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Field Validation of the DNDC-Rice Model for Methane and Nitrous Oxide Emissions from Double-Cropping Paddy Rice under Different Irrigation Practices in Tamil Nadu, India

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Abstract: Two-year field experiments were conducted at Tamil Nadu Rice Research Institute, Aduthurai, Tamil Nadu, India, to evaluate the effect of continuous flooding (CF) and alternate wetting and drying (AWD) irrigation strategies on rice grain yield and greenhouse gas emissions from double-cropping paddy rice. Field observation results showed that AWD irrigation was found to reduce the total seasonal methane (CH_4) emission by 22.3% to 56.2% compared with CF while maintaining rice yield. By using the observed two-year field data, validation of the DNDC-Rice model was conducted for CF and AWD practices. The model overestimated rice grain yield by 24% and 29% in CF and AWD, respectively, averaged over the rice-growing seasons compared to observed values. The simulated seasonal CH_4 emissions for CF were 6.4% lower and 4.2% higher than observed values and for AWD were 9.3% and 12.7% lower in the summer and monsoon season, respectively. The relative deviation of simulated seasonal nitrous oxide (N_2O) emissions from observed emissions in CF were 27% and −35% and in AWD were 267% and 234% in the summer and monsoon season, respectively. Although the DNDC-Rice model reasonably estimated the total CH_4 emission in CF and reproduced the mitigation effect of AWD treatment on CH_4 emissions well, the model did not adequately predict the total N_2O emission under water-saving irrigation. In terms of global warming potential (GWP), nevertheless there was a good agreement between the simulated and observed values for both CF and AWD irrigations due to smaller contributions of N_2O to the GWP compared with that of CH_4. This study showed that the DNDC-Rice model could be used for the estimation of CH_4 emissions, the primary source of GWP from double-cropping paddy rice under different water management conditions in the tropical regions.

Keywords: DNDC-Rice; greenhouse gas; water-saving irrigation; crop yield; mitigation; tropical regions

1. Introduction

Rice cultivation is a major source of atmospheric methane (CH_4), one of the significant potent greenhouse gases (GHG) and is responsible for approximately 11% of global anthropogenic CH_4 emissions [1]. Rice paddies are also known to emit high nitrous oxide (N_2O) fluxes under nitrogen fertilization and specific water management regimes [2,3].

Methane emission from rice fields is the net result of CH_4 production and oxidation in soil and transport of CH_4 gas from soil to the atmosphere through rice plants [4]. Conventional management practices of continuously flooded irrigation in paddy fields enhance anaerobic fermentation of carbon sources supplied by the rice plants and added organic matter and results in high CH_4 production. Water management is one of the most effective options for reducing CH_4 emission from irrigated rice. Recently, midseason drainage and alternate wetting and drying irrigation (AWD) practice have been promoted as a strategy to decrease CH_4 emissions from paddy rice fields [3,5–8]. However, it can result in increased N_2O emissions due to a trade-off between CH_4 and N_2O [2,3,9]. Frequent alternations in soil redox conditions under water saving irrigation are known to substantially increase N_2O emissions by favoring both nitrification and denitrification processes [10]. It can substantially offset the advantages of CH_4 mitigation under water-saving irrigation [11,12]. Irrigation management plays a vital role in determining the trade-off between CH_4 and N_2O emissions from paddy rice fields.

Water management practices relating to the drying and wetting of soil conditions are known to be important factors for CH_4 emissions from paddy rice soil. CH_4 emissions are highly variable depending on practices, and therefore will lead to high uncertainties in the estimation of the emissions for regional and national scales. Evaluation of regional CH_4 emissions from rice paddy differs largely depending on the techniques, approaches, and databases used for extrapolation [13]. Advances are needed in how to effectively scale the measurements from point sources to a regional scale, and it is beneficial to link the available data on CH_4 emissions to a knowledge of underlying processes, such as through a process-based model, DNDC (Denitrification-Decomposition) model [13]. The DNDC model simulates carbon and nitrogen biogeochemistry in agroecosystems and can estimate CO_2, CH_4, N_2O, nitric oxide, and ammonia simultaneously [14–16].

