamber was set for each plot. Standard deviation error bars are shown in 2017 because gas sampling was conducted at two points per plot. CH_4 emissions in the C1 and C2 plots were higher than in the W and S plots in the 2016 SA although there were no significant differences.

3.3.4 Rice yield

The unhulled rice yields for each water management treatment and each plot are shown in **Table 3.6** and **Fig. 3.9**, respectively. Over the three years, the average yields in WS and SA were statistically different at 5.89×10^3 kg ha^{-1} and 4.46×10^3 kg ha^{-1}, respectively (Welch's test, $p =$

Table 3.4 Daily CH_4 emission flux for different water management block in the winter-spring season and the summer-autumn season in three years

	Sampling number for each treatment	Daily average CH_4 emission flux (g CO_2 m^{-2} d^{-1})						Average for each year		Average for each season	
		C		W		S					
2015WS	2	1.9	a+	1.0	a+	2.2	a+	1.7	a*	4.6	a§
2016WS	2	15.2	b++	9.0	a++	4.6	a++	9.6	b*		
2017WS	4	4.3	a+++	3.2	a+++	3.0	a+++	3.5	a*		
Average for each treatment in WS		6.4	a#	4.1	a#	3.2	a#				
2015SA	2	8.2	a-	10.3	ab-	16.0	b-	11.5	a**	16.3	b§
2016SA	2	35.6	a–	15.0	a–	16.0	a–	22.2	a**		
2017SA	4	20.7	a—	12.4	a—	14.2	a—	15.8	a**		
Average for each treatment in SA		21.3	a##	12.5	a##	15.1	a##				

Note: Letters (a and b) mean the results of Tukey HSD test for different groups of same symbols (+, ++, +++, #, *, -, --, ---, ##, and **). Welch' s test is for the average for each season (§). The *p*-value criterion is < 0.05 for both tests. WS, the winter-spring season (February or March to June); and SA, the summer-autumn season (June to September). Experiments were conducted for both seasons in 2015, 2016, and 2017. The experimental site was divided into three experimental blocks: conventional (C), weak-dry (W), and strong-dry (S).

Table 3.5 Daily N_2O emission flux for different water management block in the winter-spring season and the summer-autumn season in three

	Sampling number for each treatment	Daily average N_2O emission flux (g CO_2 m^{-2} d^{-1})						Average for each year		Average for each season	
		C		W		S					
2015WS	2	0.2	a+	0.0	a+	0.0	a+	0.1	a*		
2016WS	2	0.2	a++	0.6	a++	1.8	a++	0.9	a*	0.5	a§
2017WS	4	0.4	a+++	0.6	a+++	0.5	a+++	0.5	a*		
Average for each treatment in WS		0.3	a#	0.5	a#	0.7	a#				
2015SA	2	2.0	a-	1.5	a-	0.6	a-	1.4	b**		
2016SA	2	0.1	a –	0.6	a –	0.7	a –	0.4	a**	0.6	a§
2017SA	4	0.4	a—	0.1	a—	0.2	a—	0.3	a**		
Average for each treatment in SA		0.7	a##	0.6	a##	0.4	a##				

Note: Letters (a and b) mean the results of Tukey HSD test for different groups of same symbols (+, ++, +++, #, *, -, --, ---, ##, and **). Welch' s test is for the average for each season (§). The *p*-value criterion is < 0.05 for both tests. WS, the winter-spring season (February or March to June); and SA, the summer-autumn season (June to September). Experiments were conducted for both seasons in 2015, 2016, and 2017. The experimental site was divided into three experimental blocks: conventional (C), weak-dry (W), and strong-dry (S).

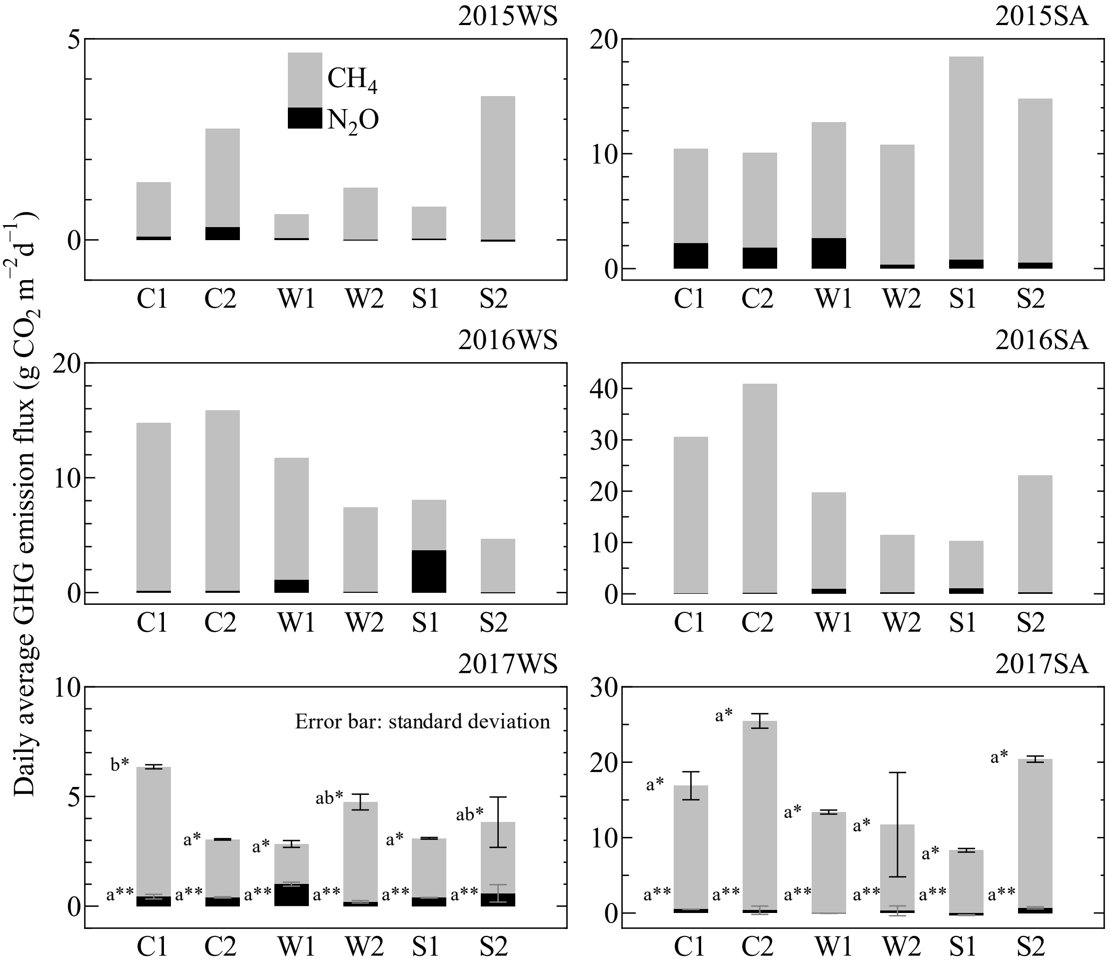

Fig. 3.8 Daily average greenhouse gas (GHG) emission fluxes (of CH_4 and N_2O) converted to the equivalent CO_2 in the observation plots: calculated by dividing the cumulative emission amount by the observation period in each cropping season. WS, the winter-spring season (February or March to June); and SA, the summer-autumn season (June to September). Experiments were conducted for both seasons in 2015, 2016, and 2017. The experimental site was divided into three experimental water management blocks with two observation plots in each block: conventional (C1, C2), weak-dry (W1, W2), and strong-dry (S1, S2). Letters (a, b, and ab) mean the results of the Tukey HSD test in 2017. Symbol * is for CH_4 and ** for N_2O

Table 3.6 Rice yield for different water management block in the winter-spring season and the summer-autumn season in three years

	Sampling number for each treatment	Rice yield (10^3 kg ha^{-1})						Average for each year		Average for each season	
		C		W		S					
2015WS	6	5.82	a+	6.93	a+	6.26	a+	6.34	a*		
2016WS	6	4.88	a++	5.30	a++	6.03	a++	5.40	a*	5.89	a§
2017WS	12	5.56	a+++	5.57	a+++	6.63	a+++	5.92	a*		
Average for each treatment in WS		5.46	a#	5.84	a#	6.38	a#				
2015SA	16	3.10	a-	4.68	b-	4.71	b-	4.16	a**		
2016SA	18	4.96	a –	4.89	a –	5.18	a –	5.01	b**	4.46	b§
2017SA	4	3.07	a—	3.12	a—	3.31	a—	3.17	a**		
Average for each treatment in SA		3.98	a##	4.62	a##	4.79	a##				

Note: Letters (a and b) mean the results of Tukey HSD test for different groups of same symbols (+, ++, +++, #, *, -, --, ---, ##, and **). Welch' s test is for the average for each season (§). The *p*-value criterion is < 0.05 for both tests. WS, the winter-spring season (February or March to June); and SA, the summer-autumn season (June to September). Experiments were conducted for both seasons in 2015, 2016, and 2017. The experimental site was divided into three experimental blocks: conventional (C), weak-dry (W), and strong-dry (S).

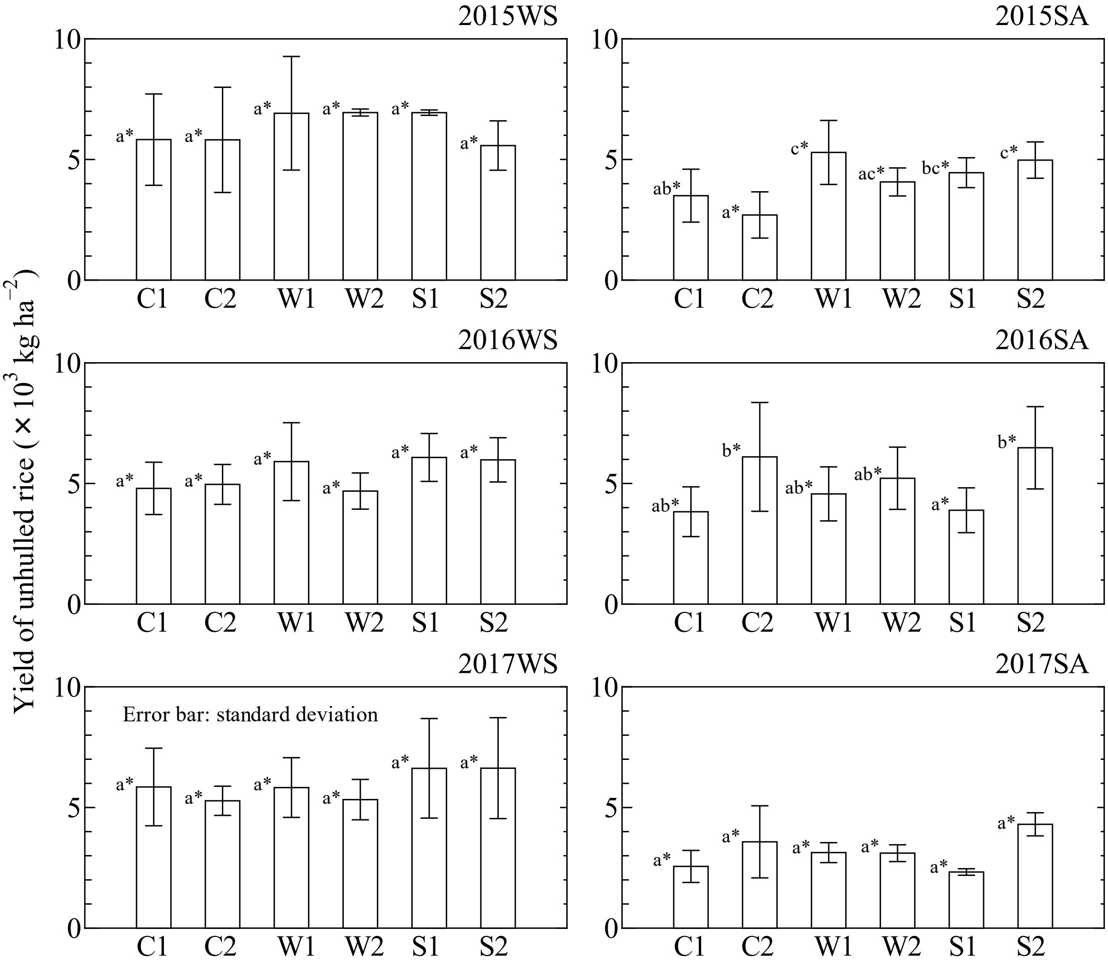

Fig. 3.9 Yields of unhulled rice in the observation plots. WS, the winter-spring season (February or March to June); and SA, the summer-autumn season (June to September). Experiments were conducted for both seasons in 2015, 2016, and 2017. The experimental site was divided into three experimental water management blocks with two observation plots in each block: conventional (C1, C2), weak-dry (W1, W2), and strong-dry (S1, S2). Letters (a, b, c, ab, ac, and bc) mean the results of the Tukey HSD test in 2017

7.7×10^{-10}). In WS, no significant differences were observed among 2015, 2016, and 2017. In SA, significant differences were observed between 2015 and 2016 and between 2016 and 2017. Considering the varieties of rice cultivated in each season (**Table 3.1**), the variety Thien uu 8 was cultivated in the 2015 SA and the 2017 SA, this variety may have fewer yields in SA. As a result of the Tukey HSD test for comparisons among water management treatments, only significant differences between C plots and S plots were observed in the 2015 SA ($p =$ 0.0001) and between C plots and W plots in the 2015 SA ($p = 0.0002$). The W plot and S plot rice yields were higher than those of the C plots in SA in 2015.

Table 3.7 shows the correlation coefficients between rice yield and other components, i.e., planting density, the number of ears per stubble, the number of grains per ear, the ripening rate, and the weight per grain. Ripening rate was defined by the ratio of the number of ripened grains and the number of total grains. The highest correlation ($R = 0.780$) was observed between rice yield and ripening rate (Pearson's product-moment correlation test, $p = 2.17 \times 10^{-8}$). Since soil drying processes, such as the midseason drainage, are important to increase ripening rate especially under higher air temperature conditions (Kitagawa et al., 2018), insufficient soil drying as a result of high rainfall may have influenced the lower yield that was recorded in SA.

3.4 Discussion

3.4.1 Effectiveness of water management by the water user group

The original schedule of water management was intermittent irrigation at short intervals (several days) mainly after the midseason drainage and the simultaneous operation of pumps and gates. However, pumps were not frequently operated because ponding depth did not frequently decrease (i.e., to a level that required irrigation), except in the 2015 WS (**Fig. 3.4**), due to high precipitation. In the 2015 WS, the ponding depth was not maintained above the soil surface in the C plots, probably because water managers may have considered it unnecessary to operate pumps because of the rainfall events in May 2015. Especially in the 2016 SA and the 2017 SA, the length of the period during which the ponding depth was lower than 0, −5, and −15 cm was longer in the W and S plots than in the C plots (**Fig. 3.4**, **Fig. 3.5**), although the elevations of the soil surface were almost the same in all observation plots (**Table 3.2**).

It was difficult for the water managers to adhere to the original schedule under the actual meteorological conditions and with the actual ponding depth. Water managers may also have intentionally avoided driving the pumps to reduce electricity expense. Furthermore, not all farmers in the district understood the pilot systematic water management and used their own manual pumps if they considered irrigation to be necessary. Hence, the effect of water management by the water user group through the operation of pumps and gates was limited. It was impossible to establish two different drying stages: the weak-dry and strong-dry blocks in this district. In the interview surveys, some farmers stated that there was a decrease in the number of times that they used a manual pump. When one or two blocks of the district were

Table 3.7 Correlation coefficients among rice yield components

	Planting density	Number of ears per stubble	Number of grains per ear	Ripening rate	Weight of a ripened grain	Yield of ripened rice
Planting density	1.000					
Number of ears per stubble	0.182	1.000				
Number of grains per ear	−0.329	−0.850	1.000			
Ripening rate	0.034	0.648	−0.607	1.000		
Weight of a ripened grain	0.036	−0.273	0.080	−0.176	1.000	
Yield of ripened rice	0.242	0.611	−0.429	0.780	0.137	1.000

irrigated by the operation of the gates, the water level of the channel in the corresponding block rose up and it was not necessary to use the manual pumps; indicating that in such scenarios the water shortage problem was possibly solved. It is hoped that organizational water management, with a simultaneous operation of pumps and gates, will be used for future block rotational irrigation and that irrigation water will spread to the end of each block not only for AWD management.

3.4.2 Effect of drying index on CH_4 emission

Daily average greenhouse gas emission flux of CH_4 converted to equivalent CO_2 was much higher in this region than N_2O (**Fig. 3.8**). N_2O emission is related to nitrogen fertilizer application. Cai et al. (1997) showed that N_2O emission increased significantly with the increase in the nitrogen application rate and that the N_2O flux was very small when the paddy plots were flooded but peaked at the beginning of the recession of the floodwater. The N_2O emission in this study was, however, not related to the non-ponding period and there was no trade-off relationship between CH_4 and N_2O with drying. Hence, N_2O emission was temporary and not continuous (**Fig. 3.7**), while CH_4 emitted continuously during flooding (**Fig. 3.6**). The soil redox potential may not have frequently exceeded +200 mV when ponding water was eliminated in this study, and the soil water content may have decreased, judging from the fact the recommended soil redox potential is −100 to +200 mV to prevent N_2O emissions (Hou et al., 2000). This study shows the importance of focusing on the mitigation of CH_4 emissions to reduce the GHG impacts of paddy areas in this region.

The CH_4 emission and the drying index (for 0 cm) were weakly negatively correlated in both seasons (**Fig. 3.10**). Emission of CH_4 from rice paddies is the result of anoxic bacterial CH_4 production (Neue et al., 1996). Minamikawa and Sakai (2005) showed that the CH_4 emissions decreased in response to the midseason drainage method and midseason plus intermittent irrigation method compared to continuous flooding. Despite the decrease in CH_4 emission by prolonged drying periods being a well-known phenomenon, the on-farm level investigation in this study did not demonstrate a distinct relationship between them, especially in SA. With regards to each cropping season, it was not observed the negative relationship between CH_4 emission and the drying index for 0 cm in response to the different water management treatments in WS. It was difficult to control the CH_4 emission by increasing the drying index for 0 cm in WS. On the other hand, since a weak negative relationship was observed in the SA in each year, except in 2015, it may be possible to manage CH_4 emissions by lengthening the drying period in the SA.

