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Article

Mitigation Potential and Yield-Scaled Global Warming Potential of Early-Season Drainage from a Rice Paddy in Tamil Nadu, India

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Abstract: Water-intensive systems of rice cultivation are facing major challenges to increase rice grain yield under conditions of water scarcity while also reducing greenhouse gas (GHG) emissions. The adoption of effective irrigation strategies in the paddy rice system is one of the most promising options for mitigating GHG emissions while maintaining high crop yields. To evaluate the effect of different alternate wetting and drying (AWD) irrigation strategies on GHG emissions from paddy rice in dry and wet seasons, a field experiment was conducted at the Tamil Nadu Rice Research Institute (TRRI), Aduthurai, Tamil Nadu, India. Four irrigation treatments were included: One-AWD (one early drying period), Two-AWD (two early drying periods), Full-AWD (wetting and drying cycles throughout the rice season), and CF (continuous flooding). Different rice varieties were also tested in the experiment. In this study, we emphasized one factor (irrigation effect) that affects the dependent variable. The results show that early AWD treatments reduced methane (CH_4) emissions by 35.7 to 51.5% in dry season and 18.5 to 20.1% in wet season, while full-AWD practice reduced CH_4 emissions by 52.8 to 61.4% compared with CF. Full-AWD in dry season not only significantly reduced CH_4 emission during that season, it also resulted in the decline of the early season emission in the succeeding wet season. Global warming potential (GWP) and yield-scaled GWP were reduced by early or full season AWD in both rice seasons. The GWP value from nitrous oxide (N_2O) was relatively low compared to that from CH_4 in both rice seasons. Rice yield was not affected by irrigation treatments although varietal differences in grain and straw yields were observed in both rice seasons. This study demonstrated that early season water managements are also effective in reducing CH_4 and total GHG emissions without affecting rice yield.

Keywords: alternate wetting and drying; GHG emissions; early drainage; mitigation; rice yield

1. Introduction

Global agriculture in the 21st century is expected to double food production to provide sufficient and healthy food for a growing population under conditions of increasing water scarcity, while minimizing environmental consequences [1,2]. Agriculture is estimated to account for 10 to 20% of anthropogenic emissions of greenhouse gases (GHGs) worldwide [3], and annual GHG emissions from agricultural production were estimated at 5.0–5.8 Gt CO_2-eq year^{-1} for the 2000–2010 period [4].

Rice is the dominant staple food crop in the world, and is particularly important in Asia. More than 75% of the world's rice is produced in irrigated rice lands that are continuously flooded throughout the rice growing season [5]. Irrigated rice accounts for about 80% of the total fresh water resources used for irrigation in Asia [6]. Furthermore, increases in rice production over the last half-century relied heavily on irrigated rice, which is increasingly constrained by water scarcity [7]. Alternate wetting and drying (AWD) is an irrigation practice in rice paddies and has been shown to reduce irrigation water use. Rice is known to be sensitive to soil water deficit [8]. Therefore, overall rice yields have been reduced in AWD; the degree of soil drying has a large effect on rice yield [9]. However, studies have reported that AWD irrigation can save irrigation water without affecting rice yield [10,11]. Yang et al. [12] and Chu et al. [13] discussed that soil drying in AWD is one of the important factors that positively affect rice yield because it can enhance root growth, grain-filling rate, and remobilization of carbon reserves from vegetative tissues to grains. In the studies conducted in China, Belder et al. [14] revealed that AWD had no significant impact on grain yield, while Xu et al. [15] observed yield decreases of up to 16%. This variability is likely due to differences in AWD water management practice between the studies; for example, AWD treatments may vary widely in their severity and timing and soil moisture monitoring methodology.

The AWD practice has been promoted as a strategy to decrease irrigation water use and reduce GHG emissions from rice cultivation while maintaining or improving yields [11,16]. Various studies have reported that AWD irrigation reduced methane (CH_4) emissions by 24 to 93% [2,11,15,17]. However, AWD irrigation can result in increased nitrous oxide (N_2O) emissions due to a trade-off between CH_4 and N_2O [11,15] which can offset the advantages of CH_4 mitigation achieved by introducing drainage periods [18,19]. Therefore, irrigation management plays an important role in determining the trade-off between CH_4 and N_2O emissions from paddy rice fields.

The development of effective mitigation strategies aimed at minimizing the global warming potential of rice cropping systems must therefore consider the emissions of both gases [20]. Water management strategy is one of the most promising options for GHG mitigation from paddy rice production. Several studies have focused on the effect of midseason drainage (MD) or AWD irrigation throughout the rice season on CH_4 emissions by altering soil Eh conditions. However, the effect of early season water management practices such as one or two wetting and drying cycles during the early growing period (vegetative growth stage) on soil CH_4 and N_2O emissions has not been extensively studied.

Rice is a major component of Indian diet, economy, employment, culture, and history. Ninety percent of the rice produced is consumed within the country. With 44 million hectares, India has the biggest area under rice cultivation worldwide; with a production of 96.4 million tons (2007–2008), it comes second only behind China in total rice production [21]. The area under rice cultivation accounts for 34% of India's food crop area and 42% of its cereal crop area. In India, the total area under irrigated rice is about 22 million hectares, which accounts for approximately 49.5% of the total area under rice crop in the country.

For example, in Tamil Nadu state, India, irrigated rice accounts for 89% of the paddy area and about 54% of the paddy rice is irrigated with groundwater. According to scientists and activists, relentless groundwater extraction for irrigation is leading to a steep drop in water tables across India—the world's fastest rate of groundwater decline. There is clearly an urgent need to find effective water management strategies to grow more rice with less water input and reduce the environmental load for sustainable rice production. Therefore, in this study, we compared currently grown rice varieties under continuous flooding and different AWD irrigation practices by measuring crop yield, water use, and GHG emissions during the dry and wet seasons at Tamil Nadu Rice Research Institute (TRRI), Aduthurai, Tamil Nadu, India. This experiment was conducted to (i) study the effect of different AWD irrigation practices on crop yield and CH_4 and N_2O emissions and (ii) evaluate the global warming potential (GWP) and yield-scaled global warming mitigation potential of different AWD irrigation strategies for sustainable rice farming.

2. Materials and Methods

2.1. Study Site Description

This study was conducted at TRRI (11°0′ N, 79°30′ E, 19.4 m above MSL), India, from May 2017 to February 2018. A black gram-rice-rice cropping rotation system is the typical practice in the study area—the state of Tamil Nadu. The experimental soil was classified as alluvial clay and composed of 13.6% sand, 61.2% silt, and 25.3% clay, 1.1 g kg^{-1} total N, 19.6 g kg^{-1} total C, pH 7.5 (1:5 H_2O), and EC 11.6 m S m^{-1} [22]. The region has a tropical wet and dry/savanna climate with total precipitation of 1361 mm from February 2017 to February 2018. Daily rainfall, and minimum and maximum temperatures are shown in Figure 1.