The DNDC model was revised to improve its ability to estimate CH_4 emitted from rice paddies under continuously flooded conditions, midseason drainage, and intermittent irrigation [17]. The revised model (DNDC-Rice) was validated with CH_4 data from paddy rice fields in Japan, China, and Thailand [17–20]. Smakgahn et al. [18] validated the DNDC-Rice model by using CH_4 emission data from nine paddy fields in Thailand under continuous flooding treatment; the simulated values were positively correlated with the observed values. Using the DNDC-Rice model, simulation of N_2O fluxes has also been reported [19,21]. Babu et al. [13] reported that the DNDC model is capable of capturing quantitatively the significant aspects of CH_4 and N_2O production and emission from rice fields under widely different geographical locations in India. However, these studies were conducted under continuous flooding (CF) or midseason drainage conditions. Katayanagi et al. [21] validated the DNDC-Rice model by using CH_4 and N_2O flux data under CF and AWD management conditions in a pot experiment and discussed that the accuracy of the simulation of gross CH_4 emissions and total global warming potential (GWP) values for the CF and AWD treatments was sufficiently good for practical use of the model. However, there is still limited information on field validation of CH_4 and N_2O fluxes simulated by the DNDC-Rice model under water-saving irrigations in intensive rice cultivation systems, such as double-cropping paddy rice per year in the tropical regions. Therefore, the objectives of this study were to assess (1) whether CH_4 and N_2O processes are similarly reflected in the DNDC-Rice model; (2) the reliability of the DNDC-Rice model to predict CH_4 and N_2O emissions from the double-cropping paddy rice system under different irrigation practices to contribute mitigation strategies in tropical rice production. The results of the simulations were validated using the flux data from two-year field observations at Tamil Nadu Rice Research Institute, Tamil Nadu, India.

2. Materials and Methods

2.1. Experimental Site and Design

The field experiments were carried out from May 2016 until January 2018, comprising four rice-growing seasons, at the Tamil Nadu Rice Research Institute (TRRI), Aduthurai, Thanjavur District, Tamil Nadu, India (11°0′ N, 79°30′ E, 19.4 m above sea level). The region has a tropical wet and dry/savanna climate with a pronounced dry season in the high-sun months, and no cold or wet seasons (monsoon season) in the low-sun months. Figure 1 shows daily rainfall and maximum and minimum temperatures from January 2016 until January 2018 measured at the study site. The soil type is alluvial clay with major properties indicated as 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 electrical conductivity (EC) 11.6 m S m^{-1} [22]. There were two rice-growing seasons per year, summer—hot and dry season (local name—Kuruvai season; from May to September) and monsoon—wet season (local name—Thaladi season; from September to January).

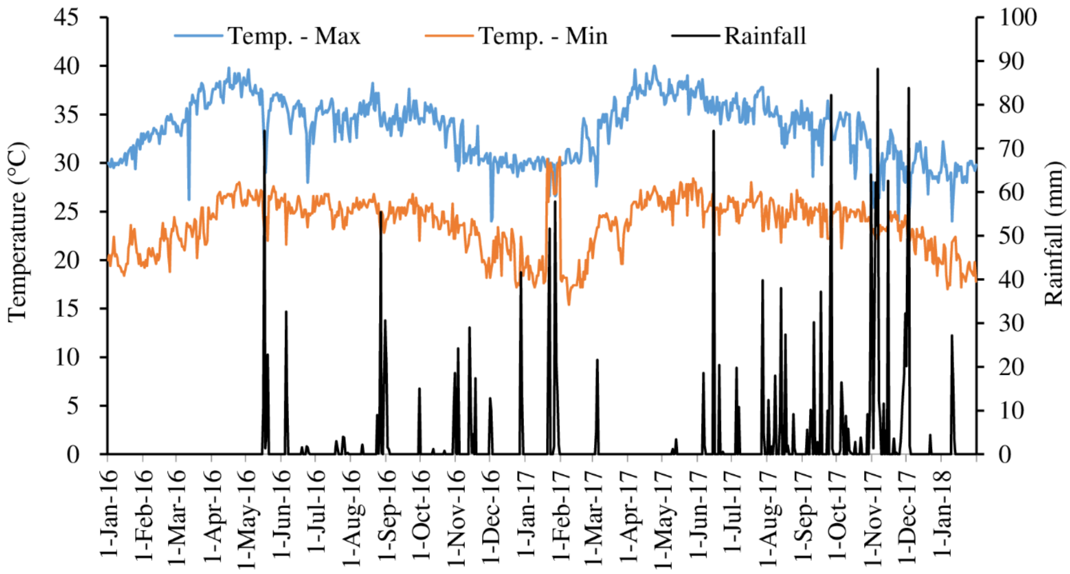

Figure 1. Daily rainfall, maximum and minimum temperature from January 2016 until January 2018 as measured at Tamil Nadu Rice Research Institute, Aduthurai, Tamil Nadu, India.