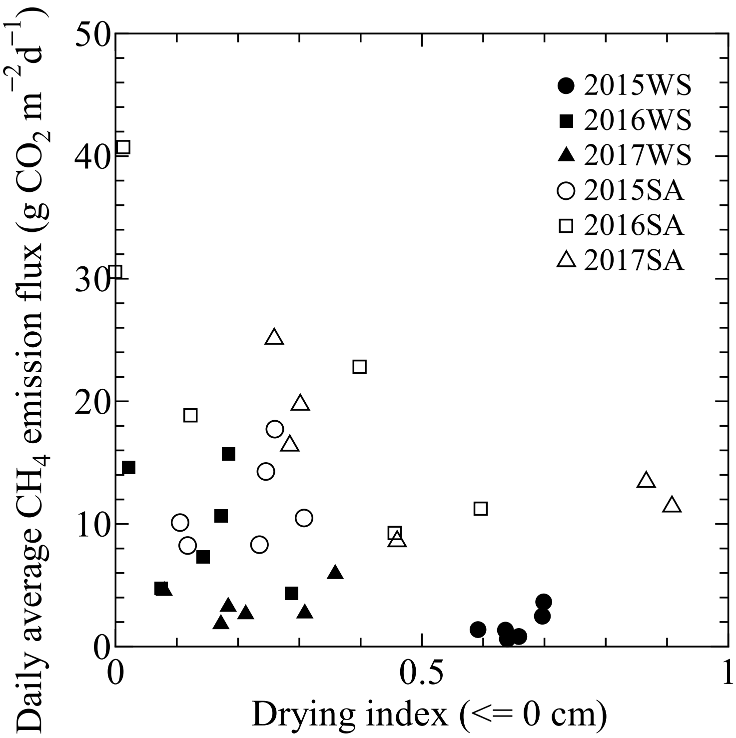

Fig. 3.10 Relationship between daily average methane emission flux (converted to the equivalent CO_2 in the observation plots, calculated by dividing the cumulative emission amount by the observation period in each cropping season) and drying index for 0 cm ponding depth in each cropping season. WS, the winter-spring season (February or March to June); and SA, the summer-autumn season (June to September). Experiments were conducted for both seasons in 2015, 2016, and 2017

Different trends were observed in the WS and SA. The CH_4 emission at the same drying index was higher in SA than in WS; presumably due to the higher temperatures. Air temperature rose approximately from 20 °C to 30 °C from March to June in WS and was constant at about 30 °C from June to September (**Fig. 3.2**). In addition, much organic matter presumably originated from the residues of rice straw at the beginning of SA because the season started immediately after WS. The rice straw after the harvesting of SA may be decomposed from September to February and the amount of organic matter at the beginning of WS is inferred to be small, although organic matter data were not collected in this study. It is thought that the effect of soil drying is likely to manifest due to the higher CH_4 emissions in SA compared with WS. The present study suggests the importance of increasing the drying period in SA to reduce CH_4 emissions from paddy areas through careful water management.

3.4.3 Effect of drying index on rice yield

In WS, the unhulled rice yield did not change with drying indexes for 0 cm and 15 cm (left side of **Fig. 3.11**). In SA, despite there being no remarkable change in rice yield with increasing drying indexes for 0 cm and 15 cm, the large drying index induced a decrease in rice yield (right side of **Fig. 3.11**). In the experiments by Minamikawa and Sakai (2005), the order of brown rice yield was as follows: midseason drainage plus intermittent irrigation > midseason drainage > continuous flooding, but excessive drying of the soil slightly affected rice yield in this study. In particular, the drying index for 0 cm ponding depth in the W1 and W2 plots in SA, 2017; sufficient ponding water may not have been present at the period around ear emergence after midseason drainage (Matsushima, 1962). Water-saving irrigation by controlling limiting values of soil water potential related to specific stages can increase grain yield (Yang et al., 2007). On the other hand, Pascual and Wang (2017) compared the effect of intermittent irrigation at 3-day intervals and at 7-day intervals to continuous flooding and showed that grain yield was comparable among irrigation regimes. Li et al. (2018) mentioned that AWD management led to a promotion in plant physiological activities and grain filling, and hence increased grain yields. The effects of water management on rice yield vary with rice varieties and meteorological conditions. In the investigated area, it was possible to conduct dry-type water management without reducing rice yield in WS, and it is advised that water management regimes avoid the excessive drying-out of paddy soils in SA. The maximum drying index for 0 cm was approximately 0.6 which was adequate in SA to reduce CH_4 emission and to maintain rice yield. In any case, it is important to flood water during periods when water is needed for rice growth physiologically.

3.4.4 Contributions to decision making process

Considering that flooding is recommended until the rooting stage after transplanting and for around 30 days before and after ear emergence, which has large effects on rice yield, and that rainfall is relatively frequent in the study region, opportunities for AWD management are in fact limited. Therefore, it is important to carry out AWD management with certainty, so it is considered that management by a water user group is more efficient than water management by individual farmers. It was proposed that AWD management by a water user group through the operation of irrigation pumps and sluice gates for water division work. Though the direct effects of pump operation and gates on ponding water management and CH_4 reduction were limited, this study showed potential for the organizational water management system to deliver sufficient water to target blocks. The fact that CH_4 emissions decreased with increased drying

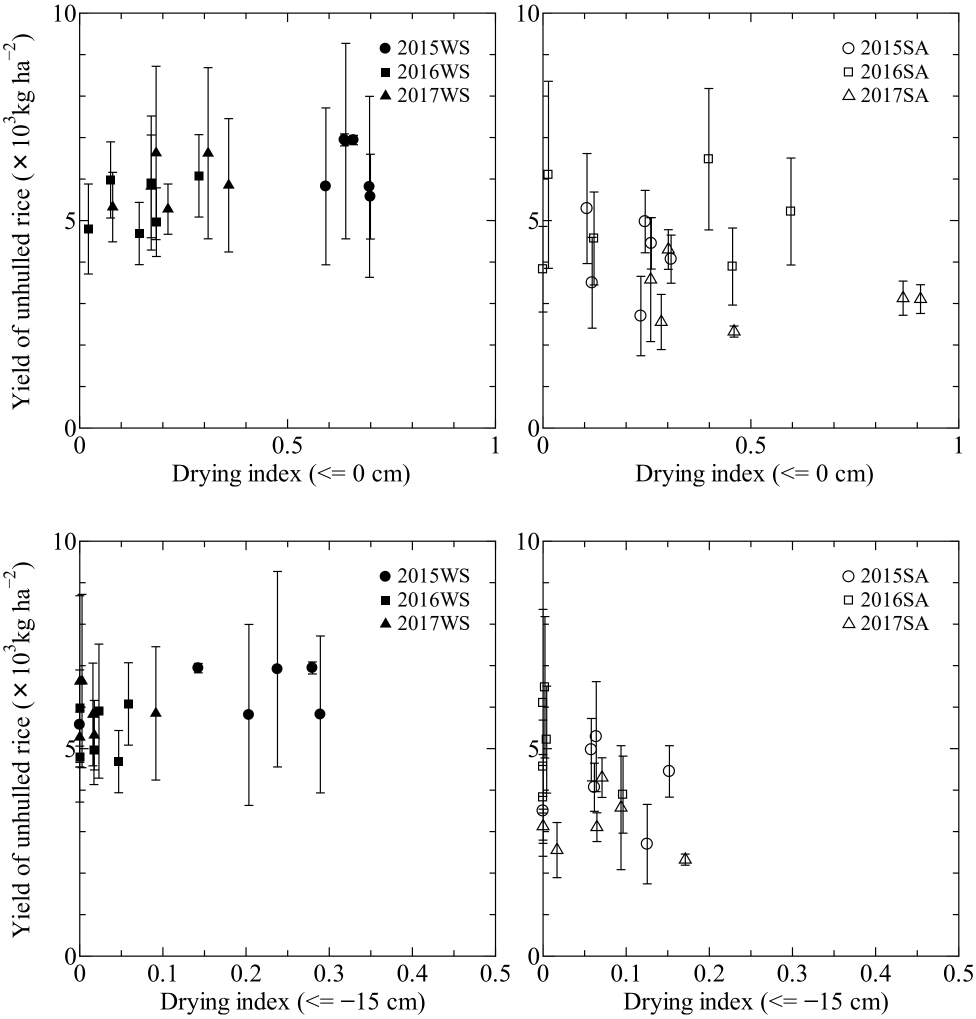

Fig. 3.11 Relationship between the yield of unhulled rice and drying index for 0 cm ponding depth in each cropping season. WS, the winter-spring season (February or March to June); and SA, the summer-autumn season (June to September). Experiments were conducted for both seasons in 2015, 2016, and 2017. Error bars represent standard deviations

index and that there was no significant reduction in rice yield with careful drying in paddy field experiments covering ca. 44 ha over the three years should be an incentive for farmers and administrative governments to develop environmentally friendly water management.

3.5 Conclusions

In this study, the organizational water management system (i.e., involving the operation of pumps and gates) was only able to be utilized on a few occasions as part of the AWD management assessment due to the timing of precipitation and because the ponding depth remained above the soil surface. The original schedule of water ponding depth was, therefore, not achieved. The drying degree of the weak-dry block and the strong-dry block may have increased compared to the conventional block, however, it was limited to the period within the cropping season. Future research on the feasibility of AWD management in this region is necessary for the organization of water management. It is important to demonstrate the feasibility of a non-flooded period for suppressing CH_4 emissions to the water management organization and farmers, taking into consideration the physiologically essential flooding period and the midseason drainage period to prevent reductions in rice yield. CH_4 emissions were much higher than N_2O emissions, so policies for reducing CH_4 emissions should be focused on in the study region. Despite the CH_4 emission having decreased with the increase in the drying index for the soil surface, it was difficult to control the CH_4 emission by increasing the drying index in the WS compared to that in the SA. The findings of this study suggest that the drying period should be increased in SA through careful water management to effectively reduce CH_4 emissions from rice paddies.

Chapter 4

Paddy ponding water management to reduce methane emission based on observations of methane fluxes and soil redox potential in the Red River Delta, Vietnam

Matsuda S. et al. (2021) *Irrig. and Drain.* 1−14. DOI: 10.1002/ird.2645

4.1 Introduction

CH_4-producing bacteria in paddy soil are obligate anaerobic bacteria that generate CH_4 under strong reducing conditions in the soil. After flooding, the redox potential (Eh) decreases as the molecular oxygen in soil decreases; this in turn affects the microbiological reactions in the soil, and finally, methanogens become active. Therefore, prolonging the soil drying period can effectively control CH_4 emission into the atmosphere. Alternate wetting and drying (AWD), an intermittent irrigation method proposed as a water-saving technology, has garnered attention recently for its applicability to reduce CH_4 emission.

Although the effectiveness of the AWD method has been demonstrated in experimental studies, this method has not been widely practiced by farmers because it does not have substantial benefits such as increase in rice yield or improvement of rice quality. Therefore, even if the farmers are requested to adapt the AWD method, they tend to maintain flooding conditions for safe rice growth. Thus, it was proposed the organizational AWD, in which water use groups, not individual farmers, manage irrigation by rotational distribution of water to each block in a paddy district using division works or sluice gates constructed in an irrigation system in the Red River Delta, Vietnam in Chapter 3. The results showed that organizational water management is possible and that it can suppress CH_4 emission, although the suppression effect is limited by weather conditions. In addition, this area had poor drainage and could not be made dry immediately. In the AWD method here, the water level was monitored, and when it reached 15 cm below the ground, the soil was flooded by about 5 cm. Under poor drainage conditions, such as in this area, a reduction condition might be maintained and CH_4 might continue to be produced. Therefore, it is important to propose specific schedules of ponding management focusing on the soil redox condition to reduce the amount of CH_4 emission.

The purpose of this chapter was to draft ponding management schedules for the suppression of CH_4 emission using observed data of ponding depth, Eh, and CH_4 flux in paddy plots in Vietnam and considering the above-mentioned CH_4 generation mechanism. Furthermore, I estimated the effects of the implementation of the proposed schedules on CH_4 reduction and water conservation. Finally, I outline AWD schedules that will help suppress CH_4 emission and increase water conservation.

4.2 Materials and methods

4.2.1 Study site

The study site is the same location as that for Chapter 3. A demonstration test of the AWD method was conducted in a paddy district of 44.2 ha in Phu Thinh commune (21°25’ N, 105°46’ E), Kim Dong District, Hung Yen Province, located in the northern part of Vietnam. The soil texture of paddy fields is clayey, and the saturated hydraulic conductivity of the upper (near the soil surface), middle (at 30 cm depth), and lower layers (at 50 cm depth) is 6.1×10^{-3}, 4.2×10^{-5}, and 2.6×10^{-4} cm s^{-1}, respectively. In this area, double rice cropping is practiced during the winter-spring (WS, February or March to June) and summer-autumn cropping seasons (SA, June or July to September). After SA cropping and until WS cropping, various vegetables are cultivated in paddy plots. In the WS season in 2017, the plants for WS cropping were transplanted from February 15 to 17 and harvested on June 20 (the cultivation period was 126 days). In the SA season in 2017, transplanting was conducted on July 5 and harvest on September 25 (the cultivation period was 83 days). The rice variety Thien uu 8 was planted in both seasons. The weather conditions during the WS and SA cropping seasons were as follows: Precipitation was 515 and 796 mm, the average temperature was 24.8 and 28.7 °C, and the average relative humidity was 81.0% and 87.4%, respectively.

Irrigation water was pumped from the main canal using one pump and was distributed through open channels in the district. These terminal open channels were dual purposes: irrigation and drainage. The district was divided into three water distribution blocks by two division works, and small gates were installed in the canal. This allowed water managers to collectively distribute irrigation water for each block.

4.2.2 AWD approach

The AWD water management was performed throughout the study period, except for the flooding period of 1 month after transplanting, non-flooding period at mid-term drainage, and flooding period of approximately 1 month during the ear emergence period. During the AWD period, water managers observed the depth of water through a perforated PVC tube (International Rice Research Institute [IRRI], 2020) installed into the paddy plots and irrigated the fields when the water level dropped to a depth of 5 cm (plots 3 and 4) or 15 cm (plots 5 and 6) below the soil surface. Flooding was maintained in all plots, except during mid-term drainage in plots 1 and 2, which were watered following the traditional non-AWD approach. Water management is described in detail in section 3.2.1.

4.2.3 Measurements

Six observation plots (plots 1–6) were set up in the study area. CH_4 emission flux was measured using the closed-chamber method at 1-week intervals. Two chambers were installed in each plot. The size of the chambers was 60 cm × 60 cm in cross section and 120 cm in height, and they were positioned to include a similar number (approximately 15) of rice stubbles. The air in the chamber was sampled 1, 10 and 20 min after installing the chamber at the base; the temperature within the chamber was measured simultaneously. CH_4 concentration was measured by a gas chromatograph equipped with a flame ionization detector of which details are described in Itoh et al. (2011), and its flux was calculated using the following equation(1) (see section 3.2.4).

The paddy ponding depth (cm) near the chamber was observed using a water level sensor (WR-HR; Intech Instruments Ltd., Christchurch, New Zealand) at 10-min intervals. By burying a perforated PVC pipe into the soil, the water level was measured approximately 30 cm below the soil surface. Soil temperature (°C) was measured at 10-min intervals at 5 and 15 cm depths (5TE; Decagon Devices, Inc., Pullman, Washington). Using platinum electrodes and Ag/AgCl reference electrodes (4400; DKK-TOA Corporation, Tokyo, Japan), the Eh (mV) at depths of 5, 15, and 30 cm was measured and converted to the values of the standard hydrogen electrode (SHE) using the following equation:

$$\mathrm{Eh} = E_{\mathrm{obs}} - 1.01T + 224 \qquad (2)$$

where Eh is the redox potential (mV vs. SHE), E_{obs} is the observed potential difference, and T is the soil temperature (°C). These parameters were measured at 20-min intervals. Meteorological factors (temperature and humidity measured using VP-3; Decagon Devices, Inc., Pullman, Washington), precipitation (ECRN-100; Decagon Devices, Inc., Pullman, Washington), and solar radiation (PYR; Decagon Devices, Inc., Pullman, Washington) were also measured at 10-min intervals at a height of 10 m above the ground.

4.3 Results and discussion

4.3.1 Winter-spring cropping season

Figure 4.1 shows the temporal changes in precipitation, CH_4 emission flux, ponding depth, and Eh in each plot during the WS cropping period after transplantation. Frequent AWD was not observed in plots 3–6, and it did not show obvious differences between plots 1 and 2 owing to the timing of precipitation; furthermore, the decrease in ponding depth above the soil surface was not large.

The ponding depth dropped below 0 cm from 48 to 54 days after transplantation (DAT), and CH_4 emission peaked from 37 or 45 DAT. During this period, the soil Eh increased, the upper soil layers up to a depth of 30 cm were oxidized, and CH_4 emission was suppressed. The increase in Eh (except in plot 1) at a depth of 15 cm occurred 1.5–2.5 days after its increase at a depth of 5 cm; the Eh at a depth of 30 cm increased 1–2.5 days later. In contrast, the increase in Eh at depths of 15 and 30 cm in plot 1 occurred later than that in the other plots; at a depth of 15 cm, the Eh increased 4.5 days after its increase at a depth of 5 cm, and it was 4 days later at a depth of 30 cm. The Eh increases mainly due to the oxidative environment caused by the entry of oxygen into the soil. The decreasing rate of the water level after the disappearance of flooding in plot 1 was not slower than in the other plots. The reason for the delay in the increase of Eh only in plot 1 was not clear, but it is possible that the measurement points in plot 1 were partially reduction conditions.

A rainfall of 95 mm occurred at 71 DAT, and all plots were flooded at least until mid-May. A CH_4 emission of 0.059 $\mathrm{mg\,m^{-2}\,min^{-1}}$ was observed again at 80 DAT, and the emission increased at 87 DAT in plot 3. CH_4 emission of 0.068 and 0.204 $\mathrm{mg\,m^{-2}\,min^{-1}}$ was observed at 87 DAT in plots 2 and 6, respectively. Because plot 4 was flooded before this rainfall event, CH_4 emission of 0.020 $\mathrm{mg\,m^{-2}\,min^{-1}}$ was observed at 65 DAT, and then it increased to around 0.4 $\mathrm{mg\,m^{-2}\,min^{-1}}$ at 87 DAT. Negligible CH_4 emission was observed in plots 1 and 5 despite the flooding after the rainfall. For CH_4 to be produced, a strong reduction condition and enough organic matter are necessary. When comparing Eh at the time of gas sampling on 87 DAT, the average values for the three depths of plots 1–6 were −107, −123, −130, −177, −149, and −133 mV, respectively. The low CH_4 emission in plot 1 was considered due to the relatively high Eh. The reason for the low CH_4 emission in plot 5 could not be determined from the results of this study, but it is possible that the amount of organic matter was low.