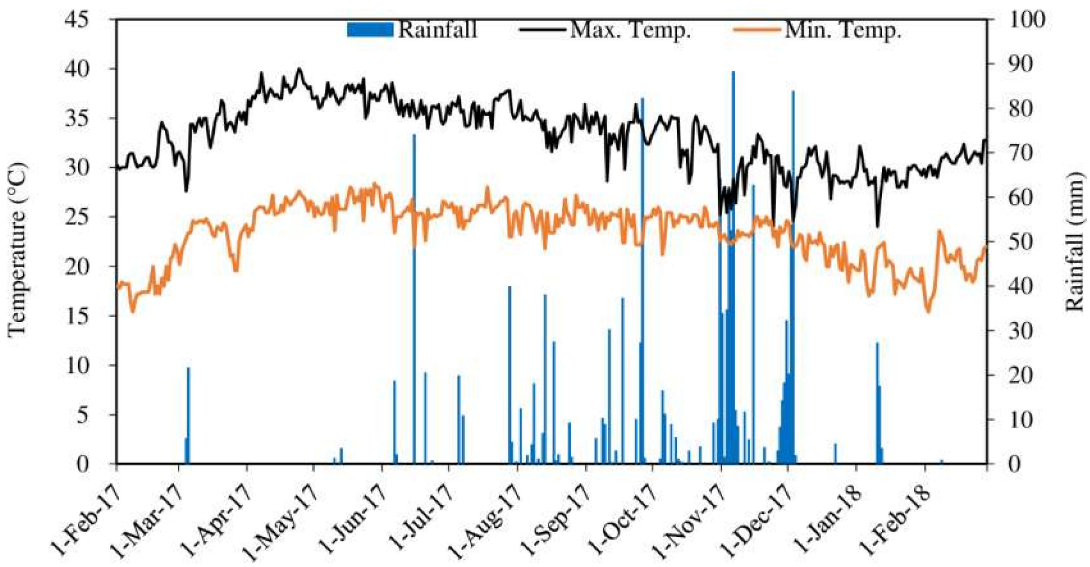

Figure 1. Daily rainfall, maximum and minimum temperature from February 2017 until February 2018 as measured at experimental site of Tamil Nadu Rice Research Institute, Aduthurai, Tamil Nadu, India.

2.2. Experimental Design and Treatments

There were three seasons, summer (February to April), dry season (local name kuruvai season; June to September), and wet season (local name thaladi season; October to February). Three crops per year was a common practice in the study area; summer black gram, dry season kharif rice, and wet season rabi rice. The field experiment was set up with two consecutive rice seasons. The experimental set-up was a 4 × 2 split plot design with three replications. The main plots were given four different water management practices, i.e., (i) One-AWD (only one drying period during the early growth stage), (ii) Two-AWD (two successive wetting and drying cycles during the early growth stage), (iii) Full-AWD (wetting and drying cycles throughout the growing season), and (iv) CF (continuous flooding throughout the growing season). The subplots were planted with two currently grown rice varieties, namely ADT 43 and CO 51 in the dry season, and variety ADT 46 and TKM 13 in the wet season. Each plot size was 25 m^2 (5 m × 5 m).

The experimental field was flooded on the 9 June 2017, in the dry season, and the 23 September 2017, in the wet season. Previous crop residues from dry season rice, which were left standing in the plot following harvest, were incorporated to a depth of 15 cm during soil preparation. The puddling was carried out with tractor-drawn cage wheel in the dry season and power tiller in the wet season. The 22-day old seedlings with 2–3 seedlings per hill were transplanted into the experimental plots on the 16th of June 2017 and 6th of October 2017 in the dry and wet season, respectively. The plant spacings were 15 cm × 10 cm in the dry season and 20 cm × 10 cm in the wet season.

After transplanting, the initial flood water level was maintained for 10 to 14 days until irrigation treatment began in both the rice seasons. In the CF practice, continuous flooded irrigation was practiced throughout the rice growing season. For AWD irrigation, a field water tube was used (11). Two weeks after transplanting in the One-AWD, Two-AWD, and Full-AWD treatments, the AWD cycle was started in dry season rice. However, AWD irrigation was started earlier (10 days after transplanting) in the wet season to avoid the peak rainfall event. In One-AWD and Two-AWD, one and two drying cycles, respectively, were introduced during early growth stage. Afterwards, reflooding was done at a water depth of 5 cm throughout the rest of growing season until 14 days before harvest. In Full-AWD, alternate wetting and drying cycles were practiced throughout the rice growing season until the final drying period before harvest. Pump irrigation was practiced by using groundwater in all crops.

The fertilizer application rates were 150 kg N ha^{-1} as urea, 50 kg P_2O_5 ha^{-1} as diammonium phosphate (DAP), 50 kg K_2O ha^{-1} as muriate of potash (MOP), 25 kg zinc sulfate ($ZnSO_4$) ha^{-1}, and 500 kg gypsum ($CaSO_4 \cdot 2\ H_2O$) ha^{-1}. Gypsum, zinc sulfate, and DAP were applied as the basal dose. Urea and MOP were applied in four equal split doses at basal, active tillering, panicle initiation, and heading stages. Pests and disease were appropriately controlled and manual weeding was done as necessary. The crops were harvested on 21 September 2017 in the dry season, and 9 January and 3 February 2018 in the wet season.

2.3. Gas Sample Collection, Analysis, and Calculation

The CH_4 and N_2O fluxes were measured using a closed chamber method. In both rice seasons, the sampling frequency was once every week. However, whenever there was a fertilizer application event, air sampling was done one day and three days after fertilization in dry season rice. The gas sampling procedure adopted by Oo et al. (11) was followed. The CH_4 and N_2O concentrations in collected gas samples were analyzed using a gas chromatograph (GC 2014, Shimadzu Corporation, Kyoto, Japan) equipped with a flame ionization detector (FID) and an electron capture detector (ECD), respectively. The CH_4 and N_2O fluxes were calculated from the linear regression of the concentrations at each sampling time (0, 15, and 30 min during the time of chamber closure).

The seasonal total CH_4 and N_2O emissions were calculated by successive linear interpolation of average gas emissions on the sampling days, assuming that gas emissions followed a linear trend during the periods when no sample was taken. The global warming potential (GWP) was calculated using the following equation.

$$\text{GWP (kg CO}_2\text{-eq ha}^{-1}) = (E_{CH4} \times 34 + E_{N2O} \times 298)$$

where E_{CH4} and E_{N2O} are the total amount of each gas emission (kg ha^{-1}), and 34 and 298 are the IPCC's GWPs for CH_4 and N_2O, respectively, to CO_2 over a 100-year time horizon [23].