The field experiment was set up on four rice-growing seasons. Two water management practices, (1) continuous flooding (CF) and (2) alternate wetting and drying irrigation (AWD), were compared in each growing season with three replications. Specific management conditions are summarized in Table 1, along with the rice season weather summaries (average maximum and minimum temperatures and accumulated rainfall for each rice-growing season). For AWD irrigation, a perforated 25-cm long field water tube was inserted in the soil to observe the water level below the soil surface. Irrigation was applied to re-flood the field when the water level had dropped to about 15 cm below the soil surface in AWD irrigation. Pump irrigation was practiced by using groundwater in all growing seasons. Rice stubbles of previous season were incorporated by ploughing the field before rice cultivation, except the summer season of 2017 when rice stubbles were incorporated soon after the previous season's rice harvest.

Table 1. Field management practices. Dates are described as Day/Month/Year.

		Summer Rice June–September 2016	Monsoon Rice October 2016–January 2017	Summer Rice June–September 2017	Monsoon Rice October 2017–January 2018
Residue amendment		20/5/2016: 650 kg C ha^{-1}	23/9/2016: 850 kg C ha^{-1}	20/2/2017: 850 kg C ha^{-1}	25/9/2017: 850 kg C ha^{-1}
Crop cultivation		Planting: 10/6/2016 Harvest: 14/9/2016	Planting: 5/10/2016 Harvest: 18/1/2017	Planting: 16/6/2017 Harvest: 21/9/2017	Planting: 6/10/2017 Harvest: 18/1/2018
Rice variety		ADT 43	ADT 46	ADT 43	ADT 46
Fertilizer application		150 kg N ha^{-1} as urea, 50 kg P_2O_5 ha^{-1} as diammonium phosphate, 50 kg K_2O ha^{-1} as muriate of potash, 25 kg $ZnSO_4$ ha^{-1}, and 500 kg gypsum ha^{-1} Basal—DAP, gypsum, zinc sulfate Urea and muriate of potash were applied in four equal split doses at basal, active tillering, panicle initiation, and heading stages			
Water management (CF, continuous flooding; AWD, alternate wetting and drying)					
CF	Flooded:Drained	15/5/2016 1/9/2016	23/9/2016 3/1/2017	9/6/2017 6/9/2017	23/9/2017 3/1/2018
AWD	Flooded: 1st drained: Final drained:	15/5/2016 30/6/2016 1/9/2016	23/9/2016 26/10/2016 3/1/2017	9/6/2017 30/6/2017 6/9/2017	23/9/2017 17/10/2017 3/1/2018
Rice season weather summaries					
Ave. Max. T. (°C) [a]		34.8	31.3	34.9	30.2
Ave. Min. T. (°C) [b]		25.2	21.6	25.1	22.6
Rainfall (mm)		160.5	195.0	314.4	781.2

[a] Average maximum temperature; [b] Average minimum temperature.

2.2. Gas Sample Collection, Measurement, and Calculation

The gas samples were collected using the closed chamber method. In all rice seasons, the sampling frequency was once every week. Whenever there was a fertilizer application event, however, air sampling was done one day and three days after fertilization [3,9]. Gas samples were obtained using a 50 mL plastic syringe at 0, 15, and 30 min after chamber closure. The collected 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) to determine the concentrations of CH_4 and N_2O, respectively.

The CH_4 and N_2O emission fluxes were calculated by examining the linear increases in CH_4 and N_2O concentrations in the headspace of the chambers over time. The cumulative seasonal CH_4 and N_2O emissions were calculated by successive linear interpolation of individual flux values on the sampling days.

The global warming potential (GWP) was calculated using the following equation.

$$\text{GWP (kg CO}_2\text{ eq ha}^{-1}) = (\text{TCH}_4 \times 34 + \text{TN}_2\text{O} \times 298)$$

where TCH_4 and TN_2O are the total amounts of each gas emission (kg ha^{-1}), and 34 and 298 are the Intergovernmental Panel on Climate Change (IPCC)'s GWPs for CH_4 and N_2O, respectively, to CO_2 over a 100-year time horizon [1].

2.3. The DNDC-Rice Model

The DNDC-Rice model consists of three major submodels that simulate soil climate, crop growth, and soil biogeochemistry. The features and scientific background of the DNDC-Rice model are given by

Fumoto et al. [17] and all the input parameters are listed in Fumoto et al. [19]. In this study, the site mode of the DNDC-rice model was tested for CH_4 and N_2O emissions under different water management practices during four rice-growing seasons.