4.3.2 Summer–autumn cropping season

Figure 4.2 shows the observation results during the SA cropping period. The ponding depth dropped to less than 0 cm from17 to 25 DAT in all plots, and the rainfall event at 26 and 27 DAT caused flooding in plots 1, 2, 5, and 6. The ponding depth dropped below 0 cm again in all plots at 36 DAT. During the first non-flooding period, the Eh at 5 cm depth in plots 1 and 5 increased

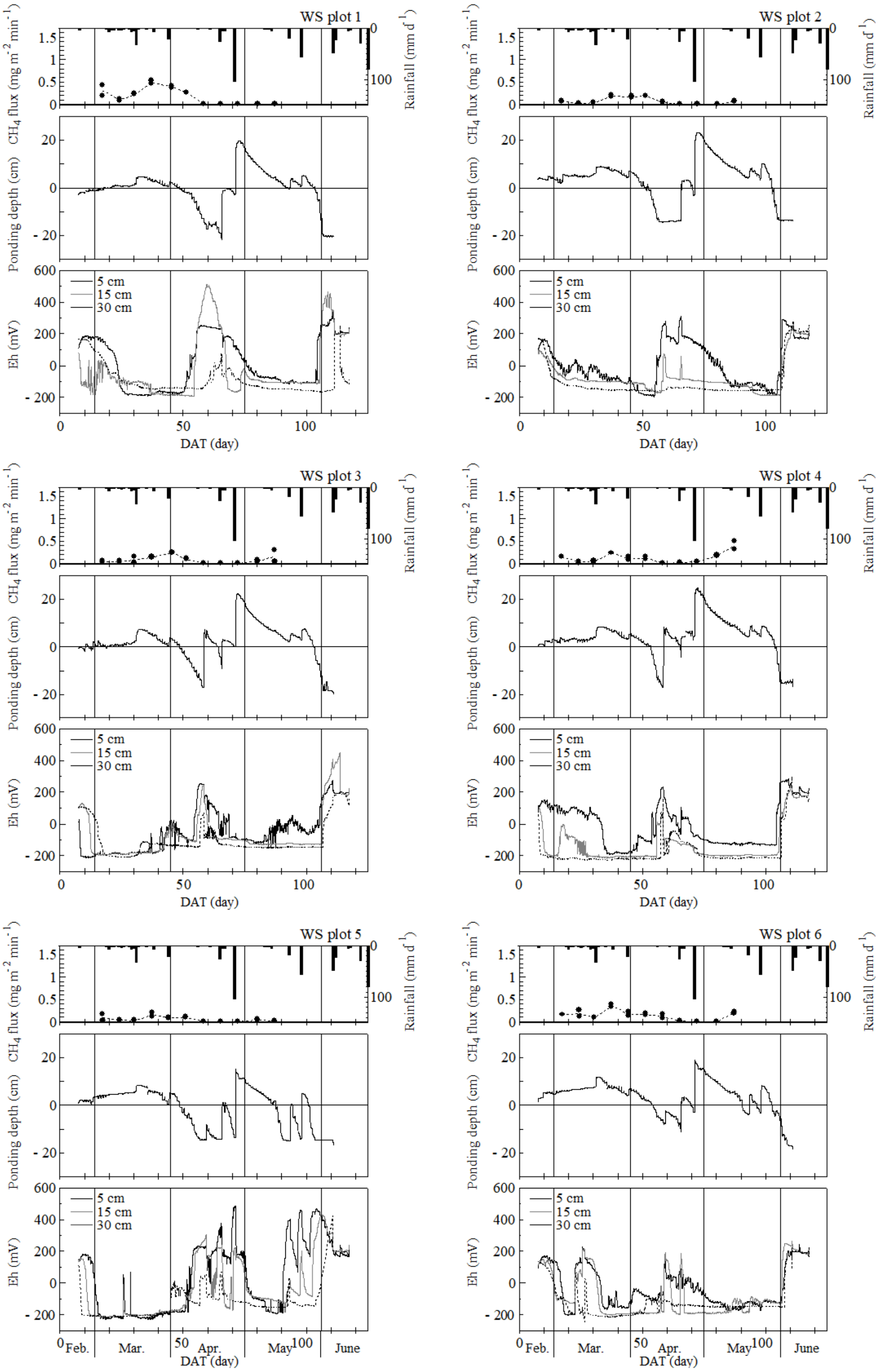

Fig. 4.1 Temporal changes in rainfall, methane flux, ponding depth, and soil redox potential (Eh) in the winter-spring cropping season (WS) in 2017. For methane flux, the plots represent the measured values and the dotted lines represent the average. The vertical dashed lines indicate the boundaries between months

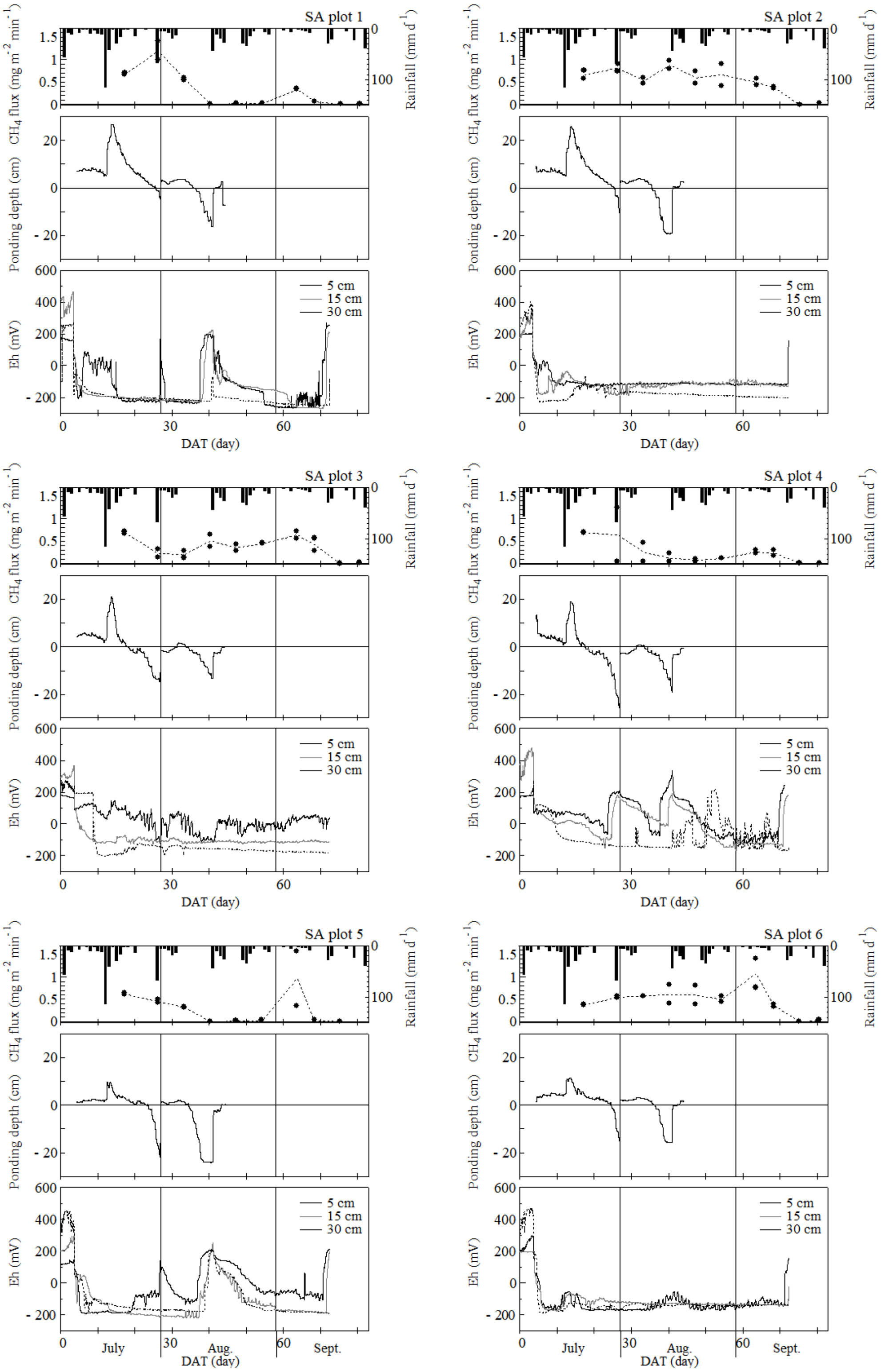

Fig. 4.2 Temporal changes in rainfall, methane flux, ponding depth, and soil redox potential (Eh) in the summer-autumn cropping season (SA) in 2017. For methane flux, the plots represent measured values and the dotted lines represent the average. The vertical dashed lines indicate the boundaries between months

by 397 and 287 mV, respectively, and the Eh in plot 4 at 5 and 15 cm depths increased by 294 and 331 mV, respectively. The Eh at a depth of 30 cm did not increase, and CH_4 emission during this period was not significantly reduced. In plot 3, the Eh at 5 cm depth remained well above 0 mV even during the flooding following transplanting, and that at 15 and 30 cm depths was around −100 and −200 mV, respectively. CH_4 emission decreased at 26 DAT when the flooding was ceased, but it did not approach zero. Plots 2 and 6 showed no increase in Eh at all depths during the short non-flooding period at 24–26 DAT, and there was no suppression of CH_4 emission. During the second non-flooding period at 34–43 DAT, the Eh increased at all depths and CH_4 emission almost ceased in plots 1 and 5. In plot 4, the Eh started to increase at depths of 5 and 15 cm at 37–39 DAT, whereas CH_4 emission decreased although it was still observed (0.125 $mg\,m^{-2}\,min^{-1}$) at 40 DAT. In contrast, in plots 2 and 6, the Eh did not increase during the second non-flooding period and CH_4 emission was not suppressed. In plot 3, during the first non-flooding period, the Eh at 15 and 30 cm depth, as well as CH_4 emission, changed marginally. Similar to that in the WS cropping season, a lag in the increase in Eh was observed in four plots (excluding plots 2 and 6) at multiple depths; at 15 cm depth, the increase in Eh was delayed by 0.5–2 days and at 30 cm by an additional 1.5–2 days after its increase at 5 cm depth.

Although the data of ponding depth after 44 DAT were missing, flooding likely continued until early September based on the Eh values, which decreased or remained low in all plots. In plots 1 and 5, CH_4 emission was suppressed from 40 to 54 DAT and re-emission was observed at 63 DAT, caused by continuous flooding.

4.3.3 Effect of the temporal changes in soil Eh at each depth on CH_4 emission suppression

The increase in Eh, which occurs during the period between the time when the flooding depth drops below the soil surface and the time when CH_4 emission almost ceases, can clarify the relationship between the temporal changes in Eh and CH_4 emission. For example, in plot 4 during the WS season (**Fig. 4.1**), the ponding depth dropped below 0 cm at 53 DAT and the Eh at 30 cm depth increased at 57 DAT. The CH_4 emission flux was 0.120 $mg\,m^{-2}\,min^{-1}$ at 51 DAT and 0.007 $mg\,m^{-2}\,min^{-1}$ at 58 DAT. Therefore, the increase in the Eh at 30 cm depth in addition to 5 cm and 15 cm during this period may suppress CH_4 emission. Given that there was no change in Eh in plots 1, 2, 5, and 6 at 30 cm depth before and after the measurement day when CH_4 emission almost ceased, the Eh at 15 cm depth may suppress CH_4 emission (**Fig. 4.1**). The relationship between the Eh at the three depths and CH_4 emission showed that the effective depth for CH_4 emission was 0–15 cm for plots 1, 2, 5, and 6 and 0–30 cm for plots 3 and 4.

In the SA cropping season, the effective depth for CH_4 suppression was also different among the plots. For example, the increase in Eh at 30 cm depth in plot 1 occurred 40 DAT, when CH_4 emission was almost zero (0.008 mg m^{-2} min^{-1}) (**Fig. 4.2**). Thus, the Eh at 30 cm depth does not contribute to CH_4 emission, as in plot 1 in the WS cropping. In plot 5, the Eh at 5 cm depth increased and that at 15 and 30 cm depths was maintained around −200 mV at 26 DAT, whereas CH_4 emission was detected until 33 DAT. Thereafter, the Eh at 30 cm depth increased and CH_4 emission was suppressed at 38 DAT, suggesting that CH_4 emission is affected at 30 cm soil depth in addition to 5 and 15 cm. Although the plots are located in the same district, effective depths for CH_4 suppression were different, and this may be due to heterogeneous soil hydro-biochemical properties, such as soil hydraulic parameters and oxidation-reduction processes.

4.3.4 Suppression of CH_4 by non-flooding

Based on the discussion in the previous section, the data presented in **Table 4.1** show the period from the time when the ponding depth dropped below 0 cm to the time when the Eh increased at a depth that contributes to CH_4 emission cessation in WS and SA cropping. The changes in Eh shown in **Table 4.1** are the values immediately before the increase in Eh and the maximum value after this increase when CH_4 emission was almost zero (< 0.05 mg m^{-2} min^{-1}). The increase in Eh lagged by 3–8 days after the ponding depth dropped below 0 cm in WS cropping. Wang et al. (1993) showed that CH_4 emission started when the Eh reached approximately −150 mV at a soil pH of 6.7–6.9 under laboratory conditions. In paddy field experiments, the timing of substantial CH_4 emission coincided with the timing of Eh drop to below −200 mV in the plow layer (Yagi and Minami, 1993). However, in the present study, CH_4 emission was detected in the Eh range of −101 to −218 mV. In plot 2 and plot 5, CH_4 was emitted at relatively high Eh values of −101 mV, which suggested that CH_4 was produced deeper than the observed depth (30 cm). The soil in SA cropping rarely reached a dry state because of frequent rainfall, and there was no increase in Eh in plots 2, 3, 4, and 6 (**Table 4.1**). As a result, CH_4 emission was not suppressed (**Fig. 4.2**).

4.3.5 Re-emission of CH_4 induced by flooding

Under the non-flooding conditions, the soil dries and CH_4 emission is suppressed by the increase in soil Eh. When the paddy is flooded again, the Eh decreases and CH_4 re-emission commences, as observed in plots 2, 3, 4, and 6 in WS cropping (**Fig. 4.1**). The period from the time when the flooding starts to the time of CH_4 re-emission in WS cropping was focused.

Table 4.1 Period required for soil redox potential (Eh) to increase after the ponding depth dropped below 0 cm and the depth at which the Eh increase occurred in the winter–spring cropping season (WS) and summer–autumn cropping season (SA) in 2017

	Plot No.	Date and time when ponding depth drops below 0 cm	Date, time, and depth from the soil surface (cm) when the Eh increase occurs		Eh change (mV)	Period (day)
WS	1	48 DAT (Apr. 4 15:20 h)	54 DAT (Apr. 10 14:20)	15	-190 to 429	6.0
	2	52 DAT (Apr. 8 11:20 h)	58 DAT (Apr. 14 12:00)	15	-101 to -87	6.0
	3	48 DAT (Apr. 4 14:40 h)	56 DAT (Apr. 12 19:00)	30	-139 to 70	8.2
	4	53 DAT (Apr. 9 10:40 h)	57 DAT (Apr. 13 11:00)	30	-218 to 159	4.0
	5	48 DAT (Apr. 4 15:20 h)	52 DAT (Apr. 8 2:00)	15	-101 to 263	3.4
	6	54 DAT (Apr. 10 11:40 h)	58 DAT (Apr. 14 15:00)	15	-180 to 193	4.1
SA	1	35 DAT (Aug. 9 18:20 h)	37 DAT (Aug. 11 23:00)	15	-226 to 212	2.2
	2		– *			
	3		–*			
	4		– *			
	5	34 DAT (Aug. 8 11:20 h)	38 DAT (Aug. 12 19:00)	15	-177 to 176	4.3
	6		– *			

* Methane emission suppression was not observed. DAT: days after transplantation.

Table 4.2 shows the date and time when flooding was started, CH_4 flux was observed before CH_4 re-emission, and CH_4 re-emission was observed. The period of possible CH_4 re-emission is shown for each plot.

The data of plots 2, 3, 4, and 6 suggest a tendency for CH_4 re-emission after continuous flooding for 14–22 days. The flooding in mid-April might have affected soil reduction and triggered CH_4 emission. Immediately after the flooding, the Eh at 15 and 30 cm depth decreased to values at which CH_4 emission could occur, but the actual emission of CH_4 was delayed. This delay was because ferrous iron (Fe^{2+}) is oxidized under decreasing soil moisture conditions, which occur due to drainage and evapotranspiration, but the subsequent flooding suppresses the activity of CH_4-producing bacteria by the reduction of Fe^{3+} and the accompanying consumption of hydrogen ions (H^+) before CH_4 production (Ma et al., 2012).

4.3.6 Ponding management schedules for CH_4 suppression and their effect

The results of the present study suggest that CH_4 emission is suppressed when the non-flooded state is maintained for 3–8 days (**Table 4.1**), and re-emission occurs when the flooding state is continued for 14–22 days (**Table 4.2**). Therefore, establishing a 3–8-day-long non-flooded state 1 day before the end of the 14–22-day-long flooding state (i.e., flooding periods of 13 and 21 days) would suppress the emission of CH_4. In addition, even if the Eh is low under flooded conditions and CH_4 is released, maintaining the non-flooded state for at least 3–8 days will suppress the emission of CH_4 and then allow farmers to irrigate the paddy plots. Applying the AWD management method that can implement these flooding and non-flooding periods will continue to suppress CH_4 emissions.

Considering the variations in soil hydraulic and biochemical properties of paddy plots, the following four combinations of the ponding depth management schedule are proposed for the non-flooding periods of 3 and 8 days and flooding periods of 13 and 21 days to control CH_4 emission, in addition to the control or conventional schedule (CF, conventional flooding):

- CF: continuous flooding except during the mid-term drainage and pre-harvest non-flooding periods;
- Case I: 8 days of non-flooding, 13 days of flooding;
- Case II: 8 days of non-flooding, 21 days of flooding;
- Case III: 3 days of non-flooding, 13 days of flooding; and
- Case IV: 3 days of non-flooding, 21 days of flooding.

Table 4.2 Period from the start of flooding until the start of methane emission in the winter–spring cropping season (WS) in 2017

	Plot No.	Date and time when flooding starts	CH_4 flux observation date and time before CH_4 re-emission	Date and time when CH_4 re-emission is observed	Period (day)
WS	2	65 DAT (Apr. 21 18:40 h)	80 DAT (May 6 9:27 h)	87 DAT (May 13 10:29 h)	14.6–21.7
	3	58 DAT (Apr. 14 18:20 h)	72 DAT (Apr. 28 8:23 h)	80 DAT (May 6 8:42 h)	13.9–21.9
	4	58 DAT (Apr. 14 15:00 h)	72 DAT (Apr. 28 7:53 h)	80 DAT (May 6 8:12 h)	13.7–21.7
	6	65 DAT (Apr. 21 18:40 h)	80 DAT (May 6 6:56 h)	87 DAT (May 13 8:35 h)	14.5–21.6

DAT: days after transplantation

In these scenarios of AWD-based ponding water management (cases I − IV), the flooding period is controlled as long as possible within the range at which CH_4 emission is suppressed, while avoiding the risk of soil drying, which could hinder rice growth.

Some common requirements are set for cases I–IV to secure rice yield. First, the rice transplanting date and the harvest date are set to February 15 and June 20, respectively, based on the WS in 2017 and the cultivation period of 126 days. Second, soil puddling is performed 2 days before transplanting. Third, flooding periods of 14 days each after transplanting and 1 week before and after heading will ensure unaffected rice growth (Siopongco et al., 2013). Fourth, the period of mid-term drainage is set to 15 days in early April based on WS cropping data in 2017. Fifth, the heading date is set to May 1 based on the cultivation experiments (Kotera et al., 2004) conducted to develop a model for estimating the heading date. Sixth, the non-flooding period before harvest is from May 28 to the harvest date as inferred from the actual ponding depth data of WS cropping in 2017. Although the above dates and periods depend on actual weather conditions, showing the example for rice cultivation in 2017 at this experimental site helps water managers and farmers to understand the days available between intermittent irrigation and the effects of optimal AWD on CH_4 reduction and water conservation. Furthermore, the schedule can be easily modified depending on the cropping season.

Figures 4.3a–4.3d show ponding management schedules under CF and cases I − IV. The required non-flooding period for controlling CH_4 emission is repeated two or three times, except during the mid-term drainage and before the harvest. Frequent non-flooding conditions are not always necessary for reducing CH_4 emission—a non-flooding period twice before the mid-term drainage and once afterward will be sufficient (case I, III, and IV). The water-saving efficiency of these ponding water management practices is discussed in the next section.