2.4. Other Data Measurements

Soil temperature and daily surface water depth were recorded. Soil redox potential (hereafter referred to as soil Eh) was recorded using a battery-operated Eh meter (YK-23RP, Taiwan). The grain yield of harvested rice (14% moisture content) and straw yield were measured from 1 m^{-2} sampling area. The yield-scaled GWP was calculated by dividing the total GWP by the grain yield.

2.5. Statistical Analysis

Statistical analysis was performed using CropStat 7.2 statistical software (International Rice Research Institute, IRRI, Los Baños, Philippines). We conducted an analysis of variance (ANOVA) using a split plot design, where irrigation method was treated as the main factor and rice variety as the split-plot factor. To test the differences among the water managements, treatment mean comparisons were done at a 5% level of probability using the least significant difference (LSD) test. Since varietal effect was not observed, we emphasized the effect of irrigation method on GHG emissions from paddy rice soil.

3. Results

3.1. Weather Conditions and Irrigation Water Use

The seasonal total rainfall was 409 mm for the dry season rice (June to September), and 799 mm for the wet season rice (October to February) (Figure 1). The mean maximum and minimum air temperatures were 35.1 °C and 25.2 °C in the dry season, and 30.2 °C and 22.1 °C in the wet season, respectively.

In paddy rice, the surface water level was well controlled under different AWD irrigation practices throughout the rice growing season in dry and wet seasons (Figure 2). The number of times irrigation provided in the CF method was 21 and 24 in the dry and wet seasons, respectively (Table 1). The number of irrigation times was reduced to 17 and 19 times for One-AWD, 17 and 18 times for Two-AWD, and 6 and 6 times for Full-AWD irrigation in the dry and wet seasons, respectively.

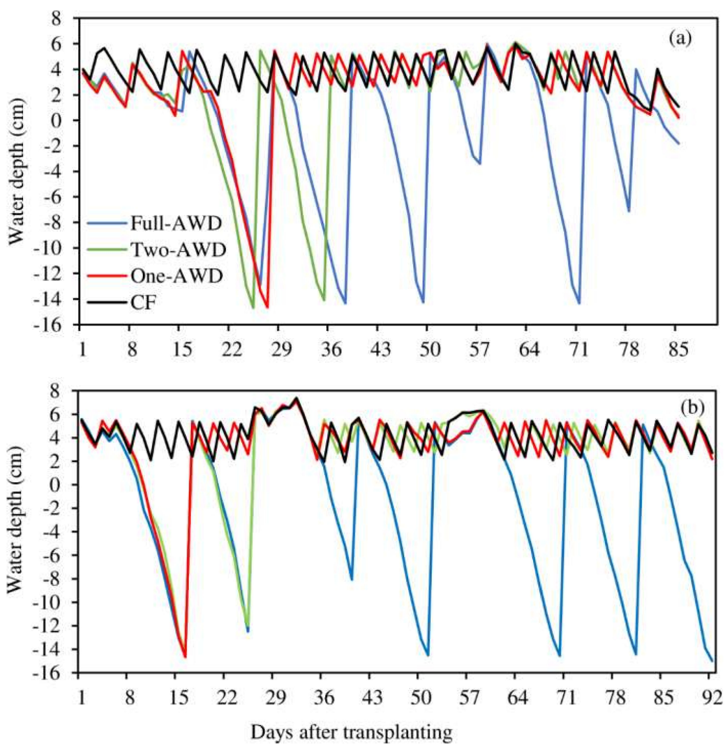

Figure 2. Seasonal variation in daily water depth during dry (**a**) and wet (**b**) rice growing seasons for different water management practices. Full-AWD—wetting and drying cycles throughout the growing season, Two-AWD—two early drying periods, One-AWD—one early drying period, CF—continuous flooding.

Table 1. Irrigation during the rice growing period under different irrigation regimes.

Season	Treatment	No. of Irrigation
Dry season rice (June–September 2017)	Full-AWD	6
	Two-AWD	17
	One-AWD	17
	CF	21
Wet season rice (October 2017–January 2018)	Full-AWD	6
	Two-AWD	18
	One-AWD	19
	CF	24

Full-AWD—wetting and drying cycles throughout the growing season, Two-AWD—two early drying periods, One-AWD—one early drying period, and CF—continuous flooding.

3.2. Soil Temperature and Redox Potential

Soil temperature was higher during the early and middle growing periods in the dry season and then showed a decreasing trend to the end of the growing period (Figure S1a,b). In the wet season, soil temperature was highest during the early growing period and decreased gradually during the middle and later growing periods (Figure S1c,d). Although soil temperature showed some variations, no difference in soil temperature changes among the irrigation practices was observed in both rice seasons.

Soil Eh values were mostly lower than -100 mV throughout the rice growing seasons except at harvest time for both rice seasons (Figure S2). Compared with CF, higher soil Eh values were observed in Full-AWD throughout the rice growing season in both rice seasons. One-AWD and Two-AWD also clearly showed higher soil Eh values over CF in dry season but was only slightly different soon after water management in wet season.

3.3. Methane Fluxes

The seasonal variation pattern of CH_4 fluxes over the whole rice growing period was strongly influenced by the water regime in both rice seasons (Figure 3a,b and Figure 4a,b). In dry season rice, CH_4 flux showed an increasing trend until the flowering period and then gradually decreased to the end of the growing period for both the rice varieties (Figure 3a,b). In all the treatments, a high emission peak was observed during the flowering period. A similar emission pattern was observed among the treatments during the early growing period before starting irrigation treatments. However, soon after starting AWD irrigations, low emission trends were observed in Full-AWD, Two-AWD, and One-AWD treatments compared to CF.

In the wet season, a high emission peak of CH_4 flux appeared shortly after rice transplanting at three days after transplanting (DAT), and then decreased suddenly until 18 DAT for both rice varieties (Figure 4a,b). Afterwards, it showed a gradually decreasing trend to the end of the growing period. Differences in emission peaks were observed among the treatments soon after transplanting of wet season rice before irrigation treatments were begun in both rice varieties. Before starting irrigation treatments in the wet season, low emission peaks were observed in variety ADT 46 from Full-AWD and in variety TKM 13 from Full-AWD and Two-AWD treatments. After starting irrigation treatments, low emission trends were also observed in Full-AWD, Two-AWD, and One-AWD treatments compared to CF in both rice varieties.