The temporal changes in CH_4 emission from the soil puddling to harvest for each case were estimated using the actual measured CH_4 emission fluxes at the six plots to calculate the efficiency of AWD irrigation on the suppression of CH_4 emission. For CF, the average value observed on each measurement day in the six plots was used. The value on one measurement date was assumed constant until the next measurement date. For cases I − IV, the maximum value of observed CH_4 emission was applied to avoid overestimating the emission suppression effect. The CH_4 flux from flooding to beginning of CH_4 emission was considered the maximum value under the same conditions in the six plots ($0.012\ mg\ m^{-2}\ min^{-1}$ was obtained from the measurements). Subsequent emissions gradually increased from the point CH_4 re-emission as

Fig. 4.3a Ponding depth management and estimated methane emission for continuous flooding (CF; except mid-term drainage and before harvest) and case I (non-flooding 8 days, flooding 13 days). Shaded parts indicate flooding period for a given ponding depth. DAT, days after transplantation

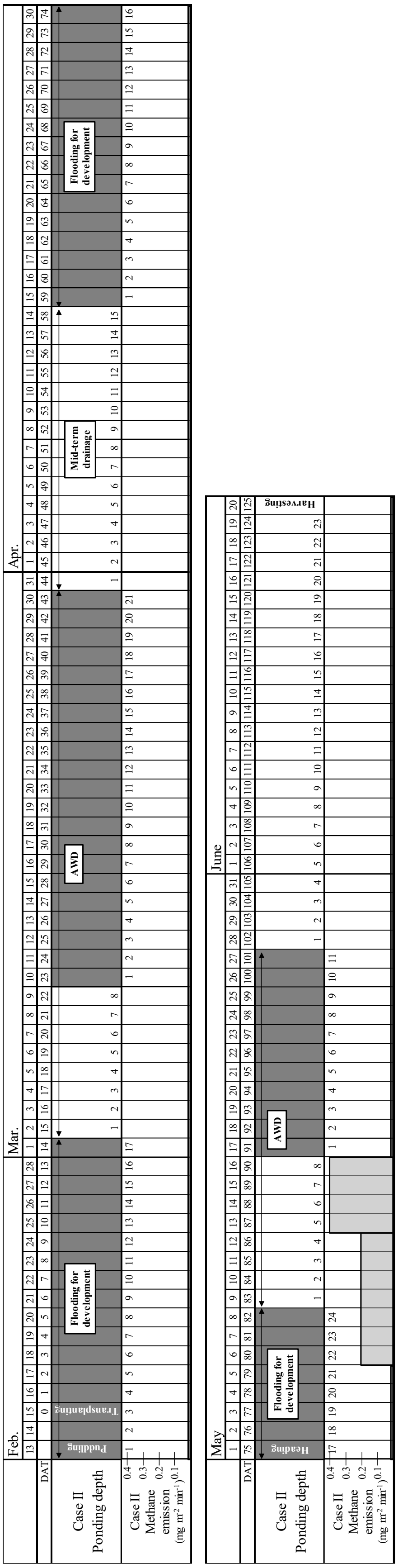

Fig. 4.3b Alternate wetting and drying (AWD)-based ideal ponding depth management and estimated amount of methane emission for case II (non-flooding 8 days, flooding 21 days). Shaded parts indicate flooding period for a given ponding depth. DAT, days after transplantation

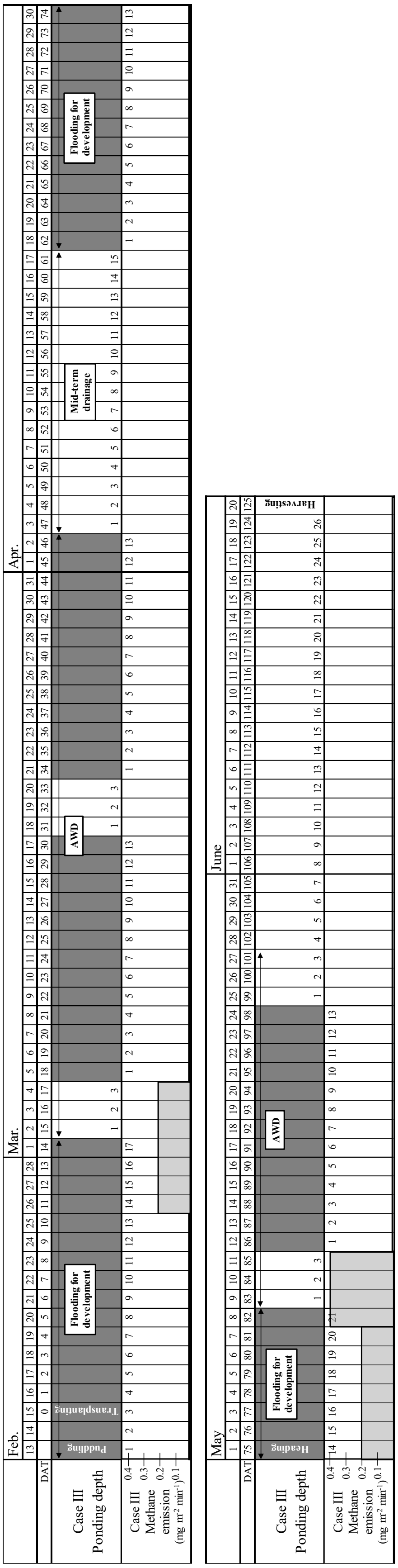

Fig. 4.3c Alternate wetting and drying (AWD)-based ideal ponding depth management and estimated amount of methane emission for case III (non-flooding 3 days, flooding 13 days). Shaded parts indicate flooding period for a given ponding depth. DAT, days after transplantation

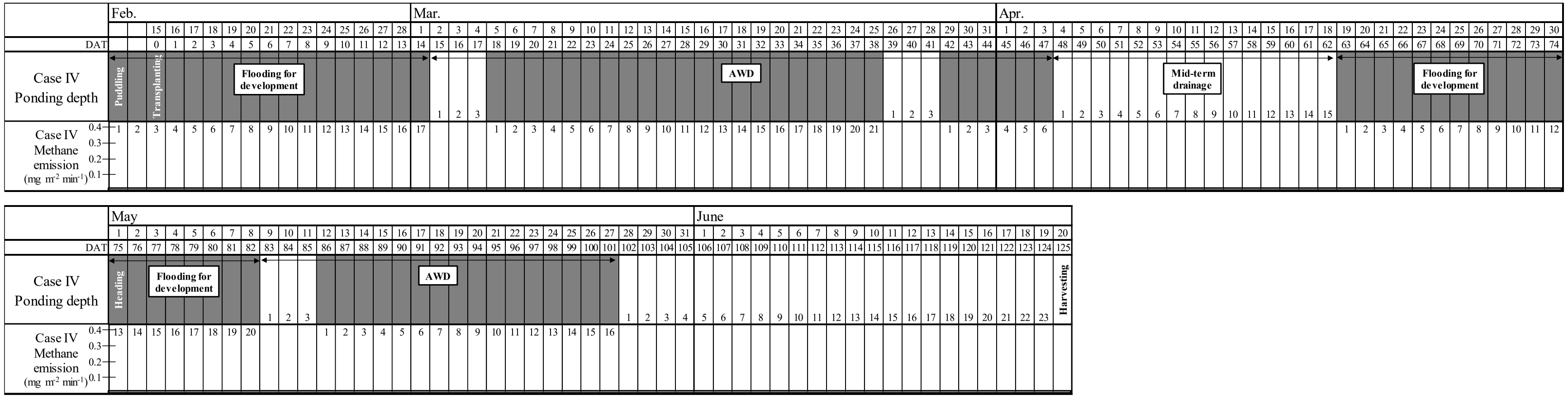

Fig. 4.3d Alternate wetting and drying (AWD)-based ideal ponding depth management and estimated amount of methane emission for case IV (non-flooding 3 days, flooding 21 days). Shaded parts indicate flooding period for a given ponding depth. DAT, days after transplantation

observed in plot 4 (**Fig. 4.1**), and then the values in the first and second weeks of re-emission of CH_4 were 0.204 and 0.404 mg m^{-2} min^{-1}, respectively, based on the observed maximum values.

Figures 4.3a–4.3d show the emission patterns under CF and cases I – IV. For example, in case I (**Fig. 4.3a**), CH_4 emission was almost zero 8 days after switching from flooded to non-flooded conditions, and it increased 13 days after switching to flooded conditions. Thus, CH_4 emission significantly increased on February 26, which is 13 days after the first flooding. It continued for 8 days after switching to non-flooding conditions on March 2, and reached almost zero levels from March 10, when flooding of the fields was allowed. Nevertheless, CH_4 emission was suppressed for the next 13 days after flooding, until March 22. Although, in practice, CH_4 emission can be expected to decrease during the non-flooding period from March 2 to 9, especially in the latter half of the period, the CH_4 emission amount at which flooding is continued is used to avoid the underestimation of CH_4 emission risk.

Flooding periods of 14 DAT and 1 week before and after heading for securing rice growth significantly increase CH_4 emission from the end of the flooding period to the end of the non-flooding period. The amount of CH_4 emitted during the cultivation period was 10.6, 6.4, 8.3, and 2.2 g m^{-2} for cases I – IV, respectively, compared with 14.5 ± 7.5 g m^{-2} (± standard deviation) for CF (**Fig. 4.4**). Therefore, the CH_4-suppression efficiency of AWD water management was 27%, 56%, 43%, and 85% for cases I – IV, respectively. More CH_4 was emitted in case I than in case II, and in case III than in case IV, even though the required non-flooding period was the same. This was due to the flooding period after transplanting (and the flooding period before and after the ear emergence in case III). It is presumed that even if the ponding water management is performed by considering farmers' intention to maintain the plots flooded as much as possible, a certain level of CH_4-suppression effect would be expected.

CH_4 emission depends on rainfall, especially during the non-flooding period, and on air and soil temperatures during the cropping season. The actual water management also depends on the water requirement rate, which is determined by infiltration and evapotranspiration. Therefore, the actual CH_4 suppression may be in accordance with the characteristics of the region and flexible based on weather conditions.

4.3.7 Effect of schedules on water conservation

The expected water-saving effects of the AWD management proposed for CH_4 emission suppression were also estimated in the present study. The amount of irrigation for each plot was

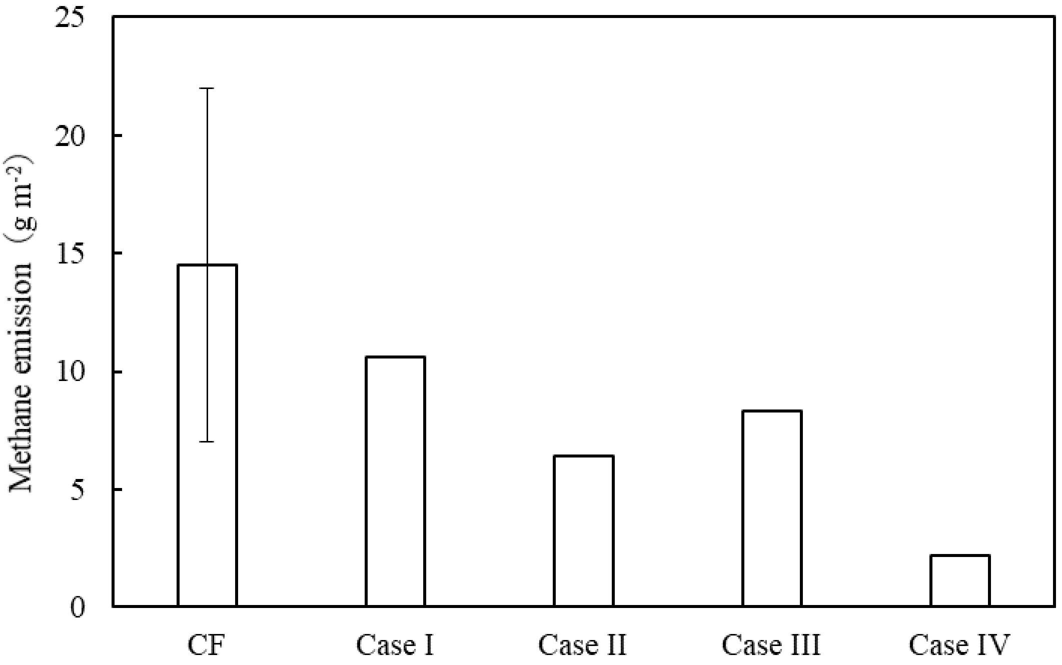

Fig. 4.4 Estimated total methane emission in the winter-spring cropping season under different ponding water management schedules (**Fig. 4.3a–4.3d**). For conventional flooding, it was estimated based on the average measured methane emission (the error bars indicate standard deviation). For cases I-IV, it was estimated based on the maximum measured methane emission

indirectly calculated by taking into account the water requirement rate and the water table in plots where the water table was lowered below the soil surface during the non-flooding period.

To calculate the water requirement rate, the actual evapotranspiration was assumed to be equal to the potential evapotranspiration, which was calculated using the Penman equation (Penman, 1948) from the meteorological data and expressed as the average values of evapotranspiration for every 15 days from late February to late May. The daily evapotranspiration values increased from around 2 to 4 mm day^{-1}. The amount of infiltration was assumed to be the amount of ponding depth reduction at night (7:00 p.m. to 5:00 a.m. the following day in the no-rainfall period), because there is no irrigation, with little drainage and evapotranspiration. The average infiltration values were calculated before and after mid-term drainage because the amount of infiltration increases due to the formation of soil cracks after the mid-term drainage. The daily infiltration values were 3.5 and 5.7 mm day^{-1} before and after the mid-term drainage, respectively. The irrigation amount was set to be equal to the sum of evapotranspiration and infiltration during the flooding period in the cropping season to ensure a ponding depth of zero at the end of the flooding period.

It is necessary to consider the amount of water required to switch from unsaturated to saturated soil conditions when calculating the amount of irrigation water after the non-flooding period. According to the above proposed schedules, the non-flooding period is up to 15 days from the mid-term drainage. Except for plot 4, the water level decreased to the average of −9 cm in 5 days, and in plot 4 it decreased to −17 cm in 5 days (**Fig. 4.1**). Therefore, the water level was estimated to decrease to a maximum depth of 50 cm for plot 4 and 30 cm for other plots from the actual water levels in 15 days. Measured soil water retention curves for the plots indicate that the saturated volumetric water content (porosity) was 0.634, and the volumetric water content at pressure heads of −50 and −30 cm was 0.557 and 0.575, respectively. Assuming that the volumetric water content from the soil surface to the water table is uniform at a value corresponding to a pressure head of −50 or −30 cm, the water amount required to reach the saturated state from the unsaturated state was estimated to be 39 mm (50 × [0.634–0.557] × 10) or 18 mm (30 × [0.634–0.575] × 10).

The irrigation amount during the cultivation period, excluding the amount of water required at the start of irrigation before soil puddling, was estimated to be 681 for CF and 623, 652, 710, and 737 mm for cases I – IV, respectively, when the irrigated water volume at flooding was 39 mm (**Fig. 4.5a**). The values would be 660 for CF and 539, 589, 626, and 653 mm for cases I – IV, respectively, when the irrigated water volume at flooding was 18 mm (**Fig. 4.5b**). The water-saving efficiency (the percentage of saved water relative to CF) is expected to be 18.3%, 10.8%, 5.2%, and 1.1% for cases I – IV, respectively, compared with CF, when the water volume at flooding was 18 mm. In contrast, the water-saving efficiency of 8.5% and 4.3% was calculated for cases I and II, respectively. In cases III and IV, the required irrigation amount increased by 4.2% and 8.2%, respectively, when the water volume at flooding was 39 mm. The number of flooding days was 89, 65, 73, 77, and 80 days in CF and cases I–IV, respectively (**Fig. 4.3a−4.3d**). The number of re-flooding events was 1, 4, 3, 4, and 4 in CF and cases I–IV, respectively (**Fig. 4.3a−4.3d**). Even if the number of flooding days in cases III and IV was lower than that in CF, the amount of irrigation water was higher in cases III and IV than in CF because of the higher amount of water required for re-flooding and the increased frequency of re-flooding in cases III and IV. Because CH_4 emission is suppressed by a shorter non-flooding period in cases III and IV, the frequency of re-flooding increases and the water-saving effect is reduced. It is desirable to set the non-flooding period such that its duration does not harm rice growth.

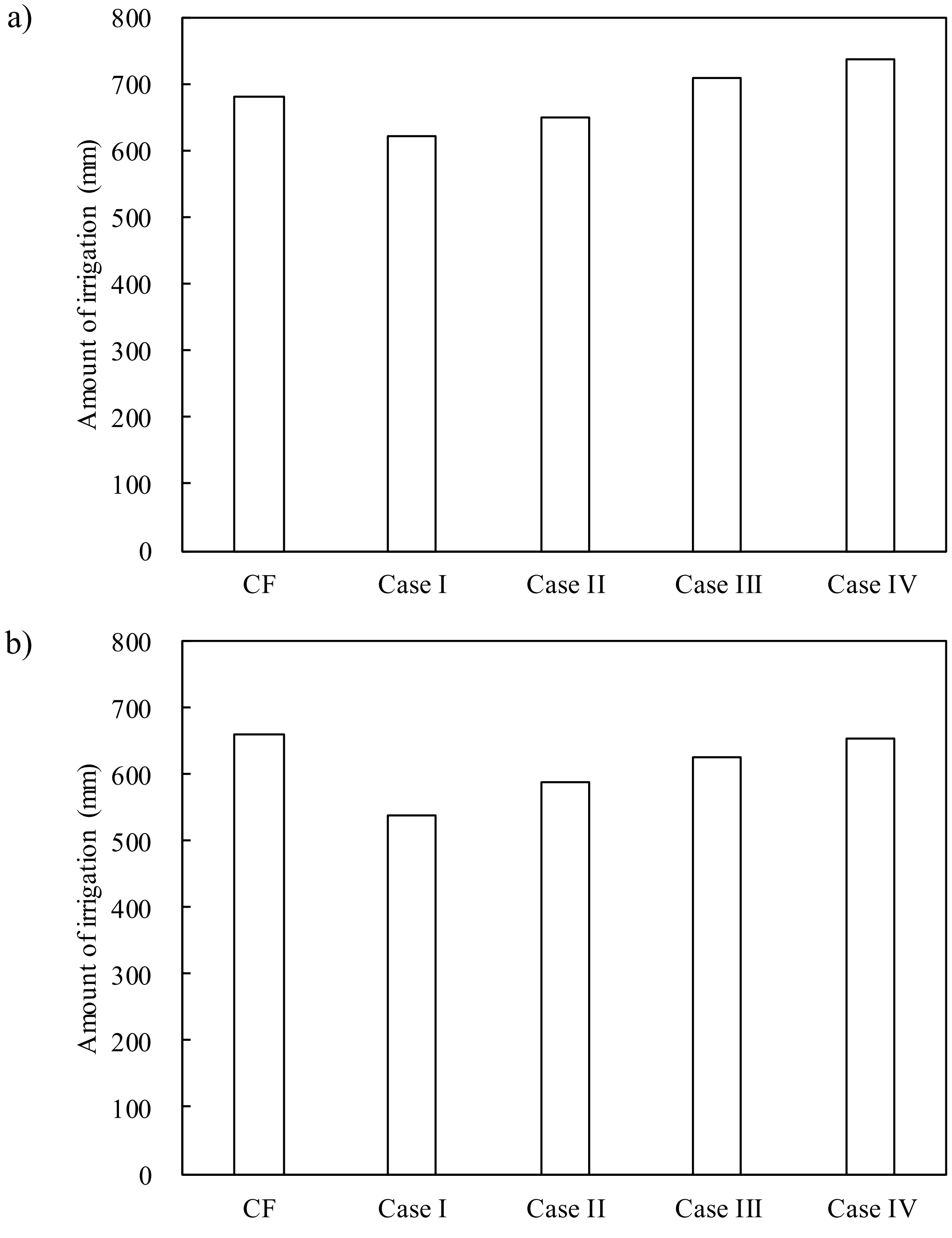

Fig. 4.5 Estimated irrigation amount in the winter-spring cropping season, excluding the amount of water needed at the start of irrigation before soil puddling, under different ponding water management schedules (**Fig. 4.3a–4.3d**) when the irrigated water volume at flooding was (a) 39 mm and (b) 18 mm. CF, conventional flooding

4.4 Conclusions

In this study, the ponding management schedule of AWD for suppressing CH_4 emission was proposed based on the temporal changes in CH_4 emission and the observed Eh at different depths within the 30-cm surface layer. CH_4 emission reduction and water-saving efficiency of AWD water management were compared with the CF water management using observed and estimated data of CH_4 emission and hydrological factors. Although the CH_4 emission reduction and water-saving efficiency depend on the climate condition of each year, effective schedules based on the actual soil and meteorological characteristics are expected to help farmers and managers of water use groups because a concrete target flood management is specified. Future research should focus on modeling the relationship among hydrological and biochemical characteristics of soil, meteorological properties, and CH_4 emission to establish a more generalized model for the required non-flooding period and the allowable flooding period aimed to reduce CH_4 emissions.

Chapter 5

Effect of infiltration rate on methane emission properties in pot-cultured rice under alternate wetting and drying irrigation

Unpublished manuscript

5.1 Introduction

When the soil is flooded, the redox potential (Eh) decreases along with reduction processes in the soil, and CH_4 is produced by methanogens when Eh reaches a strongly reduced state, i.e., –150 mV (e.g., Wang et al., 1993). Thus, periodically drying the soil to create an oxidative environment is effective at inhibiting CH_4 generation (e.g., Watanabe et al., (2010)).

The optimal non-flooding period that should be maintained to suppress CH_4 emission and the optimal continuous flooding period that can be tolerated to maintain CH_4 emission suppression vary from plot to plot. One of the factors affecting the length of these periods is the infiltration rate. Previous studies have suggested that the infiltration rate also affects the amount of CH_4 emission and the reduction rate during flooding. Infiltration reduces CH_4 emissions by leaching large amounts of carbon dioxide, which is a substrate of methanogens, from the soil solution, which decreases CH_4 production (Inubushi et al., 1992). However, Ishikawa and Iida (2019) investigated the relationship between CH_4 emission flux and infiltration rate at different growth stages and found that the CH_4 flux increased with increasing infiltration rate, except during the ripening stage, when this relationship was reversed. They suggested the following explanation. Before the ripening stage, the greater the infiltration rate, the more likely it is that methanogens will come into contact with low-molecular-weight compounds (substrates) dissolved in the infiltrating water per unit time, whereas during the ripening period, some substances inhibit the activity of methanogens and are distributed through the soil by infiltration.

These results suggest that the infiltration rate affects the CH_4 flux during the flooding period; however, the results are not consistent and the mechanism is unclear. One method of analyzing the effect of infiltration on CH_4 emissions is to study the redox state in the soil. Recently, there are few findings on the effect of water infiltration on Eh in paddy soils. Uchiyama et al. (1956) observed changes in soil Eh for 90 days after the start of irrigation in paddy soil and showed that, within one month of flooding, Eh decreased with increasing infiltration rate. Thus, they conjectured that microbial activity under anaerobic conditions became stronger with increasing infiltration rate (0–6 cm d^{-1}, infiltration rate was adjusted twice a day). Kira et al. (1960) showed that Eh was higher during water infiltration through two years of pot tests (with and without rice, with infiltration rates of 0, 20, and 70 mm d^{-1}), regardless of the presence or absence of rice. The authors attributed this to the flow of infiltrated water, which reduced the concentration of reducing substances; thus, the oxygen dissolved in irrigation water was mostly consumed in the soil near the ground surface, according to the results of dissolved oxygen measurements in ponding and infiltrated water. Furthermore, rice plants with no infiltration did not grow well. Therefore, the authors concluded that the significance of infiltration was not the delivery of dissolved oxygen to the soil, but rather the removal of harmful reducing substances such as H_2S. Furthermore, Takai et al. (1969) conducted four experiments on flooded soil in pots with and without rice and with and without infiltration. The results showed that Eh decreased to a similar degree, regardless of whether the soil was infiltrated or not and whether rice was planted or not. Subsequently, Takai et al. (1974) measured the Eh of flooded soil with infiltration (20 and 25 mm d^{-1}) and without infiltration, using four types of paddy soil with different characteristics, and found that infiltration reduced Eh during active organic matter decomposition with high amounts of easily decomposable organic matter, but increased Eh with low amounts of easily decomposable organic matter.

Owing to inconsistent findings on the effect of water infiltration on Eh in paddy soils, it is necessary to clarify the effect of infiltration rate on the reduction process and consider regionally appropriate ponding management techniques in order to improve the suppression effect of AWD on CH_4 emissions. The withdrawal of flooding and subsequent unsaturation of the soil leads to the emission of CH_4 trapped in the soil (Adviento-Borbe et al., 2015; Wassmann et al., 1994; Yagi et al., 1996). Therefore to accurately evaluate the effect of AWD with multiple non-flooding periods on CH_4 emissions, it is important to focus on CH_4 emissions during unsaturated soil conditions.

The following hypothesis was formulated for this study. In a paddy plot with a low infiltration rate, it takes time for flooding to recede and the soil to become oxidized. CH_4 continues to be produced, and more CH_4 is emitted when the soil becomes unsaturated owing to flood withdrawal. The purpose of this chapter is to investigate the effect of infiltration rate on CH_4 emissions and Eh during AWD application through rice cultivation in pots under different infiltration rates.

5.2 Materials and methods

5.2.1 Experimental conditions

Rice was grown in pots in a glass greenhouse in 2020 under two different irrigation conditions: continuous flooding (CF) without infiltration and AWD with three different infiltration rates in three replicates (numbered 1–3 for each condition). The soil used for the experiment was collected from a paddy plot in Shiga Prefecture, Japan, and passed through a 5-mm sieve. The soil texture was light clay (sand 51.1%, silt 19.7%, clay 29.2%; ISSS), the soil particle density was 2.64 g cm^{-3}, and the total organic carbon and nitrogen contents of the soil were 2.4% and 0.21% of dry soil weight, respectively (C/N ratio = 11.4). Wagner pots (size 0.05 m^2) were filled with gravel to a thickness of 5 cm and non-woven fabric (Paopao 90; MITSUBISHI CHEMICAL AGRI DREAM), then filled with soil to a thickness of 15 cm (bulk density: 1.18 g cm^{-3}) on June 3 (**Fig 5.1**). Nipponbare (*Oryza sativa* L.) was transplanted into all pots on June 5, and a chemical fertilizer (14–14–14 NPK, 1.0 g per pot) was added as a base fertilizer on the following day (0.75 g as an additional fertilizer on August 7 (63 days after transplanting (DAT)). Subsequently, flooding was maintained until 20 DAT for all conditions of AWD without infiltration. Then, intermittent irrigation was conducted with three different infiltration rates (AWD-1: 0 mm d^{-1} (no infiltration), AWD-2: 9 mm d^{-1}, and AWD-3: 18 mm d^{-1}) by manually adjusting the rate every 2 h until October 2–3 (119–120 DAT) using the following method. The position of the tip of the tube installed at the bottom of the pot was adjusted to achieve drainage volumes of 39 cm^3 and 78 cm^3 per 2 h for AWD-2 and AWD-3. The schedule for intermittent irrigation is shown in **Table 5.1**. After the flooding receded, when the Eh at a depth of 15 cm increased then plateaued to approximately 700 mV, the entire pot was considered to be sufficiently oxidized, and water was supplied from the top of the pot so that the water surface

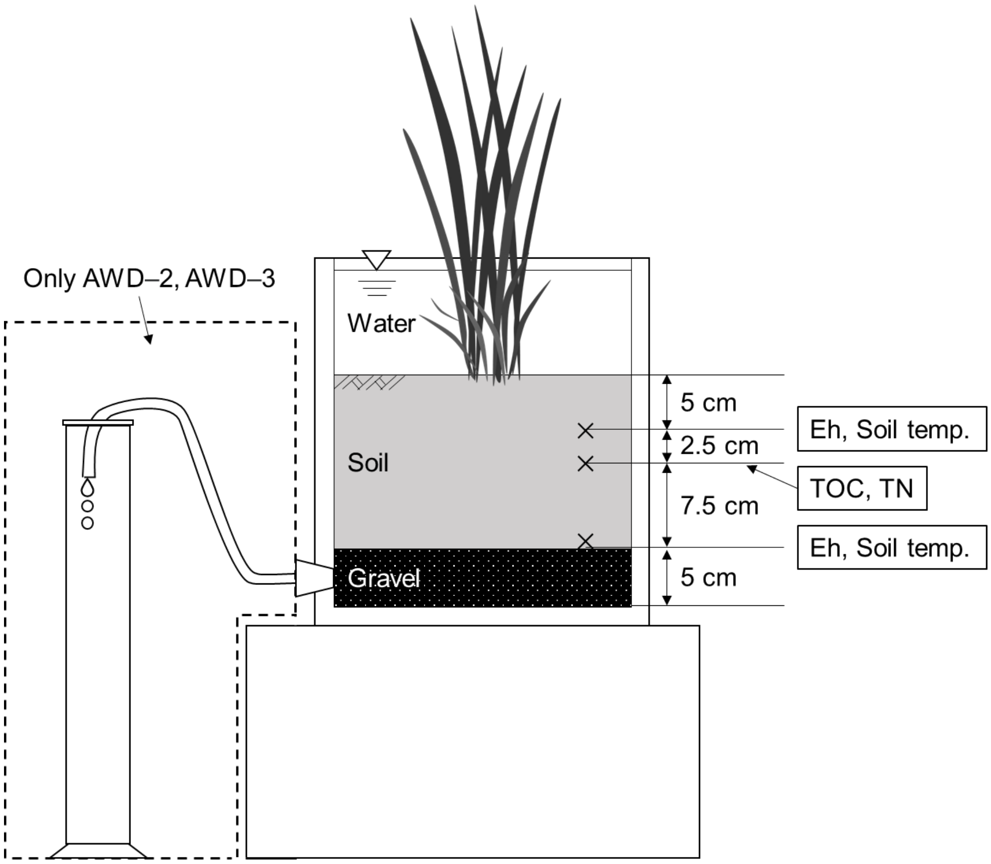

Fig. 5.1 Schematic of the experimental setup

Table 5.1 Flooding periods under each condition. Each number represents the day after transplanting (DAT). Flooding periods are numbered according to the date when the flooding started; therefore, Flooding periods 2 and 4 are blank for AWD-1

	AWD-1	AWD-2	AWD-3
Infiltration rate	0 mm d^{-1}	9 mm d^{-1}	18 mm d^{-1}
Flooding 1	0–29	0–23	0–22
Flooding 2		30–37	30–34
Flooding 3	43–56	43–48	43–46
Flooding 4		55–59	55–58
Flooding 5	62–92	62–92	62–91
Flooding 6	96–103	96–101	96–99
Flooding 7	107–120	107–119	107–120

*For CF, flooding was maintained during 0–119 DAT

was 1 cm below the top of the pot. A flooding period before and after ear emergence is necessary for rice growth (Matsushima, 1962); thus, flooding was started at 62 DAT and maintained until 92 DAT after ear emergence was observed at 87 DAT. For CF, when the ponding depth was lower than 1 cm, water was supplied in the same way as for the AWD conditions.

5.2.2 Measurements

Soil temperature (5TE; METER) and Eh (Pt electrode, Ag/AgCl reference electrode (4400; DKK-TOA)) were measured at depths of 5 cm and 15 cm at 10-min intervals. CH_4 fluxes were measured at one-week intervals, and 1 h and 2 h after the surface water disappeared and the water level was the soil surface, by gas sample collection via the closed chamber method and analysis via gas chromatography with a flame ionization detector (GC-14B; SHIMADZU). The chamber used in the closed chamber method was a polyvinyl chloride chamber with an inner diameter of 25 cm and a height of 100 cm. The air inside the chamber was sampled immediately after installation, 10 minutes later, and 20 minutes later. Soil water was withdrawn using a syringe connected to a porous cup (DIK-8393; DAIKI) buried at a depth of 7.5 cm at one-week intervals, and water drained during that day was also collected, and after filtered with a 0.45 μm membrane filter, the total organic carbon (TOC) and total nitrogen (TN) were measured by the NPOC method (TOC-L; SHIMADZU). The drainage water was discarded every day after measuring the volume. In addition, the ponding depth was observed once per day in the morning.

5.3 Results and discussion

5.3.1 Periods of intermittent irrigation

Temporal changes in the flooding depth and Eh are shown in **Fig. 5.2**. The Eh at a depth of 15 cm in pot 3 of AWD-2 and at both depths in pot 1 of AWD-3 were excluded because of the malfunction of the measurement sensors. Additionally, the Eh at both depths in pot 3 of AWD-1 at 53–70 DAT was omitted due to human error. For every condition, Eh reached –150 mV (the value at which CH_4 is produced; Wang et al. (1993)) by 20 DAT under infiltration treatment. **Figure 5.3** shows the temporal changes in CH_4 flux, TOC, and TN in soil water and drainage water for AWD-2 and AWD-3.

In AWD-1, after the Eh decreased to –150 mV, it remained at approximately –200 mV until the water level reached 0 cm at 29 DAT. The Eh at depths of 5 cm and 15 cm increased after the flooding receded and CH_4 emission ceased. After confirming that Eh had increased at a depth of 15 cm, the pot was re-flooded at 43 DAT. During this period, Eh at a depth of 15 cm decreased to approximately –180 mV, whereas Eh at a depth of 5 cm exhibited a relatively oxidative state of approximately 30 mV, and CH_4 emission was not observed. After the flooding receded, Eh increased again and the soil was re-flooded at 62 DAT. After the end of the flooding period in the heading stage (Flooding period 5), temporary CH_4 emission was observed (2.83 ± 2.91 μg m^{-2} s^{-1}) 2 h after the water level reached 0 cm. During Flooding period 6, which started at 96 DAT, Eh did not decrease to –150 mV at both depths, and minimal CH_4 emission was observed.

For AWD-2 and AWD-3, the soil environment was more oxidative than that generally considered necessary for CH_4 production during Flooding period 2 and 3 (**Table 5.1**); however, temporary emission of CH_4 was observed immediately after Flooding period 3 (1.12 μg m^{-2} s^{-1} in pot 1 of AWD-2 and 0.798 ± 0.450 μg m^{-2} s^{-1} in AWD-3). Despite the fact that Eh was higher than –150 mV in the subsequent Flooding period 4, CH_4 emissions were observed immediately after the flooding receded (0.196 ± 0.103 and 0.414 ± 0.218 μg m^{-2} s^{-1} for AWD-2 and AWD-3, respectively). Thus, the CH_4 produced during Flooding period 1 may have been trapped for a

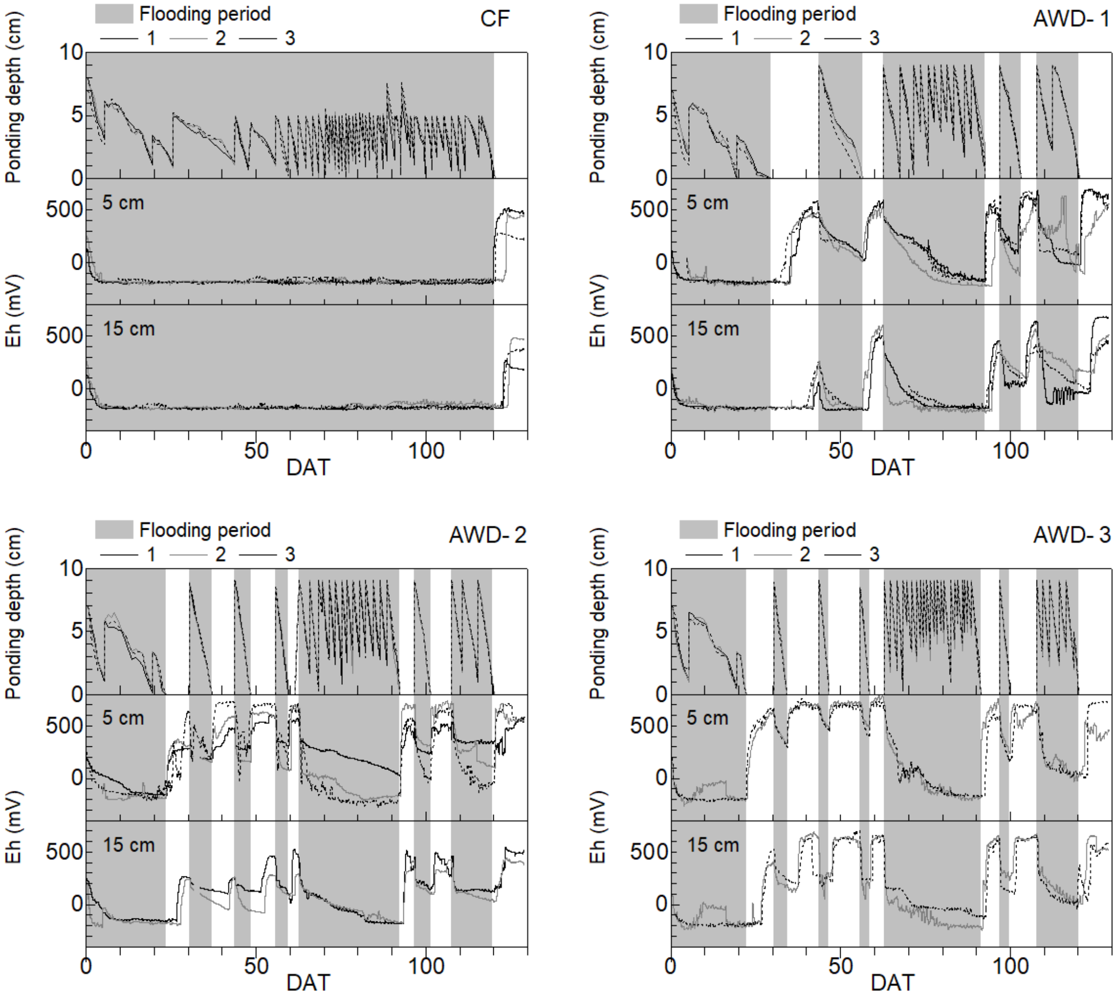

Fig. 5.2 Temporal changes in ponding depth and Eh at depths of 5 cm and 15 cm under each condition. CF, AWD-1, AWD-2, and AWD-3 indicate continuous flooding conditions, and AWD under infiltration rates of 0 mm d^{-1}, 9 mm d^{-1}, and 18 mm d^{-1}, respectively

long time or produced in localized areas of strong reduction. After the end of the flooding period in the heading stage (Flooding period 5), temporary CH_4 emission was also observed (1.62 ± 2.42 and 14.4 ± 9.07 μg m^{-2} s^{-1}) 2 h after the water level reached 0 cm. During Flooding period 6, which started at 96 DAT and ended at 101 DAT for AWD-2 and 99 DAT for AWD-3, the Eh did not decrease to –150 mV at both depths, with minimal CH_4 emission.