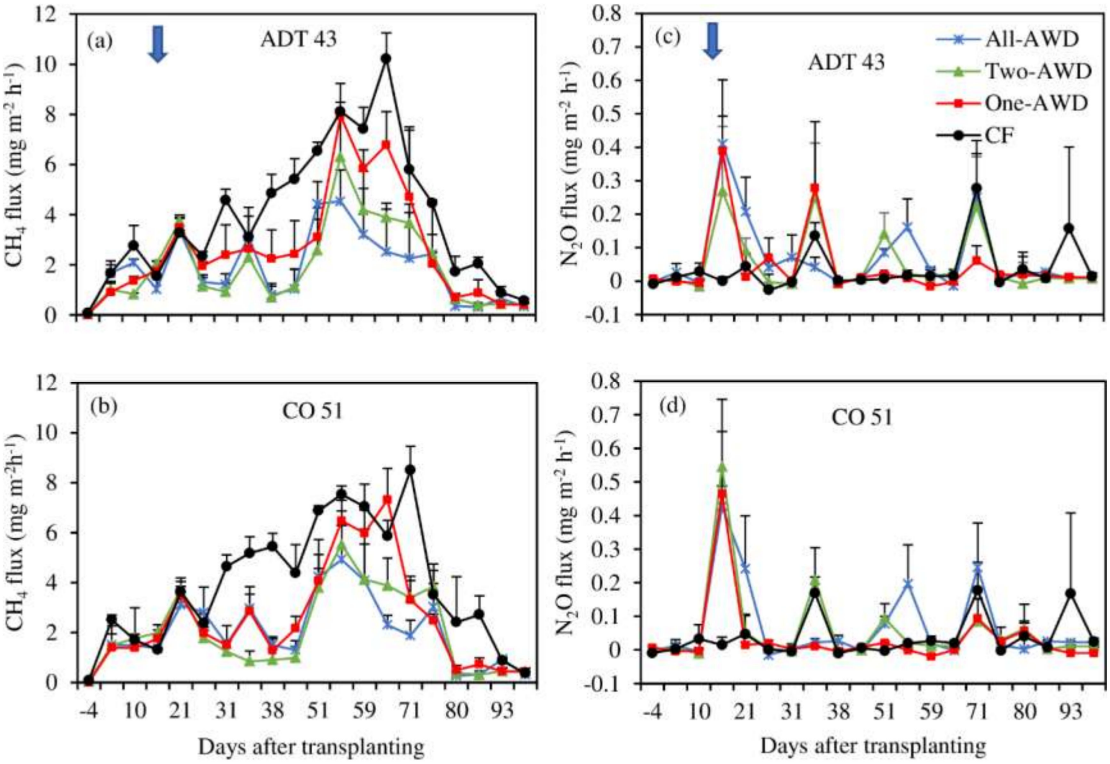

Figure 3. Variation in CH_4 (**a**,**b**) and N_2O (**c**,**d**) fluxes during dry season rice for different water management practices. Error bars indicate standard error of means (n = 3). Arrow—start AWD irrigation. Full-AWD—wetting and drying cycles throughout the growing season, Two-AWD—two early drying periods, One-AWD—one early drying period, CF—continuous flooding.

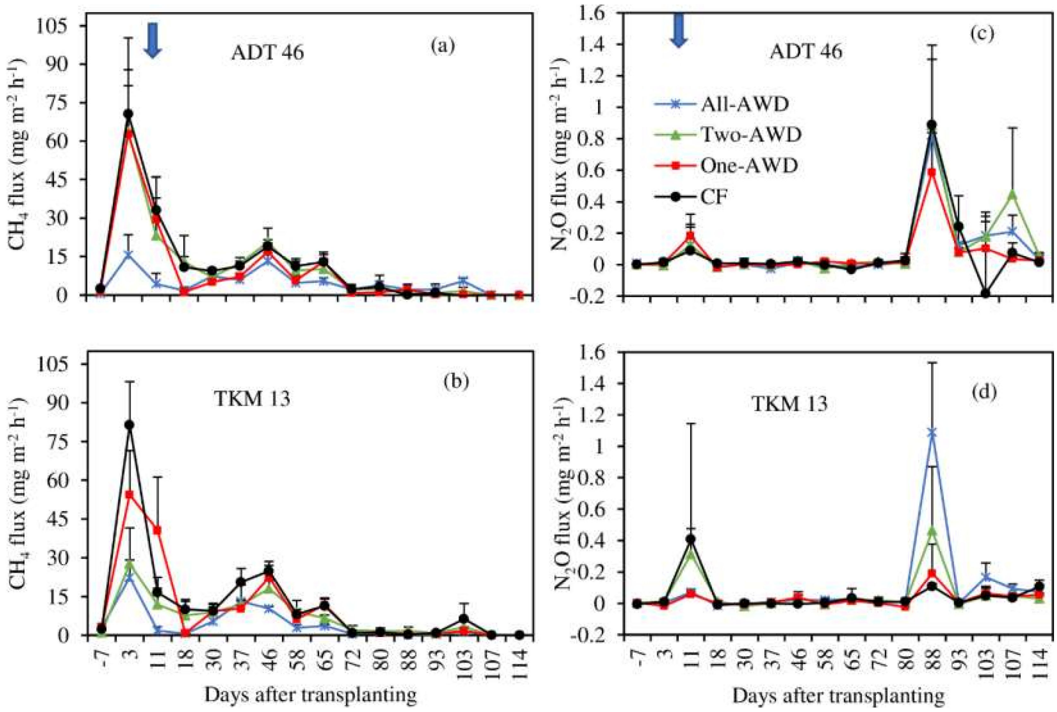

Figure 4. Variation in CH_4 (**a**,**b**) and N_2O (**c**,**d**) fluxes during wet season rice for different water management practices. Error bars indicate standard error of means (n = 3). Arrow—start AWD irrigation. Full-AWD—wetting and drying cycles throughout the growing season, Two-AWD—two early drying periods, One-AWD—one early drying period, CF—continuous flooding.

A significant ($p < 0.01$) difference in the cumulative CH_4 emission was observed among the irrigation practices in the dry season (Figure 5a). Significantly higher cumulative CH_4 emission was observed in CF compared with different AWD irrigations. The reductions in cumulative CH_4 emissions by Full-AWD, Two-AWD, and One-AWD were 55.1%, 53.9%, and 34.2% in ADT 43 and 50.5%, 49.1%, and 37.2% in CO 51, respectively, compared with CF. Cumulative CH_4 emissions of Full-AWD, Two-AWD, and One-AWD were statistically similar. No varietal difference and interaction effects were observed in the dry season.

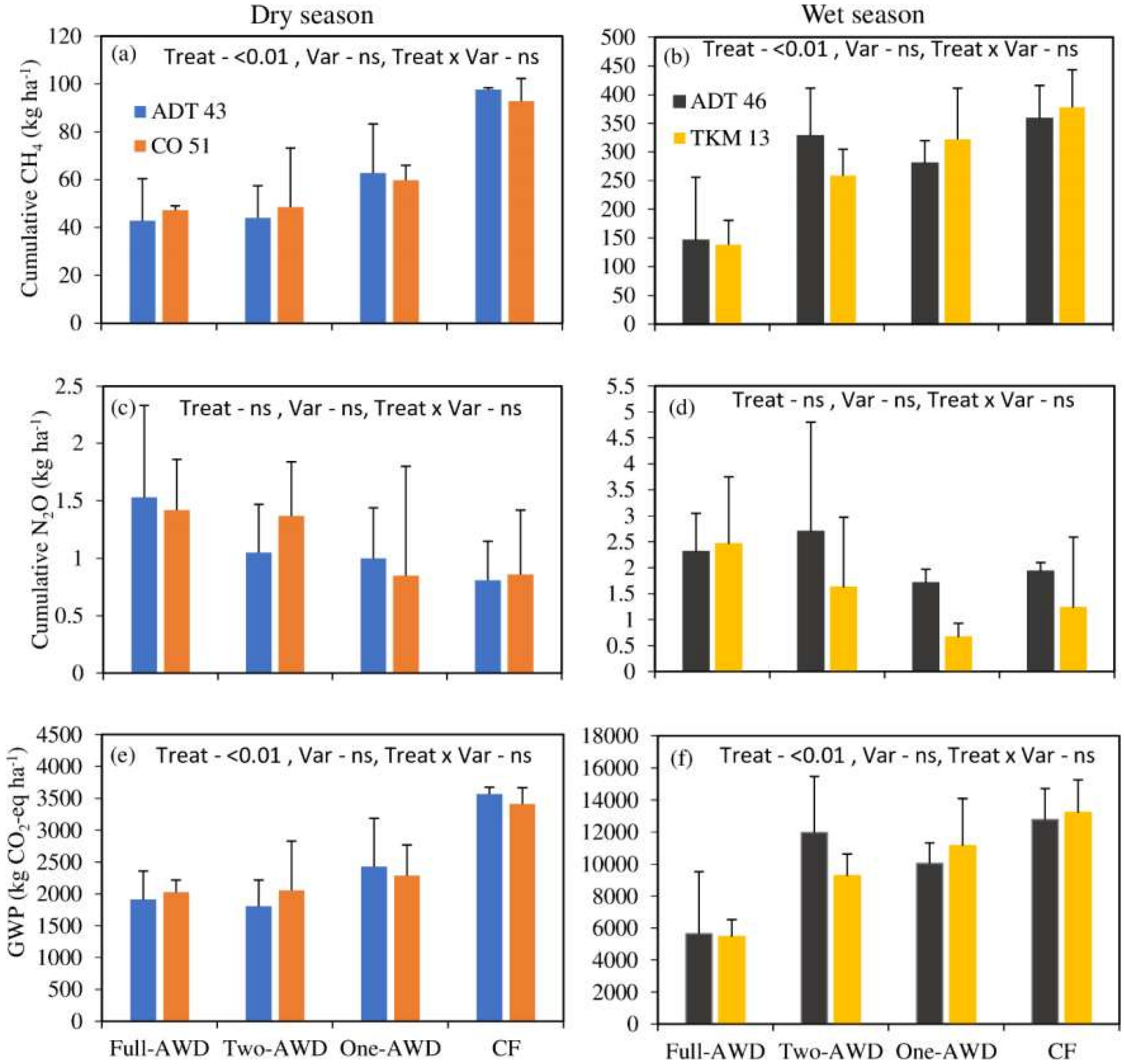

Figure 5. Cumulative CH_4 (**a**,**b**) and N_2O (**c**,**d**) emissions from rice paddies and their contribution in the global warming potentials (**e**,**f**) as affected by different water management practices. Error bars indicate standard error of means ($n = 3$). The y axes scales are different. Arrow—start AWD irrigation. Full-AWD—wetting and drying cycles throughout the growing season, Two-AWD—two early drying periods, One-AWD—one early drying period, CF—continuous flooding.

In the wet season, a significant ($p < 0.05$) difference in the cumulative CH_4 emission was also observed among the irrigation practices (Figure 5b). The reductions in CH_4 emissions, compared with CF, by Full-AWD, Two-AWD, and One-AWD were 59.4%, 8.5%, and 22.0% in ADT 46 and 63.3%, 31.7%, and 14.9% in TKM 13, respectively. Compared with CF, the Full-AWD treatment significantly ($p < 0.05$) decreased cumulative CH_4 emission. However, no significant difference ($p > 0.05$) in cumulative CH_4 emission was observed in early AWD treatments compared with CF due to the high level of variations. Among the AWD irrigations, cumulative CH_4 emission from Full-AWD was significantly lower compared with Two-AWD and One-AWD, and no varietal difference and interaction effects were observed in the wet season.

3.4. Nitrous Oxide Fluxes

The seasonal variation pattern of N_2O fluxes over the rice season was strongly influenced by the water regime and N fertilization (Figure 3c,d and Figure 4c,d). In dry season, five N_2O emission peaks were observed that were associated with N fertilization and the drying period. In wet season, three N_2O emission peaks were observed that were also associated with N fertilization and the dry period (Figure 4c,d).

In dry season rice, no significant ($p > 0.05$) difference in the cumulative N_2O emission was observed among the irrigation practices (Figure 5c). The CF treatment had the lowest N_2O emission, while the AWD treatment with the most drying periods (Full-AWD) had the highest N_2O emission. Averaged over the rice varieties, Full-AWD, Two-AWD, and One-AWD methods increased cumulative N_2O emissions by 77%, 45%, and 11%, respectively, compared with CF.

In wet season rice, there was also no significant ($p > 0.05$) difference in the cumulative N_2O emission among the irrigation practices (Figure 5d). Averaged over the rice varieties, Full-AWD and Two-AWD methods increased cumulative N_2O emissions by 51% and 37%, respectively, compared with CF. However, the One-AWD method lowered N_2O emissions by 25% compared with CF. No significant ($p > 0.05$) difference in the cumulative N_2O emission was observed between the tested rice varieties and there were no interaction effects in either crop season.