TOC increased during the flooding period and decreased during the non-flooding period (**Fig. 5.3**). The increase in TOC concentration was attributed to the *Birch effect* (Birch, 1958), which occurs when the soil is dried and rewetted, resulting in a rapid increase in the amount of substrate and its decomposition, which releases CO_2 and nutrients. The increased

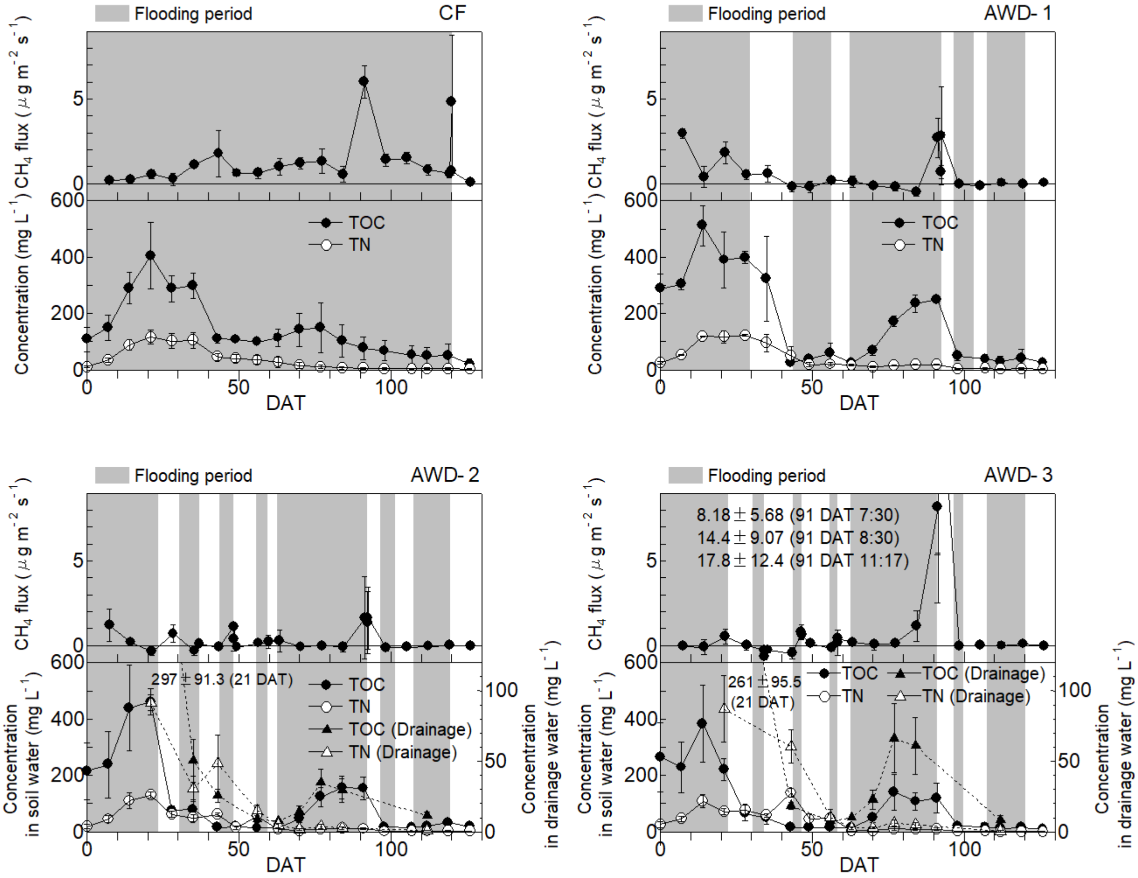

Fig. 5.3 Temporal changes in CH_4 fluxes and TOC and TN concentrations in soil water under each condition and drainage water under AWD-2 and AWD-3. CF, AWD-1, AWD-2, and AWD-3 indicate continuous flooding conditions, and AWD under infiltration rates of 0 mm d^{-1}, 9 mm d^{-1}, and 18 mm d^{-1}, respectively

substrates consist of, for example, dead fungi and readily degradable organic matter in the aggregates released by their disintegration (Xiang et al., 2008). In the case of TN, both CF and AWD showed similar changes, with no difference observed between the water management techniques.

5.3.2 Periods where flooding was maintained

For CF, the peak TOC and CH_4 emissions occurred at 77 DAT and 91 DAT, respectively (**Fig. 5.3**). The peak TOC was mainly considered to be caused by the decomposition of dead roots. The increase in CH_4 emissions after the heading stage was attributed to the supply of organic carbon to the soil due to the decomposition of dead roots (Tokida et al., 2011); this TOC increase may have affected the peak in CH_4 emissions. The same trend was observed under AWD conditions, which may be attributed to a combination of decomposition of dead roots, and the Birch effect. During this flooding period, Eh was below –150 mV at all conditions and depths, except for pot 1 in AWD-2. The infiltration rate did not have a significant effect on the time required to reach –150 mV at either depth (Tukey HSD). However, it was observed that CH_4 was emitted on 84 DAT in AWD-3 (1.15 ± 0.89 μg m^{-2} s^{-1}), which was ahead of other AWD treatments. Furthermore, under all infiltration conditions of AWD treatments, temporary CH_4 emission was observed after the water level reached 0 cm (2.83 ± 2.91, 1.62 ± 1.83, and 14.43 ± 9.07 μg m^{-2} s^{-1} in AWD-1, AWD-2, and AWD-3, respectively; **Fig. 5.3**).

Based on the results of Flooding period 5, another period in which flooding was maintained was set from 107 DAT (Flooding 7) to confirm whether a higher infiltration rate led to faster CH_4 production. However, during this period, the Eh of AWD-1 to AWD-3 did not decrease to –150 mV at both depths, with minimal CH_4 emission.

5.3.3 Change in total CH_4 emission by AWD treatment

To evaluate the effectiveness of the AWD, the total amount of emissions was calculated and compared. The calculation period was from 20 DAT, when infiltration started, to 126 DAT, one week after the pre-harvest drainage, and the measured values were accumulated according to the measurement interval. The cumulative fluxes were 11.6 ± 0.900 g m^{-2} for CF, and 1.57 ± 0.258 g m^{-2}, 0.953 ± 0.978 g m^{-2}, and 3.44 ± 2.18 g m^{-2} for AWD-1 to AWD-3, respectively (**Fig. 5.4**). Although the CF condition was continuously flooded, the period of 62–92 DAT was set as Flooding period 5. Temporary CH_4 emission immediately after Flooding period 5 was included in "Flooding 5" because the emitted CH_4 was considered to be produced during Flooding period 5. When compared over the entire period under all conditions, AWD treatment significantly suppressed CH_4 emissions compared to CF (Tukey HSD: $p < 0.01$). Temporary emissions were observed at the time of flooding withdrawal under every condition. This phenomenon has been reported as the emission of CH_4 trapped in soil in some studies (Adviento-Borbe et al., 2015; Wassmann et al., 1994; Yagi et al., 1996), but has not received much attention to date. However, this phenomenon is important for the accurate evaluation of CH_4 emissions when applying intermittent irrigation methods in which flooding recedes multiple times, such as AWD. To capture the phenomenon more accurately, it was necessary to measure the CH_4 flux more frequently.

5.3.4 Effect of infiltration rate on CH_4 emission

Prior to Flooding period 5, CH_4 emissions tended to decrease as the infiltration rate increased (**Fig. 5.4**), which may be due to the fact that the flooding period became shorter as the infiltration rate increased. In addition, CH_4 emissions appeared to increase in AWD-3 during Flooding period 5 (Tukey HSD; $p < 0.10$). There was no significant difference between AWD-1, AWD-2, and AWD-3 because the temporary emission after flooding withdrawal was not captured for one of the pots in AWD-3, which increased the variance of the data. If the pot for that period was excluded, the amount of emission in AWD-3 was significantly greater than that of AWD-1 and AWD-2 (Tukey HSD; $p < 0.01$). The major reasons for the higher CH_4 emissions in AWD-3 during Flooding period 5 included the fact that emission in AWD-3 occurred at 84 DAT, before that under the other conditions, and the emission caused by flooding withdrawal after ear emergence (**Fig. 5.2**). In other words, the high infiltration rate increased the amount of CH_4 produced in soil and emitted to the atmosphere through rice plants (Setyanto et al., 2004)

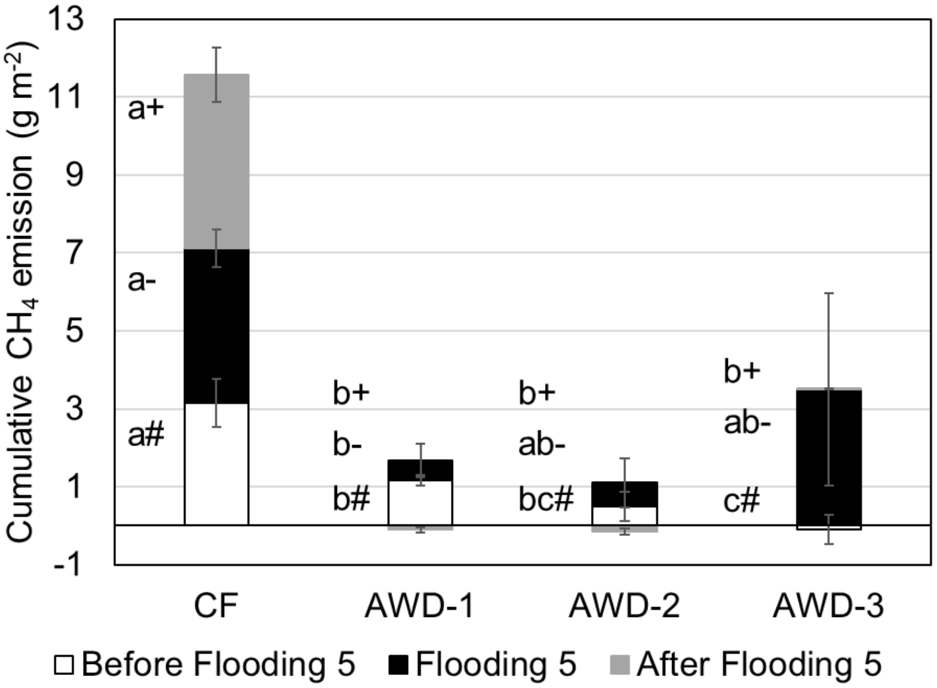

Fig. 5.4 Accumulated CH_4 emissions during the cropping season from the start of infiltration (20 DAT) under each condition. CF, AWD-1, AWD-2, and AWD-3 indicate continuous flooding conditions, and AWD under infiltration rates of 0 mm d^{-1}, 9 mm d^{-1}, and 18 mm d^{-1}, respectively. Letters (a, b, and c) represent the results of the Tukey HSD test for different groups with the same symbols (+, -, and #). The *p*-value criterion is <0.05 for both tests

during the flooding period and, as a result, more CH_4 trapped in the soil was emitted into the atmosphere after the flooding receded. Inubushi et al. (1992) investigated the effect of infiltration on CH_4 emissions in pot experiments by infiltrating 52 mm every two weeks. They compared the amount of CH_4 emitted during the flooding period, and found that infiltration reduced the amount of CH_4 emitted, which they attributed to the leaching of CO_2. Yagi et al. (1998) studied the effect of infiltration on CH_4 emission using a lysimeter for four years (infiltration rates of 0, 5, and 20 mm d^{-1} in the first three years, and 0, 7.7, and 25 mm d^{-1} in the fourth year) and found that the decrease in Eh was suppressed and CH_4 emission was reduced as the infiltration rate increased when the flooded state was maintained throughout the cultivation period. Ishikawa and Iida (2019) used a lysimeter to set infiltration rates of 0, 15, and 20 mm d^{-1} and applied mid-term drainage and intermittent irrigation, and reported that the CH_4 emission flux increased with increasing infiltration rate, except during the ripening period. They speculated that methanogens in strongly reduced soil have a greater chance of contacting the substrate per unit time at a higher infiltration rate. Regarding the TOC concentration in the drainage water on 84 DAT in our experiment, when CH_4 emission was observed in AWD-3 ahead of the other two AWD treatments, values were 29.3 ± 8.44 mg L^{-1} in AWD-2 and 60.9 ± 20.1 mg L^{-1} in AWD-3, indicating a significant increase in AWD-3 (t-test; $p < 0.05$). These and the Eh measurements suggest that the water management history before the heading stage affects the effect of infiltration rate on CH_4 emissions, and that a greater infiltration rate increases the amount of substrate that can penetrate downward under AWD conditions, rather than shortening the time to reach the reduced state required for CH_4 production. It is not clear whether the lower TOC concentration in the soil water of AWD-3 was due to the fact that more water was drained or that the larger infiltration rate lowered the amount of carbon supplied to the pot (dead roots, root exudates, etc.). Detailed monitoring of the amount of carbon emitted as CH_4 and CO_2, in addition to the concentrations of organic carbon in the pots, is required in the future in order to elucidate the mechanism controlling the different amounts of CH_4 emission with infiltration.

5.4 Conclusions

This study hypothesized that CH_4 production would increase with decreasing infiltration rate because the soil would be maintained in a reductive state for a longer period. However, CH_4 emission was greatest under the highest infiltration rate (18 mm d^{-1}); thus, the hypothesis was refuted. In particular, when flooding was artificially maintained for a long period for rice growth, such as during the heading stage, more CH_4 was emitted during the subsequent period of flooding withdrawal. Although the effect of infiltration rate on the rate of Eh decrease could not be confirmed, a difference in TOC concentrations in drainage water caused by the difference in infiltration rate suggested that infiltration affected the amount of substrate movement.

Chapter 6

Summary and conclusions

6.1 Summary of the study

Paddy fields are one of the main agricultural sources of CH_4, a greenhouse gas, and the implementation of global warming adaptation and mitigation strategies is important for the sustainable development of rice cultivation in the future. This thesis has reported on a water management study conducted in paddy fields to investigate the efficacy of this practice as a global warming mitigation strategy. In order to investigate the potential for using water management as a means of controlling CH_4 emissions, hydrological and meteorological observations, soil water content and redox potential measurements, and CH_4 emission estimates were determining in the field and in the laboratory tests. Based on the analysis of these data, a management method from the perspective of farmers and water managers was proposed. In this chapter, the key findings of the experiments detailed in Chapters 3 to 5 are summarized (Section 6.1) and future research directions are discussed (Section 6.2).

In Chapter 3, the feasibility of AWD in experimental block units (conventional, weak-dry, and strong-dry) in paddy fields of approximately 44 ha in the Red River Delta area of Vietnam was investigated by examining the effects of intermittent irrigation (i.e., AWD) on the ponding depth, CH_4 and N_2O emissions, and rice yield in blocked experimental plots. Although AWD water management is known to be effective and save water, practical examples of AWD at the district or farm level are limited. Intermittent irrigation was expected to be achieved through the operation of irrigation pumps and sluice gates of water division works by the water management organization (water user group) of the district. However, the ponding depth was not controlled as initially planned because of frequent rainfall and low rate of decrease of the ponding depth in the study area. It was, however, confirmed that the period during which the ponding depth decreased below the soil surface was mostly (but not always) longer in the dry-type blocks. CH_4 emissions decreased with an increase in the drying period and this reduction was large in the summer-autumn season. There appeared to be no relationship between N_2O emissions and water management. Rice yield decreased due to extreme drying in the summer-autumn season but was not affected by drying in the winter-spring season. This study demonstrated that CH_4 emissions can be reduced and rice yield can be maintained by achieving a maximum drying index (i.e., ratio of the period during which the ponding depth is below the soil surface) of 0.6 in the summer-autumn season in the paddy fields of the target area.

In chapter 4, to achieve organizational ponding water management sustainably, the optimal ponding water management schedule to reduce CH_4 emissions was identified by using the measured data of ponding depth, soil redox potential (Eh), and CH_4 fluxes from field experiments in the Red River Delta area of Vietnam and its effects on CH_4 emission and water conservation was shown. Observations in the winter-spring cropping season showed that the non-flooding period of 3–8 days suppressed CH_4 emission, and the continuous flooding period of 14–22 days caused CH_4 re-emission. Information regarding the non-flooding period to be maintained and the flooding period to be avoided to suppress CH_4 emission was not obtained for the summer-autumn cropping season due to abundant rainfall. The proposed schedule could suppress CH_4 emission by 27%–85% and increase the amount of conserved water by up to 18% compared with traditional flooding protocols, but it may increase irrigation water due to the frequency and the amount of re-flooding.

Since the schedule proposed in Chapter 4 is only specific to the region where the study site is located, it was considered important to expand the scope of its application. In Chapter 5, to investigate the effect of infiltration rate, which is thought to affect the non-flooding period to be maintained and the continuous flooding period to be avoided, which is important in determining the schedule, rice plants were cultivated in pots with three different infiltration rates (0, 9, and 18 mm d^{-1}) under AWD. As a result, the soil was more oxidative than the conditions generally required for CH_4 production (Eh > −150 mV) under intermittent irrigation, regardless of the infiltration rate. CH_4 emission was suppressed by at least 37% compared to continuous flooding and no-infiltration conditions; however, temporary emission was observed 1–2 h immediately after the flooding receded. This phenomenon is important for more accurately determining CH_4 emissions in water management techniques such as AWD. CH_4 emissions during the heading stage, including temporary emissions after the flooding receded, were greatest under the highest infiltration rate (18 mm d^{-1}). The infiltration rate did not affect the rate of soil Eh reduction; however, the total organic carbon concentration in the drainage water suggested that more carbon, a substrate for methanogens, migrated to the bottom of the pot with increasing infiltration rate, which likely increased CH_4 emissions.

6.2 Conclusions and future research

The overall conclusions and future research directions are as follows.

Chapter 3

Although the organizational AWD water management system (including pump and gate operation) increased the dryness of the weak and strong dry blocks compared to the conventional block in some years, the timing of rainfall and poor drainage prevented the achievement of the originally planned ponding depth in some years. In order to improve the feasibility of AWD management in this region in the future, it is important to provide water management organizations and farmers with a concrete ponding management schedule for the non-flooding period to control CH_4 emissions, taking into account the physiologically necessary flooding period and the mid-term drainage period to prevent rice yield loss. CH_4 emissions are much higher than N_2O emissions and policies to reduce CH_4 emissions should be emphasized in the study area. CH_4 emissions decreased with increasing duration of soil surface drying, but excessive drying in Summer–Autumn cropping season could lead to yield loss.

Chapter 4

Based on the temporal variation of CH_4 emissions and redox potential observed at different depths within 30 cm of the surface layer, water management schedules for AWD to reduce CH_4 emissions were proposed in this study. The observed and estimated CH_4 emissions and hydrological factors were used to compare the CH_4 emission reduction and water-saving effects of AWD water management with conventional water management (continuously flooding). Although the CH_4 emission reductions and water-saving efficiency depend on the climatic conditions of each year, effective schedules based on actual soil and weather characteristics are expected to be useful for farmers and water users' managers because concrete targeted ponding management is identified. Future research should focus on establishing a more general model for the required non-flooding period and allowable flooding periods to reduce CH_4 emissions. Also, in order to implement this technology in the future, it is necessary to provide incentives for organized water management, including financial support from the government and technological improvements that will improve yield and quality.

Chapter 5

This study hypothesized that CH_4 production would increase with decreasing infiltration rate because the soil would be maintained in a reduced state for a longer period. However, this hypothesis was rejected as CH_4 emissions were maximum at the highest infiltration rate (18 mm d^{-1}). In particular, when rice plants were artificially flooded for a long time for growth, such as during the heading stage, more CH_4 was released during the subsequent non-flooding period. Although the effect of infiltration rate on the rate of Eh reduction could not be confirmed, the difference in TOC concentration in the drainage water due to different infiltration rates suggested that infiltration affected the amount of substrate transported.

From the conclusions of the above chapters, it was found that it is necessary to focus on the temporary CH_4 emission phenomenon immediately after the flooding receded in addition to the infiltration rate in order to more accurately evaluate the effect of water management on the suppression of CH_4 emission and to make the schedule more effective under AWD. It was difficult to determine when and where the CH_4 was produced, and in fact, in Chapter 5, a temporary emission of CH_4 was observed after the flooding receded in the pots where AWD was applied, even though the redox potential was maintained high (oxidated state).

Therefore, one of the future tasks is to monitor the redox potential and the amount of CH_4 produced in the soil in detail in order to determine when the CH_4 emitted after the flooding receded was produced. In other words, it is important to clarify whether the amount produced during the flooding period is retained for a long time and emerges accidentally when the soil becomes unsaturated, or whether there are localized areas of strong reducing conditions that continue to be produced while the oxidative environment is thought to be maintained by intermittent irrigation. It would also be helpful to clarify the effect of infiltration rate on CH_4 production and emission, which is considered to be one of the factors that determine the non-flooding period to be maintained and the continuous flooding period to be avoided in the ponding depth management schedule, while taking into account the carbon balance, including the physiology of rice (carbon fixation and emission to the soil) and soil chemistry (carbon content), to draft a more universal schedule.