3.5. Rice Grain Yield and above Crop Biomass

There was no significant ($p > 0.05$) difference in grain yield and straw biomass among the different irrigation practices in both rice seasons (Table 2). In dry season rice under One-AWD and CF, a marginal increase in grain yield was observed in variety ADT 43 compared to that under Two-AWD and Full-AWD irrigation treatments. Similar grain yields were observed in variety CO 51 between Full-AWD and CF, while relatively low yields were produced by One-AWD and Two-AWD irrigations. In both rice varieties, a marginal increase in straw biomass was observed in CF compared to the different AWD irrigation practices in dry season rice. Comparing the two rice varieties, the grain yield and straw biomass of CO 51 were significantly ($p < 0.05$) higher than those of ADT 43 in the dry season.

Table 2. Crop productivity and yield-scaled GWP from black gram and rice paddies as affected by different water management practices. Numbers in the table represent means ± standard deviation ($n = 3$). * $p < 0.05$, ** $p < 0.01$, ns = not significant at 0.05 level.

		Grain Yield ($t\ ha^{-1}$)	Straw Yield ($t\ ha^{-1}$)	Yield-Scaled GWP ($kg\ CO_2$-eq t^{-1})
Dry season rice				
ADT 43	Full-AWD	5.18 ± 0.21	9.30 ± 0.25	371 ± 95
	Two-AWD	5.23 ± 0.20	8.64 ± 0.55	347 ± 87
	One-AWD	5.42 ± 0.34	9.05 ± 0.40	453 ± 163
	CF	5.41 ± 0.40	9.45 ± 0.19	661 ± 58
CO51	Full-AWD	5.85 ± 0.37	9.47 ± 0.41	349 ± 49
	Two-AWD	5.53 ± 0.20	9.33 ± 0.14	369 ± 125
	One-AWD	5.61 ± 0.36	9.44 ± 0.32	408 ± 89
	CF	5.85 ± 0.22	9.52 ± 0.25	584 ± 27
Wet season rice				
ADT 46	Full-AWD	6.44 ± 0.36	8.59 ± 0.26	859 ± 546
	Two-AWD	6.10 ± 0.84	8.87 ± 0.49	1956 ± 498
	One-AWD	6.58 ± 0.17	8.76 ± 0.29	1525 ± 196
	CF	6.26 ± 0.58	8.90 ± 0.18	2063 ± 455
TKM 13	Full-AWD	3.35 ± 0.17	4.70 ±0.44	1642 ± 401
	Two-AWD	2.64 ± 0.18	4.97 ± 0.59	3501 ± 310
	One-AWD	3.41 ± 0.27	5.23 ± 0.42	3267 ± 859
	CF	2.89 ± 0.32	5.43 ± 1.19	4658 ± 1175

Table 2. *Cont.*

		Grain Yield (t ha^{-1})	Straw Yield (t ha^{-1})	Yield-Scaled GWP (kg CO_2-eq t^{-1})
Analysis of Variance				
Dry season rice	Treat.	ns	ns	**
	Var.	**	*	ns
	Treat. × Var.	ns	ns	ns
Wet season rice	Treat.	ns	ns	**
	Var.	**	**	**
	Treat. × Var.	ns	ns	ns

Full-AWD—wetting and drying cycles throughout the growing season, Two-AWD—two early drying periods, One-AWD—one early drying period, and CF—continuous flooding.

In wet season rice, a marginal increase in grain yield was observed in both rice varieties under One-AWD and Full-AWD treatments compared to CF and Two-AWD. However, relatively more straw biomass was observed in CF compared to the different AWD irrigation treatments in both rice varieties. Comparing the two rice varieties, the grain yield and straw biomass of variety ADT 46 were significantly ($p < 0.05$) higher compared to those of variety TKM 13.

3.6. GWP and Yield-Scaled GWP

In dry season rice, there were significant ($p < 0.01$) differences in the GWP among the irrigation practices (Figure 5e). The highest GWP was observed in CF. The reduction in GWP from Full-AWD, Two-AWD, and One-AWD were 46%, 49%, and 31% in ADT 43 and 41%, 40%, and 33% in CO 51, respectively, compared with CF. The GWP for Full-AWD, Two-AWD, and One-AWD were statistically similar. Averaged over the rice varieties, CH_4 emissions accounted for 77%, 80%, 89%, and 93% of the GWP from Full-AWD, Two-AWD, One-AWD, and CF, respectively. Averaged over rice varieties and treatments, N_2O emissions accounted for 7 to 23% of the GWP in the dry season.

In wet season rice, significant ($p < 0.01$) differences in the GWP were also observed among the irrigation practices (Figure 5f). The highest GWP was recorded in CF treatment. The reductions in GWP for Full-AWD, Two-AWD, and One-AWD were 56%, 6%, and 21% in ADT 46 and 59%, 30%, and 16% in TKM 13, respectively, compared with CF. Averaged over the rice varieties, the percentage of the GWP resulting from CH_4 emissions during the wet season were approximately 85% under Full-AWD, 94% under Two-AWD, 96% under One-AWD, and 96% under CF. The contribution from N_2O emissions to GWP ranged from 4 to 15% in the wet season. There was no varietal difference ($p > 0.05$) in the GWP between the rice varieties and no interaction effects in either crop season.

The yield-scaled GWP from CF was significantly ($p < 0.01$) higher compared with AWD treatments in dry season rice (Table 2). Compared with CF, the Full-AWD, Two-AWD, and One-AWD treatments significantly ($p < 0.01$) decreased yield-scaled GWP by 42%, 43%, and 31%, respectively, averaging over the rice varieties. The yield-scaled GWP for Full-AWD, Two-AWD, and One-AWD were statistically similar.

In wet season rice, significant ($p < 0.01$) differences in the yield-scaled GWP were also observed among the irrigation practices (Table 2). Yield-scaled GWP was also higher in the CF treatment. Compared with CF, the Full-AWD significantly decreased yield-scaled GWP by 58% in ADT 46. However, no significant difference was found between the One-AWD, Two-AWD, and CF treatments in the ADT 46 variety. In variety TKM 13, the Full-AWD, two-AWD, and One-AWD treatments significantly decreased yield-scaled GWP by 65%, 24%, and 29%, respectively, compared with CF. Comparing the two rice varieties, the yield-scaled GWP was significantly ($p < 0.01$) higher in TKM 13 compared with ADT 46. There were no interaction effects in either crop season.

4. Discussion

4.1. Methane Emission in Relation to Different AWD Management

The seasonal variation pattern of CH_4 fluxes differed between the two rice seasons (Figure 3a,b and Figure 4a,b). In dry season rice, high emission peak at flowering stage was in line with other studies [24–26]. High emission peak during the middle and later growing period of dry season could probably be attributed to high soil organic matter turnover due to increased microbial activities under high soil temperature, the decomposition of plant residues from shed leaves and root turnover [26,27], and the higher availability of substrates in the rice rhizosphere [24]. Among the irrigation methods, on most days, high CH_4 emissions were observed from CF compared with the AWD irrigations, due to the low soil Eh (Figure S2a,b) under the continuously flooded condition in the CF treatment.

In contrast to the dry season rice, a high CH_4 emission peak occurred very soon after transplanting in wet season rice (Figure 4a,b). This was attributed to high soil temperature (Figure S1c,d) with low Eh (Figure S2c,d) and increased availability of substrates due to residue incorporation before planting the wet season rice. Wet season rice was transplanted immediately after the harvest of dry season rice, and rice stubbles left from the previous dry season rice was a major source of organic substrate for CH_4 production. The field was drained for only a short period for the harvesting of dry season rice before wet season rice transplanting, and thus methanogenic archaea could resume their CH_4 production activity soon after transplanting [28]. A few days after transplanting, rice plants were still too young to transport CH_4 to the atmosphere, and thus, ebullition was the major transport pathway [29].

The previous dry season rice water management greatly influenced the early growing season CH_4 emissions from the succeeding wet season (Figure 4a,b). In CF treatment, the soil that was continuously flooded for dry season rice prior to the wet season rice growing period was already reduced when wet season rice was transplanted, and thus, soil Eh was low (Figure S1c,d) and favored high CH_4 emission very soon after transplanting in the wet season. In Full-AWD, continuous wetting and drying cycles in the previous dry season might have affected the microbial population and activities during early growing period of the succeeding wet season rice and thus greatly reduced CH_4 emission, especially during the initial peak emission period soon after transplanting in the wet season.

Although the conditions have been generally different with our study, other studies have also reported that soil drainage during the winter fallow season significantly decreases CH_4 emission in the previous winter fallow season and the following rice seasons [30,31]. These authors have suggested that drainage increases soil aeration and hence effectively reduces the survival rate and activity of methane-producing archaea. Therefore, in this study, the introduction of frequent drying periods by Full-AWD in the previous dry season increased soil aeration, which could reduce methanogenic activity during the early growing period of the subsequent wet season rice.

In both rice seasons, cumulative CH_4 emission was significantly affected by different irrigation practices (Figure 5a,b). In the CF treatment, continuously flooded conditions throughout the rice growing season cuts off the oxygen supply from the atmosphere into the soil, which reduced soil Eh and favored high CH_4 production and emission in both rice varieties.

As expected, alternate wetting and drying conditions were effectively maintained in the Full-AWD throughout the rice growing period of dry season; however, there was also sufficient soil drying that was achieved even under high rainfall conditions of the wet season (Figure 2), which resulted in reduced CH_4 emission from either crop season (Figure 5a,b). This result is in line with findings of other studies [2,11,15,17,32]. Reductions in the irrigation water in the Full-AWD treatment led to a lower surface standing water depth (Figure 2) in both rice seasons, which increased oxygen penetration into the soil and led to soil organic carbon being oxidized to CO_2 instead of CH_4, thus suppressing CH_4 emissions [33]. Water management practices can improve soil permeability and increase the soil Eh, resulting in the mitigation of CH_4 emission from paddy rice soil [11].

In the wet season, high emission of CH_4 was observed at the early growth stage (within 10 days after transplanting of wet season rice), which accounted for 43% and 45% of the cumulative emission in

ADT 46 and TKM 13, respectively, under CF conditions. Our results point out that Full-AWD irrigation management in the previous rice season greatly affected and reduced early season CH_4 emission in the succeeding wet rice growing season.

The earlier AWD irrigation is performed in both crop seasons, the shorter the period that the field is under continuous flooding and, thus, the less CH_4 is emitted from paddy rice soil (Figure 5a,b). The reduction in CH_4 emissions from One-AWD and Two-AWD treatments could be attributed to soil aeration, resulting in increased soil Eh and faster aerobic carbon mineralization of added or native organic substrate during the early stages. Under the early-season drainage of 4 to 7 days, the soil was aerated and Eh increased (between +110 to +167) [34], which suppressed methanogenic activity and instead favored methanotrophs to oxidize CH_4 [35]. Tariq et al. [36] reported that for fields with early plus midseason drainage, there was a significant reduction in cumulative CH_4 emission by 88 to 91% compared to midseason drainage (MD) alone. The results of Islam et al. [34] suggests that early drainage + MD may have the potential to reduce CH_4 emissions by 85 to 90% compared to CF and by 75 to 77% compared to MD only. Their studies point out the importance of early season water management in combination with MD in the mitigation of CH_4 emission from paddy rice soil. Our results show that only early season water management has the potential to mitigate CH_4 emission; especially significantly high emission reduction was possible during the dry season. Early season drainage has been proposed as an effective approach to mitigate CH_4 fluxes by reducing carbon availability late in the season, even after reflooding [37].

Comparing among the different AWD irrigation practices, the more soil drying periods in AWD irrigation the less CH_4 emission was observed in either crop season. However, one or two drying periods of early AWD irrigation treatments in the early growing season was also nearly as effective as Full-AWD treatment in the reduction of CH_4 during the dry season. Early season AWD irrigations prevented the development of soil reducing conditions by increasing soil Eh due to soil aeration; and even after reflooding, it took longer to attain a low soil Eh value (Figure S2a,b) for methanogenic activity and thus reduced CH_4 emission in the dry season. Under aerobic soil conditions, rice plants have been shown to have less developed aerenchyma compared to those under anaerobic conditions [38], which might have further reduced CH_4 transportation and emissions from paddy rice soil [34]. In the wet season, although early season AWD irrigation was still feasible, the possibility of mitigating CH_4 emission from One-AWD and Two-AWD treatments was lower when compared with the Full-AWD treatment due to the already low soil Eh value after reflooding in the One-AWD and Two-AWD treatments.

In all the irrigation practices, cumulative CH_4 emission in the wet season was 3–4 times higher than that in the dry season (Figure 5a,b). This result is in line with findings of other studies [11,26,39]. The higher emission in wet season could be attributed to the shorter dry period between two crop seasons and the incorporation of fresh rice stubbles from the previous season, which would provide a large addition of organic materials to soil for greater methane production.

Many studies have reported that there are substantial differences in the rates of CH_4 emission from different rice cultivars [40–42]. The effect of rice cultivars on methane emissions is mostly related to rice growth performance, i.e., the number of plant tillers, and the plant above- and belowground biomass affect CH_4 transport potential and root exudation [40–42]. There were no significant differences in cumulative CH_4 emissions between the tested rice varieties in both rice seasons (Figure 5a,b). Therefore, varieties with high grain yield potential should be used for a specific crop season; e.g., the CO 51 variety is appropriate in the dry season and the ADT 46 variety in the wet season.