References

Adviento-Borbe M.A., Necita Padilla G., Pittelkow C.M., Simmonds M., van Kessel C., Linquist B. (2015) Methane and nitrous oxide emissions from flooded rice systems following the end-of-season drain. *Journal of Environmental Quality*, 44: 1071–1079. DOI: 10.2134/jeq2014.11.0497

Banger K., Tian H., Lu C. (2012) Do nitrogen fertilizers stimulate or inhibit methane emissions from rice fields? *Global Change Biology*, 18: 3259–3267. DOI: 10.1111/j.1365-2486.2012.02762.x

Begum K., Kuhnert M., Yeluripati J.B., Ogle S.M., Parton W.J., Williams S.A., Pan G., Cheng K., Ali M.A., Smith P. (2019) Modelling greenhouse gas emissions and mitigation potentials in fertilized paddy rice fields in Bangladesh. *Geoderma*, 341: 206–215. DOI: 10.1016/J.GEODERMA.2019.01.047

Bhattacharjya S., Chandra R., Pareek N., Raverkar K.P. (2016) Biochar and crop residue application to soil: effect on soil biochemical properties, nutrient availability and yield of rice (Oryza Sativa L.) and wheat (Triticum Aestivum L.). *Archives of Agronomy and Soil Science*, 62: 1095–1108. DOI: 10.1080/03650340.2015.1118760

Birch H.F. (1958) The effect of soil drying on humus decomposition and nitrogen availability. *Plant and Soil*, 10: 9–31. DOI: 10.1007/BF01343734

Bouman B.A.M., Tuong T.P. (2001) Field water management to save water and increase its productivity in irrigated lowland rice. *Agricultural Water Management*, 49(1): 11–30. DOI: 10.1016/S0378-3774(00)00128-1

Butterbach-Bahl K., Baggs E.M., Dannenmann M., Kiese R., Zechmeister-Boltenstern S. (2013) Nitrous oxide emissions from soils: how well do we understand the processes and their controls? *Philosophical Transactions of the Royal Society B*, 368: 20130122. DOI: 10.1098/rstb.2013.0122

Cai Z., Xing G., Yan X., Xu H., Tsuruta H., Yagi K., Minami K. (1997) Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilisers and water management. *Plant Soil*, 196: 7–14. DOI; 10.1023/A:1004263405020

Cao M., Gregson K., Marshall S., Dent J.B., Heal O.W. (1996) Global methane emissions from rice paddies. *Chemosphere*, 33: 879–897. DOI: 10.1016/0045-6535(96)00231-7

Carracelas G., Hornbuckle J., Rosas J., Roel A. (2019) Irrigation management strategies to increase water productivity in Oryza sativa (rice) in Uruguay. *Agricultural Water Management*, 222: 161–172. DOI: 10.1016/j.agwat.2019.05.049

Carrijo D.R., Akbar N., Reis A.F.B., Li C., Gaudin A.C.M., Parikh S.J., Green P.G., Linquist B.A. (2018) Impacts of variable soil drying in alternate wetting and drying rice systems on yields, grain arsenic concentration and soil moisture dynamics. *Field Crops Research*, 222: 101–110. DOI: 10.1016/j.fcr.2018.02.026

Chang J.H. (1970) Global distribution of net radiation according to a new formula. *Annals of the Association of American Geographers*, 60(2): 340–351. DOI: 10.3178/jjshwr.11.451

Conrad R. (1999) Contribution of hydrogen to methane production and control of hydrogen concentrations in methanogenic soils and sediments. *FEMS Microbiology Ecology*, 28(3): 193–202. DOI: 10.1111/j.1574-6941.1999.tb00575.x

Conrad R. (2002) Control of microbial methane production in wetland rice fields. *Nutrient Cycling in Agroecosystems*, 64: 59–69. DOI: 10.1023/A:1021178713988

Corton T.M., Bajita J.B., Grospe F.S., Pamplona R.R., Assis Jr. C.A., Wassmann R., Lantin R.S., Buendia L.V. (2000) Methane Emission from Irrigated and Intensively Managed Rice Fields in Central Luzon (Philippines). *Nutrient Cycling in Agroecosystems*, 58: 37–53. DOI: 10.1023/A:1009826131741

Darzi-Naftchali A., Karandish F., Šimůnek J. (2018) Numerical modeling of soil water dynamics in subsurface drained paddies with midseason drainage or alternate wetting and drying management. *Agricultural Water Management*, 197: 67–78. DOI: 10.1016/j.agwat.2017.11.017

Denier van der Gon H.A.C., Kropff M.J., van Breemen N., Wassmann R., Lantin R.S., Aduna E., Corton T.M., van Laar H.H. (2002) Optimizing grain yields reduces CH_4 emissions from rice paddy fields. *Proceedings of the National Academy of Sciences of the United States of America*, 99(19): 12021–12024. DOI: 10.1073/pnas.192276599

Dong H., Yao Z., Zheng X., Mei B., Xie B., Wang R., Deng J., Cui F., Zhu J. (2011) Effect of ammonium-based, non-sulfate fertilizers on CH_4 emissions from a paddy field with a typical Chinese water management regime. *Atmospheric Environment*, 45(5): 1095–1101. DOI: 10.1016/j.atmosenv.2010.11.039

Dubey S.K. (2005) Microbial ecology of methane emission in rice agroecosystem: a review. *Applied Ecology and Environmental Research*, 3(2): 1–27. DOI: 10.1.1.520.8794

Dunfield P., Knowles R., Dumont R., Moore T.R. (1993) Methane production and consumption in temperate and subarctic peat soils: Response to temperature and pH. *Soil Biology and Biochemistry*, 25(3): 321–326. DOI: 10.1016/0038-0717(93)90130-4

Fang C., Moncrieff J.B. (2001) The dependence of soil CO_2 efflux on temperature. *Soil Biology and Biochemistry*, 33(2): 155–165. DOI: 10.1016/S0038-0717(00)00125-5

Farooq M., Siddique K.H.M., Rehman H., Aziz T., Lee D.-J., Wahid A. (2011) Rice direct seeding: Experiences, challenges and opportunities. *Soil and Tillage Research*, 111(2): 87–98. DOI: 10.1016/j.still.2010.10.008

Feng Y., Xu Y., Yu Y., Xie Z., Lin X. (2012) Mechanisms of biochar decreasing methane emission from Chinese paddy soils. *Soil Biology and Biochemistry*, 46: 80–88. DOI: 10.1016/j.soilbio.2011.11.016

Food and Agriculture Organization of the United Nations (FAO) (2017) FAOSTAT Database Collections. http://www.fao.org/faostat (accessed 14 April 2020)

Fertitta-Roberts C., Oikawa P.Y., Jenerette G.D. (2019) Evaluating the GHG mitigation-potential of alternate wetting and drying in rice through life cycle assessment. *Science of the Total Environment*, 653: 1343–1353. DOI: 10.1016/J.SCITOTENV.2018.10.327

Gao X.P., Zou C.Q., Fan X.Y., Zhang F.S., Hoffland E. (2006) From flooded to aerobic conditions in rice cultivation: consequences for zinc uptake. *Plant Soil*, 280: 41–47. DOI: 10.1007/s11104-004-7652-0

Green S.M. (2013) Ebullition of methane from rice paddies: the importance of furthering understanding. *Plant Soil*, 370: 31–34. DOI: 10.1007/s11104-013-1790-1

Hama T., Nakamura K., Kawashima S. (2010) Effectiveness of cyclic irrigation in reducing suspended solids load from a paddy-field district. *Agricultural Water Management*, 97: 483–489. DOI: 10.1016/j.agwat.2009.11.007

Hama T., Nakamura K., Kawashima S., Kaneki R., Mitsuno T. (2011) Effects of cyclic irrigation on water and nitrogen mass balances in a paddy field. *Ecological Engineering*, 37(10): 1563–1566. DOI: 10.1016/j.ecoleng.2011.03.032

Hou A.X., Chen G.X., Wang Z.P., Van Cleemput O., Patrick Jr.W.H. (2010) Methane and nitrous oxide emissions from a rice field in relation to soil redox and microbiological processes. *Soil Science Society of America Journal*, 64: 2180–2186. DOI: 10.2136/sssaj2000.6462180x

Hussain S., Peng S., Fahad S., Khaliq A., Huang J., Cui K., Nie L. (2015) Rice management interventions to mitigate greenhouse gas emissions: a review. *Environmental Science and Pollution Research*, 22: 3342–3360. DOI: 10.1007/s11356-014-3760-4

Iida T., Kakuda K., Ishikawa M., Okubo H. (2007) Variation in methane and nitrous oxide emission from practical paddy fields with intermittent irrigation. *Transactions of the Japanese Society of Irrigation, Drainage and Reclamation Engineering*, 247: 45–52. DOI: 10.11408/jsidre1965.2007.45

Intergovernmental Panel on Climate Change (IPCC) (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York.

Intergovernmental Panel on Climate Change (IPCC) (2021) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press. Cambridge, UK and New York.

Inubushi K., Muramatsu Y., Umebayashi M. (1992) Influence of percolation on methane emission from flooded paddy soil. *Japanese Journal of Soil Science and Plant Nutrition*, 63: 184–189. (in Japanese with English abstract). DOI: 10.20710/dojo.63.2_184

Ishikawa M., Iida T. (2019) Effects of paddy percolation rates on greenhouse gases emission from rotation of rice and other crops with farm land consolidation regarding volcanic ash soil – A step towards the achievement of farm land consolidation enhanced air environmental preservation function. Transactions of The Japanese Society of Irrigation, *Drainage and Rural Engineering*, 309(87–2): 313–325 (in Japanese with English abstract). DOI: 10.11408/jsidre.87.I_313

Islam S.M.M., Gaihre Y.K., Biswas J.C., Jahan Md.S., Singh U., Adhikary S.K., Satter M.A., Saleque M.A. (2018) Different nitrogen rates and methods of application for dry season rice cultivation with alternate wetting and drying irrigation: fate of nitrogen and grain yield. *Agricultural Water Management*, 196: 144–153. DOI: 10.1016/j.agwat.2017.11.002

Itoh M., Sudo S., Mori S., Saito H., Yoshida T., Shiratori Y., Suga S., Yoshikawa N., Suzue Y., Mizukami H., Mochida T., Yagi K. (2011) Mitigation of methane emissions from paddy fields by prolonging midseason drainage. *Agriculture, Ecosystems & Environment*, 141: 359–372. DOI: 10.1016/J.AGEE.2011.03.019

Jalindar M.K., Rao V.P., Ramulu V., Kumar K.A., Devi M.U. (2019) Effectiveness of field water tube for standardization of alternate wetting and drying (AWD) method of water management in lowland rice (Oryza Sativa L.). *Irrigation and drainage*, 68(4): 679–689. DOI: 10.1002/ird.2354

Jansing M.S., Mahichi F., Dasanayake R. (2020) Sustainable irrigation management in paddy rice agriculture: A comparative case study of Karangasem Indonesia and Kunisaki Japan ocr. *Sustainability*, 12(3): 1180. DOI: 10.3390/su12031180

Kanno T., Miura Y., Tsuruta H., Minami K. (1997) Methane emission from rice paddy fields in all of Japanese prefecture. *Nutrient Cycling in Agroecosystems*, 49: 147–151. DOI:

10.1023/A:1009778517545

Kima A.S., Chung W.G., Wang Y.M., Traore S. (2015) Evaluating water depths for high water productivity in irrigated lowland rice field by employing alternate wetting and drying technique under tropical climate conditions, Southern Taiwan. *Paddy Water Environment*, 13(4): 379–389. DOI: 10.1007/s10333-014-0458-7

Kira Y., Shiina K., Takenaka H. (1960) On the influence of the percolation upon paddy soil and rice plant (II). *Nougyou Doboku Kenkyuu Bessatsu*, 1: 7–12. (in Japanese with English abstract). DOI: 10.11408/jsidre1960.1960.7

Kitagawa H., Ichihara Y., Hara Y., Nakano K. (2018) Effect of drainage on the yield of rice and occurrence of “Hagare” symptom in the paddy fields in Nagasaki Prefecture. *Japanese Journal of Crop Science*, 87(2): 198–208 (in Japanese with English abstract). DOI: 10.1626/jcs.87.198

Kotera A., Nawata E., Chuong P.V., Giao N.N., Sakuratani T. (2004) A model for phenological development of Vietnamese rice influenced by transplanting shock. *Plant Production Science*, 7: 62–69. DOI: 10.1626/pps.7.62

Kumar V., Ladha J.K. (2011) Direct seeding of rice: recent developments and future research needs (chapter 6). Advances in Agronomy, 111, pp. 299–360, International Rice Research Institute, India office, Pusa, New Delhi, India. DOI: 10.1016/B978-0-12-387689-8.00001-1

Lagomarsino A., Agnelli A.E., Linquist B., Adviento-Borbe M.A., Agnelli A., Gavina G., Ravaglia S., Ferrara R.M. (2016) Alternate wetting and drying of rice reduced CH_4 emissions but triggered N_2O peaks in a clayey soil of central Italy. *Pedosphere*, 26: 533–548. DOI: 10.1016/S1002-0160(15)60063-7

LaHue G.T., Chaney R.L., Adviento-Borbe M.A., Linquist B.A. (2016) Alternate wetting and drying in high yielding direct-seeded rice systems accomplishes multiple environmental and agronomic objectives. *Agriculture, Ecosystems & Environment*, 229: 30–39. DOI: 10.1016/J.AGEE.2016.05.020

Lampayan R.M., Rejesus R.M.., Singleton G.R., Bouman B.A.M. (2015a) Adoption and economics of alternate wetting and drying water management for irrigated lowland rice. *Field Crops Research*, 170: 95–108. DOI: 10.1016/j.fcr.2014.10.013

Lampayan R.M., Samoy-Pascual K.C., Sibayan E.B., Ella V.B., Jayag O.P., Cabangon R.J., Bouman B.A.M. (2015b) Effects of alternate wetting and drying (AWD) threshold level and plant seedling age on crop performance, water input, and water productivity of transplanted rice in Central Luzon, Philippines. *Paddy Water Environment*, 13: 215–227. DOI: 10.1007/s10333-014-0423-5.

Leon A., Kohyama K., Yagi K., Takata Y., Obara H. (2015) The effects of current water management practices on methane emissions in Japanese rice cultivation. *Mitigation and Adaptation Strategies for Global Change*, 22: 85–97. DOI: 10.1007/s11027-015-9665-9

Li H., Guo H.Q., Helbig M., Dai S.Q., Zhang M.S., Zhao M., Peng C.H., Xiao X.M., Zhao B. (2019) Does direct-seeded rice decrease ecosystem-scale methane emissions? – A case study from a rice paddy in southeast China. *Agricultural and Forest Methodology*, 272: 118–127. DOI: 10.1016/j.agrformet.2019.04.005

Li Z., Li Z., Letuma P., Zhao H., Zhang Z., Lin W., Chen H., Lin W. (2018) A positive response of rice rhizosphere to alternate moderate wetting and drying irrigation at grain filling stage. *Agricultural Water Management*, 207: 26–36. DOI: 10.1016/j.agwat.2018.05.022

Liang X.Q., Chen Y.X., Nie Z.Y., Ye Y.S., Liu J., Tian G.M., Wang G.H., Tuong T.P. (2013) Mitigation of nutrient losses via surface runoff from rice cropping systems with alternate wetting and drying irrigation and site-specific nutrient management practices. *Environmental Science and Pollution Research*, 20(10): 6980–6991. DOI: 10.1007/s11356-012-1391-1

Liang K., Zhong X., Huang N., Lampayan R.M., Pan J., Tian K., Liu Y. (2016) Grain yield, water productivity and CH_4 emission of irrigated rice in response to water management in south China. *Agricultural Water Management*, 163: 319–331. DOI: 10.1016/j.agwat.2015.10.015.

Liesack W., Schnell S., Revsbech N.P. (2000) Microbiology of flooded rice paddies. *FEMS Microbiology Reviews*, 24(5): 625–645. DOI: 10.1111/j.1574-6976.2000.tb00563.x

Linquist B., van Groenigen K.J., Adviento-Borbe M.A., Pittelkow C., van Kessel C. (2012) An agronomic assessment of greenhouse gas emissions from major cereal crops. *Global Change Biology*, 18: 194–209. DOI: 10.1111/j.1365-2486.2011.02502.x

Ly P., Duong Vu Q., Jensen L.S., Pandey A., de Neergaard A. (2014) Effects of rice straw, biochar and mineral fertiliser on methane (CH_4) and nitrous oxide (N_2O) emissions from rice (Oryza sativa L.) grown in a rain-fed lowland rice soil of Cambodia: a pot experiment. *Paddy Water Environment*, 13: 465–475. DOI: 10.1007/s10333-014-0464-9

Ma K., Conrad R., Lu Y. (2012) Responses of methanogen mcrA genes and their transcripts to an alternate dry/wet cycle of paddy field soil. *Applied Environmental Microbiology*, 78: 445–454. DOI: 10.1128/AEM.06934-11

Malyan S.K., Bhatia A., Kumar A., Gupta D.K., Singh R., Kumar S.S., Tomer R., Kumar O., Jain N. (2016) Methane production, oxidation and mitigation: A mechanistic understanding and comprehensive evaluation of influencing factors. *Science of The Total Environment*, 572: 874–896. DOI: 10.1016/j.scitotenv.2016.07.182

Matsushima S. (1962) Some experiments on soil-water-plant relationship in the cultivation of rice. *Proceedings of the Crop Science Society of Japan*, 31(2): 115–121. DOI: 10.1626/jcs.31.115

Meyer N., Welp G., Amelung W. (2018) The temperature sensitivity (Q10) of soil respiration: controlling factors and spatial prediction at regional scale based on environmental soil classes. *Global Biogeochemical Cycles*, 32(2): 306–323. DOI: 10.1002/2017GB005644

Minami K. (1994) Methane from rice production. *Fertilizer Research*, 1994, 37, 167–179. DOI: 10.1007/BF00748935

Minamikawa K., Sakai N. (2005) The effect of water management based on soil redox potential on methane emission from two kinds of paddy soils in Japan. *Agriculture, Ecosystems & Environment*, 107: 397–407. DOI: 10.1016/j.agee.2004.08.006

Ministry of Natural Resources and Environment (MONRE) (2014) https://www.monre.gov.vn/English (accessed October 28, 2021)

Mote K., Rao V.P., Ramulu V., Kumar K.A., Devi M.U. (2018) Standardization of alternate wetting and drying (AWD) method of water management in lowland rice (Oryza sativa L.) for upscaling in command outlets. *Irrigation and Drainage*, 67: 166–178. DOI: 10.1002/ird.2179

National Agriculture and Food Research Organization (NARO) (2021) Illustration: Rice cultivation and cold damage in Tohoku General water management by growing season (written in Japanese) http://www.reigai.affrc.go.jp/zusetu/kangai.html (accessed October 28, 2021)

National Federation of Land Improvement Association (third ed.) (1986) National Federation of Land Improvement Association, Tokyo

Neue H.U., Wassmann R., Lantin R.S., Ma C.R. Alberto Aduna J.B., Javellana A.M. (1996) Factors affecting methane emission from rice fields. *Atmospheric Environment*, 30(10/11): 1751–1754. DOI: 10.1016/1352-2310(95)00375-4

Nouchi I., Mariko S., Aoki K. (1990) Mechanism of methane transport from the rhizosphere to the atmosphere through rice plants. *Plant Physiology*, 94(1): 59–66. DOI: 10.1104/pp.94.1.59

Nugroho B.D.A., Toriyama K., Kobayashi K., Arif C., Yokoyama S., Mizoguchi M. (2018) Effect of intermittent irrigation following the system of rice intensification (SRI) on rice yield in a farmer's paddy fields in Indonesia. *Paddy Water Environment*, 16: 715–723. DOI: 10.1007/s10333-018-0663-x

Oo A.Z., Sudo S., Inubushi K., Mano M., Yamamoto A., Ono K., Osawa T., Hayashida S., Patra P.K., Terao Y., Elayakumar P., Vanitha K., Umamageswari C., Jothimani P., Ravi V. (2018a) Methane and nitrous oxide emissions from conventional and modified rice cultivation systems in South India. *Agriculture, Ecosystems & Environment*, 252: 148–158. DOI: 10.1016/j.agee.2017.10.014

Oo A.Z., Sudo S., Inubushi K., Chellappan U., Yamamoto A., Ono K., Mano M., Hayashida S., Koothan V., Osawa T., Terao Y., Palanisamy J., Palanisamy E., Venkatachalam R. (2018b) Mitigation potential and yield-scaled global warming potential of early-season drainage from a rice paddy in Tamil Nadu, India. *Agronomy*, 8: 202. DOI: 10.3390/agronomy8100202

Ounvichit T., Satoh M., Chantanusart S., Yamaoka K. (2006) Cost sharing and sustainability of Pongsak Muang Fai irrigation system. *Paddy Water Environment*, 4(2): 81–88. DOI: 10.1007/s10333-006-0035-9

Pandey S., Velasco L. (2005) Trends in crop establishment methods in Asia and research issues. *Proceedings of the World Rice Research Conference*, 178–181.

Papademetriou M.K. (2000) Rice Production in the Asia-pacific Region: Issues and Perspectives, Bridging the Rice Yield Gap in the Asia-pacific Region. Food and Agriculture Organization of the United Nations, Regional Office for Asia and the Pacific http://www.fao.org/docrep/003/x6905e/x6905e04.htm

Pascual V.J., Wang Y. (2017) Impact of water management on rice varieties, yield, and water productivity under the system of rice intensification in Southern Taiwan. *Water*, 9(1): 3. DOI: 10.3390/w901003

Penman H.L. (1948) Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society of London A Mathematical, Physical and Engineering Sciences*, 193: 120–145. DOI: 10.1098/rspa.1948.0037

Pittelkow C.M., Adviento-Borbe M.A., Hill J.E., Six J., van Kessel C., Linquist B.A. (2013) Yield-scaled global warming potential of annual nitrous oxide and methane emissions from continuously flooded rice in response to nitrogen input. *Agriculture, Ecosystems & Environment*, 177: 10–20. DOI: 10.1016/j.agee.2013.05.011

Quang L.X., Nakamura K., Hung T., Tinh N.V., Matsuda S., Kadota K., Horino H., Hai P. T., Komatsu H., Hasegawa K., Fukuda S., Hirata J., Oura N., Kishimoto-Mo A.W., Yonemura S., Onishi, T. (2019) Effect of organizational paddy water management by a water user group on methane and nitrous oxide emissions and rice yield in the Red River Delta, Vietnam. *Agricultural Water Management*, 217: 179–192. DOI: 10.1016/J.AGWAT.2019.02.015

Rao A.N., Johnson D.E., Sivaprasad B., Ladha J.K., Mortimer A.M. (2007) Weed management in direct-seeded rice. *Advances in Agronomy*, 93: 153–255. DOI: 10.1016/S0065-2113(06)93004-1

Ratering S., Conrad R. (1998) Effects of short-term drainage and aeration on the production of methane in submerged rice soil. *Global Change Biology*, 4: 397–407. DOI: 10.1046/j.1365-2486.1998.00162.x.

Redfern S.K., Azzu N., Binamira J.S. (2012) Rice in Southeast Asia: Facing risks and vulnerabilities to respond to climate change. In Building resilience for adaptation to climate change in the agriculture sector, edited by Meybeck A., Lankoski J., Redfern S., Azzu N., Gitz V. 295–341. Rome: FAO.

Runkle B.R.K., Suvočarev K., Reba M.L., Reavis C.W., Smith S.F., Chiu Y.L., Fong, B. (2019) Methane emission reductions from the alternate wetting and drying of rice fields detected using the eddy covariance method. *Environmental Science & Technology*, 53: 671–681. DOI: 10.1021/acs.est.8b05535

Rural Development Bureau, Japanese Ministry of Agriculture, Forestry and Fisheries (2003) The Global Diversity of Irrigation, 33–52.
https://www.maff.go.jp/j/nousin/keityo/mizu_sigen/pdf/panf04_e.pdf

Saleque M.A., Kirk G.J.D. (1995) Root induced solubilization of phosphate in the rhizosphere of lowland rice. *New Phytologist*, 129(2): 325–336. DOI: 10.1111/j.1469-8137.1995.tb04303.x

Sánchez B., Iglesias A., McVittie A., Álvaro-Fuentes J., Ingram J., Mills J., Lesschen J.P., Kuikman P.J. (2016) Management of agricultural soils for greenhouse gas mitigation: Learning from a case study in NE Spain. *Journal of Environmental Management*, 170(1): 37–49. DOI: 10.1016/j.jenvman.2016.01.003

Sanz-Cobena A., Lassaletta L., Aguilera E., del Prado A., Garnier J., et al. (2017) Strategies for greenhouse gas emissions mitigation in Mediterranean agriculture: A review. *Agriculture, Ecosystems & Environment*, 238: 5–24. DOI: 10.1016/j.agee.2016.09.038

Saptomo S.K., Chadirin Y., Setiawan B.I., Budiasa I.W., Kato H., Kubota J. (2015) Quantifying water balance of subak paddy field based on continuous field monitoring. *Jurnal Teknologi*, 76(15): 53-59. DOI: 10.11113/jt.v76.5952

Sass R.L., Cicerone R.J. (2002) Photosynthate allocations in rice plants: Food production or atmospheric methane? *Proceedings of the National Academy of Sciences of the United States of America*, 99(19): 11993–11995. DOI: 10.1073/pnas.202483599

Satpathy S.N., Rath A.K., Ramakrishnan B., Rao V.R., Adhya T.K., Sethunathan N. (1997) Diurnal variation in methane efflux at different growth stages of tropical rice. *Plant and Soil*, 195: 267–271. DOI: 10.1023/A:1004202515767

Schlesinger W.H. (1999) Carbon sequestration in soils. *Science*, 284:2095. DOI: 10.1126/science.284.5423.2095

Schütz H., Seiler W., Conrad R. (1989) Processes involved in formation and emission of methane in rice paddies. *Biogeochemistry*, 7: 33–53. DOI: 10.1007/BF00000896

Semrau J.D., DiSpirito A.A., Yoon S. (2010) Methanotrophs and copper. *FEMS Microbiology Reviews*, 34(4): 496–531. DOI: 10.1111/j.1574-6976.2010.00212.x

Setyanto P., Rosenani A.B., Boer R., Fauziah C.I., Khanif M.J. (2004) The effect of rice cultivars on methane emission from irrigated rice field. *Indonesian Journal of Agricultural Science*, 5: 20–31. DOI: 10.21082/ijas.v5n1.2004.p20-31

Setyanto P., Pramono A., Adriany T.A., Susilawati H.L., Tokida T., Padre A.T., Minamikawa K. (2018) Alternate wetting and drying reduces methane emission from a rice paddy in Central Java, Indonesia without yield loss. *Soil Science and Plant Nutrition*, 64: 23–30. DOI: 10.1080/00380768.2017.1409600

Shaibu Y.A., Mloza Banda H.R., Makwiza C.N., Malunga J.C. (2015) Grain yield performance of upland and lowland rice varieties under water saving irrigation through alternate wetting and drying in sandy clay loams of southern Malawi. *Experimental Agriculture*, 51: 313–326. DOI: 10.1017/S0014479714000325

Shigematsu T., Tang Y.-Q., Kida K. (2009) Microbial communities related to methane fermentation processes: Monograph. *Seibutsu-kogaku kaishi*, 87(12): 570–596. (in Japanese with English abstract)

Siopongco J.D.L.C., Wassmann R., Sander B.O. (2013) Alternate wetting and drying in Philippine rice production: feasibility study for a clean development mechanism. *IRRI Technical Bulletins*, No.17. DOI: 10.22004/ag.econ.287646

Smith P., Martino D., Cai Z., Gwary D., Janzen H., Kumar P., McCarl B., Ogle S., O'Mara F., Rice C., Scholes B., Sirotenko O., Howden M., McAllister T., Pan G., Romanenkov V., Schneider U., Towprayoon S., Wattenbach M., Smith J. (2008) Greenhouse Gas Mitigation in Agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363: 789–813. DOI:10.1098/rstb.2007.2184.

Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M., Miller H.L. (Eds.), Contribution of Working Group I to the Fourth Assessment Report of the

Intergovernmental Panel on Climate Change. (2007) Cambridge University Press, Cambridge, United Kingdom and New York, USA, 996p

Son N.T., Badayos R.B., Sanchez P.B., Cruz P.C.S., Dung N.V., Thanh N.H. (2008) Water productivity and soil chemical properties under varying water regimes on spring rice (Oryza sativa L.) in Hanoi, Vietnam. *Philippine Journal of Crop Science*, 33: 56–70.

Sriphirom P., Chidthaisong A., Towprayoon S. (2019) Effect of alternate wetting and drying water management on rice cultivation with low emissions and low water used during wet and dry season. *Journal of Cleaner Production*, 223: 980–988. DOI: 10.1016/J.JCLEPRO.2019.03.212

Su J., Hu C., Yan X., Jin Y., Chen Z., Guan Q., Wang Y., Zhong D., Jansson C., Wang F., Schnürer A., Sun C.. (2015) Expression of barley SUSIBA2 transcription factor yields high-starch low-methane rice. *Nature*, 30(523): 602-6. DOI: 10.1038/nature14673

Suryavanshi P., Singh Y.V., Prasanna R., Bhatia A., Shivay Y.S. (2013) Pattern of methane emission and water productivity under different methods of rice crop establishment. *Paddy and Water Environment*, 11: 321–329. DOI: 10.1007/s10333-012-0323-5

Susilawati H.L., Setyanto P., Kartikawati R., Sutriadi M.T. (2019) The opportunity of direct seeding to mitigate greenhouse gas emission from paddy rice field. IOP Conference Series: Earth and Environmental Science, 393: 012042.

Takai Y., Koyama T., Kamura T. (1969) Suitoukon oyobi tousuiga pottonaitansuidozyou no kangenkatei ni oyobosu eikyou: suidendozyou no biseibutsutaisya ni kansuru kenkyuu (5)) (Effect of rice root and water percolation on the reduction process of flooded soil in pots: Study on microbial metabolism of paddy soil (5)). *Japanese Journal of Soil Science and Plant Nutrition*, 40: 15–19 (in Japanese). DOI: 10.20710/dojo.40.1_15

Takai Y., Wada H., Kagawa H., Kobo K. (1974) Microbial mechanism of effects of water percolation on Eh, iron, and nitrogen transformation in the submerged paddy soils. *Soil Science and Plant Nutrition*, 20: 33–45. DOI: 10.1080/00380768.1974.10433226.

Tanaka Y., Sato Y. (2005) Farmers managed irrigation districts in Japan: Assessing how fairness may contribute to sustainability. *Agricultural Water Management*, 77: 196–209. DOI:

10.1016/j.agwat.2004.09.043

Tirol-Padre A., Minamikawa K., Tokida T., Wassmann R., Yagi K. (2018) Site-specific feasibility of alternate wetting and drying as a greenhouse gas mitigation option in irrigated rice fields in Southeast Asia: a synthesis. *Soil Science and Plant Nutrition*, 64(1): 2–13. DOI: 10.1080/00380768.2017.1409602

Tokida T., Adachi M., Cheng W., Nakajima Y., Fumoto T., Matsushima M., Nakamura H., Okada M., Sameshima R., Hasegawa T. (2011) Methane and soil CO_2 production from current-season photosynthates in a rice paddy exposed to elevated CO_2 concentration and soil temperature. *Global Change Biology*, 17: 3327–3337. DOI:10.1111/j.1365-2486.2011.02475.x

Tokida T., Miyazaki T., Mizoguchi M. (2005) Ebullition of methane from peat with falling atmospheric pressure. *Geophysical Research Letters*, 32(13): L13823. DOI: 10.1029/2005GL022949

Tripathi A., Tripathi D.K., Chauhan D.K., Kumar N., Singh G.S. (2016) Paradigms of climate change impacts on some major food sources of the world: A review on current knowledge and future prospects. *Agriculture, Ecosystems & Environmen*t, 216: 356–373. DOI: 10.1016/j.agee.2015.09.034

Tuan D.D., Satoh M. (1998) An analysis of land redistribution and its impact on agricultural practices in the Red river delta, Northern Vietnam. *Transactions of The Japanese Society of Irrigation, Drainage and Reclamation Engineering*, 196, 125–139. DOI: 10.11408/jsidre1965.1998.695

Uchiyama N., Onikura Y., Takahashi S., Yoshida S. (1956) On significance of percolation in paddy soils (part 1). *Japanese Journal of Soil Science and Plant Nutrition*, 27: 23–26. (in Japanese with English summary). DOI: 10.20710/dojo.27.1_23

United Nations, Department of Economic and Social Affairs, Population Division (2017). World Population Prospects: The 2017 Revision, Key Findings and Advance Tables. Working Paper No. ESA/P/WP/248.

United Nations Framework Convention on Climate Change (UNFCCC) (2015) Intended nationally determined contribution of Viet Nam. https://www4.unfccc.int/sites/

submissions/INDC/Published%20Documents/Viet%20Nam/1/VIETNAM'S%20INDC.pdf. (accessed 20 March 2020)

Verhoeven E., Decock C., Barthel M., Bertora C., Sacco D., Romani M., Sleutel S., Six J. (2018) Nitrification and coupled nitrification-denitrification at shallow depths are responsible for early season N_2O emissions under alternate wetting and drying management in an Italian rice paddy system. *Soil Biology and Biochemistry*, 120: 58–69. DOI: 10.1016/j.soilbio.2018.01.032

Wang Z.P., DeLaune R.D., Patrick W.H., Masscheleyn P.H. (1993) Soil redox and pH effects on methane production in a flooded rice soil. *Soil Science Society of America Journal*, 57: 382. DOI: 10.2136/sssaj1993.03615995005700020016x.

Wassmann R., Aulakh M.S. (2000) The role of rice plants in regulating mechanisms of methane missions. *Biology and Fertility of Soils*, 31: 20–29. DOI: 10.1007/s003740050619

Wassmann R., Aulakh M.S., Lantin R.S., Rennenberg H., Aduna J.B. (2002) Methane emission patterns from rice fields planted to several rice cultivars for nine seasons. *Nutrient Cycling in Agroecosystems*, 64: 111–124. DOI: 10.1023/A:1021171303510

Wassmann R., Lantin R.S., Neue H.U., Buendia L.V., Corton T.M., Lu Y. (2000) Characterization of methane emissions from rice fields in Asia. III. Mitigation options and future research needs. *Nutrient Cycling in Agroecosystems*, 58: 23–36. DOI:10.1023/A:1009874014903.

Wassmann R., Neue H.U., Alberto M.C.R., Lantin R.S., Bueno C., Llenaresas D., Arah J.R.M., Papen H., Seiler W., Rennenberg H. (1996) Fluxes and pools of methane in wetland rice soils with varying organic inputs. *Environmental Monitoring and Assessment* 42: 163–173. DOI: 10.1007/BF00394048

Wassmann R., Neue H.U., Lantin R.S., Aduna J.B., Alberto M.C.R., Andales M.J., Tan M.J., Denier van der Gon H.A.C., Hoffmann H., Papen H., Rennenberg H., Seiler W. (1994) Temporal patterns of methane emissions from wetland rice fields treated by different modes of N application. *Journal of Geophysical Research*, 99: 16457–16462. DOI:10.1029/94JD00017

Watanabe T., Hosen Y., Agbisit R., Llorca L., Fujita D., Asakawa S., Kimura M. (2010) Changes in community structure and transcriptional activity of methanogenic archaea in a paddy field soil brought about by a water-saving practice – Estimation by PCR-DGGE and qPCR of 16S rDNA and 16S rRNA. In: 19Th World Congress of Soil Science, Soil Solutions for a Changing World, 5–8. DOI:10.1016/j.soilbio.2012.11.022

Xiang S.-R., Doyle A., Holden P.A., Schimel J.P. (2008) Drying and rewetting effects on C and N mineralization and microbial activity in surface and subsurface California grassland soils. *Soil Biology and Biochemistry*, 40: 2281–2289. DOI:10.1016/j.soilbio.2008.05.004.

Xu X., Boeckx P., Wang Y., Huang Y., Zheng X., Hu F., Van Cleemput O. (2002) Nitrous oxide and methane emissions during rice growth and through rice plants: effect of dicyandiamide and hydroquinone. *Biology and Fertility of Soils*, 36: 53–58. DOI: 10.1007/s00374-002-0503-3

Yagi K., Minami K. (1990) Effect of organic matter application on methane emission from some Japanese paddy fields. *Soil Science and Plant Nutrition*, 36, 599–610. DOI: 10.1080/00380768.1990.10416797

Yagi K., Minami K. (1993) Spatial and temporal variations of methane flux from a rice paddy field. in Biogeochemistry of Global Change, edited by Oremland, R.S., Springer, Boston: 353–368.

Yagi K., Sriphirom P., Cha-un N., Fusuwankaya K., Chidthaisong A., Damen B., Towprayoon S. (2020) Potential and promisingness of technical options for mitigating greenhouse gas emissions from rice cultivation in Southeast Asian countries, *Soil Science and Plant Nutrition*, 66(1): 37–49. DOI: 10.1080/00380768.2019.1683890

Yagi K., Tsuruta H., Kanda K.I., Minami K. (1996) Effect of water management on methane emission from a Japanese rice paddy field: Automated methane monitoring. *Global Biogeochemical Cycles* 10: 255–267. DOI: 10.1029/96GB00517

Yang J., Liu K., Wang Z., Du Y., Zhang J. (2007) Water-saving and high-yielding irrigation for lowland rice by controlling limiting values of soil water potential. *Journal of Integrative Plant Biology*, 49(10): 1445–1454. DOI: 10.1111/j.1672-9072.2007.00555.x

Yuan J., Yuan Y., Zhu Y., Cao L. (2018) Effects of different fertilizers on methane emissions and methanogenic community structures in paddy rhizosphere soil. *Science of The Total Environment*, 627(15): 770–781. DOI: 10.1016/j.scitotenv.2018.01.233

Zhao L.M., Wu L.H., Wu M.Y., Li Y.S. (2011) Nutrient uptake and water use efficiency as affected by modified rice cultivation methods with reduced irrigation. *Paddy Water Environment*, 9(1): 25–32. DOI: 10.1007/s10333-011-0257-3

I would like to express my sincere gratitude to my supervisor, Professor Dr. Kimihito Nakamura, Graduate School of Agriculture, Kyoto University, for his constructive suggestions, continuous support, thoughtful guidance and encouragement. I am also particularly grateful to Professor Dr. Shigeto Kawashima, Graduate School of Agriculture, Kyoto University, for inspiring suggestions and giving valuable advice in the study. Moreover, I would like to express my appreciation to Associate Professor Dr. Takehide Hama, Graduate School of Agriculture, Kyoto University, for his valuable advice and encouragement.

I gratefully thank thesis reviewers, Professor Dr. Satoshi Hoshino, Graduate School of Agriculture, Kyoto University, and Professor Dr. Masayuki Fujihara, Graduate School of Agriculture, Kyoto University, for their valuable comments and suggestions for improving the quality of this dissertation.

A special gratitude I give to Associate Professor Dr. Kenji Iwama and Mr. Tomohiro Okano, School of Environmental Science, The University of Shiga Prefecture, for collaboration including technical support to measure CH_4 flux and useful discussion. I am also grateful to Professor Dr. Haruhiko Horino, Lecturer Dr. Shinji Sakurai, Graduate School of Life and Environmental Sciences, Osaka Prefecture University, for technical support to measure TOC and TN.

I am very pleased to thank all members of the Hydrological Environmental Engineering Laboratory of Kyoto University for their great support in my research life.

Finally, I express grateful thanks to my wife, Mrs. Hinako Matsuda, for her constant support in daily life to complete the doctoral study. Also, I would like to express heartfelt gratitude to my parents for their incessant support and inspiration to build up my higher studies.

25 December 2021
Soken Matsuda