4.2. N_2O Emission in Relation to Different AWD Management

In both rice seasons, N_2O emission peaks were observed after N fertilization events and during the temporary drying periods in all treatments (Figure 3c,d and Figure 4c,d). This result is in line with previous observations [11,34,36]. Pandey et al. [17] discussed that readily available N after side dressing could enhance nitrification in aerobic zones and subsequent denitrification in anaerobic zones of the rhizosphere, resulting in increased N_2O emissions. Other studies also reported that low N_2O fluxes were observed during flooded periods, whereas high N_2O fluxes were found during temporary drained periods [43,44].

In both rice seasons, high N_2O emissions were observed in AWD treatments compared with CF (Figure 5c,d). Under continuous flooded conditions in CF, the consistently low soil Eh resulted in more complete denitrification, and consequently, reduced N_2O emission [11]. Ussiri and Lal [45] also discussed that prolonged flooding promotes the development of strong anaerobic conditions in soils, reducing any N_2O produced in the paddy fields to N_2. Under flooded conditions, negligible N_2O emission from paddy rice soil was also observed during three continuous years [46]. Zou et al. [44] and Hou et al. [47] proposed that the increase in N_2O emissions from AWD treatments upon N fertilization was due to the abundant, newly added N and the suitable soil moisture conditions. Maintaining flooded soil conditions could minimize the N_2O flux peaks observed after the topdressing [44].

Comparing different AWD irrigation methods, higher N_2O emission was observed in Full-AWD compared with One- and Two-AWD treatments (Figure 5c,d), which could be attributed to the more frequent soil moisture alternations during the growing period compared with one and two drying periods of One-AWD and Two-AWD treatments. This favored more N_2O formation and emission in both rice seasons. Brentrup et al. [48] also reported that when there are soil moisture alternations due to successive moist and dry periods, N_2O emissions increase. In this study, N_2O emission was related to N side dressing and temporary drying periods, and no varietal difference was observed among the tested rice varieties in both rice seasons. Since N_2O fluxes were measured directly after fertilization and sampling was not undertaken every day, some emission peaks could have been missed and N_2O fluxes might be underestimated in this study.

4.3. Rice Productivity

Although no significant difference was observed among the treatments, grain yield in early and Full-AWD irrigations was comparable with yield of CF in both rice seasons (Table 2). Previous meta-analysis results show that AWD irrigation conducted only during the vegetative or reproductive phase results in no yield reduction compared to an 8.1% yield reduction when it is practiced throughout the whole season [9]. Other studies have also reported no yield losses when implementing AWD irrigation compared with CF [11,32]. The results mean that there is no necessity to maintain continuous standing water throughout the rice growing season since irrigated rice had developed adaptability to the intermittently flooded conditions [49]. Under AWD irrigation, it strengthens the air exchange between soil and the atmosphere [50], thus supplies sufficient oxygen to the root system to accelerate soil organic matter mineralization, all of which should increase soil fertility and favor rice growth [50,51].

Given the absence of significant differences in grain and straw yield between rice varieties, the choice of varieties should be based on potential yield: A high yielding variety should be planted together with early or full-AWD irrigation to achieve high yield with effective water saving for sustainable rice farming.

4.4. GWP and Yield-Scaled GWP

In both rice seasons, the amount of emitted N_2O was lower (2.0–25.4% of total GWP) compared to the amount of emitted CH_4 (74.6–98.0% of total GWP) (Figure 5), and hence GWP derived from N_2O is considerably smaller than that from CH_4. Therefore, the reduction in GWP from double rice cultivation was primarily attributed to CH_4 emissions. The Full-AWD, Two-AWD, and One-AWD treatments substantially reduced GWP by 16 to 59% depending on the degree of CH_4 reduction under different AWD treatments compared with CF. Our previous study also observed that the AWD method substantially reduced GWP by 18% to 39% due to a large reduction in CH_4 emission [11]. Linquist et al. [2] also reported that greater GWP reduction was observed by 45 to 90% under AWD irrigation compared with CF. The low contribution from N_2O emissions suggests that decreasing CH_4

emissions by practicing early or Full-AWD in paddy rice is the effective way to reduce total GWP, regardless of the rice varieties in dry season; however, only the Full-AWD irrigation method is suitable for the wet season.

The yield-scaled metric is used to provide a measure of agronomic efficiency to address both climate change and future food supply [52]. The yield-scaled GWP was relatively higher in CF because CH_4 emission was higher, with no difference in grain yield compared to AWD irrigation treatments in both rice seasons (Table 2). Yield scaled GWP from Full-AWD was lowest among the treatments due to low CH_4 emissions in both rice seasons. One-AWD and Two-AWD methods were only effective in reducing yield-scaled GWP during the dry season while they were not significantly effective compared with CF in the wet season, even though some reduction was observed. Therefore, it is recommended that early or full season AWD irrigation methods can be practiced in dry season, regardless of the rice variety but only Full-AWD is suitable in the wet season for the efficient reduction of GWP without affecting grain yield. Due to the significant difference in yield-scaled CO_2 emission between the tested varieties in the wet season, high-yielding varieties should be used in combination with early or Full-AWD irrigation for effective mitigation in GWP.

5. Conclusions

Our results show that Full-AWD irrigation significantly decreased CH_4 emissions from paddy rice soil in either rice season. According to our knowledge, this is the first study showing that only early season AWD practices are an effective option for farmers to mitigate GHG emissions where full-scale practice of AWD is not feasible. Although AWD irrigation treatments increased N_2O emissions, the global warming potential resulting from increased N_2O is negligible compared to the reduction in CH_4 emissions associated with drying of the fields. Since high CH_4 emission fluxes were observed at the early growth stage of wet season rice soon after transplanting (44% of total emission), attention should be paid to this period when implementing mitigation strategies. Our results suggest strong potential for early season water management strategies to reduce the total GHG emissions from paddy rice soil, while maintaining rice yield.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4395/8/10/202/s1. Figure S1: Variation in soil temperature during dry (a and b) and wet (c and d) rice growing seasons for different water management practices. Error bars indicate standard deviation (n = 3). Full-AWD—wetting and drying cycles throughout the growing season, Two-AWD—two early drying periods, One-AWD—one early drying period, CF—continuous flooding; Figure S2: Variation in soil redox potential during dry (a and b) and wet (c and d) rice growing seasons for different water management practices. Error bars indicate standard deviation (n = 3). Full-AWD—wetting and drying cycles throughout the growing season, Two-AWD—two early drying periods, One-AWD—one early drying period, CF—continuous flooding.

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