The DNDC-Rice model incorporated the Modules of an Annual Crop Simulator (MACROS) model of rice physiology [23] into its crop growth submodel. The original codes of MACROS, written in the simulation language Continuous System Modelling Program (CSMP) and provided as text in literature [23], were rewritten in C++ to incorporate into DNDC-Rice. Crop physiology and phenology are simulated on the basis of nitrogen availability and the environments above and below the ground [17]. In a recent revision, the mechanistic description of photosynthesis [24] was added to the crop growth submodel as mentioned by Minamikawa et al. [20]. Methane flux is calculated by the fermentation submodel. Under anaerobic conditions, the model calculates the production of hydrogen (H_2) and dissolved organic carbon (DOC), which are used as the electron donors for the subsequent reduction of Mn, Fe, and S oxides and CH_4 production. Nitrous oxide production is calculated by nitrification and denitrification processes. Emission of N_2O from the soil surface is calculated as a function of soil N_2O content, air-filled porosity, temperature, and clay content.

A preliminary run of DNDC-Rice is essential to achieve a near-steady state for soil carbon pools before the start of the simulation [17]. We ran the model for a time period of 20 years, with constant inputs of weather conditions and agricultural management practices for double-cropping paddy rice per year practiced at TRRI, Aduthurai, India. The datasets of soil, climate, and crop management practices were collected at the experimental site to run the model.

DNDC-Rice can explicitly calculate volumetric soil moisture and matric potential, but not the underground water level. To simulate the irrigation under AWD of this study, therefore, the codes were adjusted to assume a condition so that the field is re-flooded when calculated matric potential is lowered to −20 kPa at the depth of 15 cm.

2.4. Statistical Analysis

The simulation result of CH_4 and N_2O fluxes were evaluated by using the root mean square error (RMSE) with the following equation:

$$\text{RMSE} = \sqrt{\frac{\sum (Fi - Ai)^2}{N}}$$

where Fi is simulated value i, Ai is observed value i, and N is the number of samples.

Relative variation between the observed and simulated values were calculated by using the following equation by Katayanagi et al. [21]:

$$\text{Relative variation (\%)} = [(\text{simulated value} - \text{observed value})/\text{observed value}] \times 100$$

3. Results and Discussion

3.1. Rice Growth

In all rice-growing seasons, the observed grain yields in the CF and AWD treatments did not show a significant difference (Table 2). Other studies have also reported no yield losses when implementing AWD irrigation compared to CF [7,9]. The results showed that water-saving irrigation is feasible in double-cropping paddy rice in the tropical region without affecting rice grain yield. 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 [25].

Table 2. Observed and simulated grain yield and straw biomass under continuous flooding (CF) and alternate wetting and drying (AWD) conditions during different rice-growing seasons. Observed values represent the means ± standard deviation (n = 3).

	Grain Yield (kg ha^{-1})		**Straw Biomass (kg ha^{-1})**	
	Observed	**Simulated**	**Observed**	**Simulated**
Summer 2016				
CF	6725 ± 418	7846	12,436 ± 787	4640
AWD	6536 ± 457	9557	10,641 ± 314	5050
Monsoon 2016–2017				
CF	6400 ± 620	8420	13,652 ± 450	4530
AWD	6093 ± 907	8122	11,500 ± 350	4482
Summer 2017				
CF	5418 ± 429	7905	9456 ± 195	4532
AWD	5186 ± 206	7852	9303 ± 259	4559
Monsoon 2017–2018				
CF	6263 ± 577	8414	8993 ± 184	4578
AWD	6440 ± 358	8511	8594 ± 268	4590

The DNDC-Rice model overestimated rice grain yield by 24% under CF and 29% under AWD on average over the rice-growing seasons compared to observed ones (Table 2). In contrast, it apparently underestimated the straw biomass under CF and AWD. To simulate rice growth, DNDC-Rice partitions photosynthetic product to different organs (root, stems, leaves, and panicles) depending on the growth stage, according to cultivar-specific functions that were calibrated for a number of rice cultivars. For the Indian cultivars used in this study (ADT 43 and ADT 46), however, we could not obtain adequate datasets (i.e., biomass of each organ measured at different growth stages) required for calibrating the cultivar-specific functions. Beside the limited data availability, the major objective of this study was to validate the DNDC-Rice model in predicting CH_4 and N_2O emissions under different irrigation practices. Therefore, we did not conduct further calibration of the cultivar-specific functions in this study. In order to accurately estimate rice grain yield and straw biomass under CF and AWD irrigations in the tropical region, however, the DNDC-Rice model will need calibration of its functions that determine the partitioning of photosynthetic product in cultivars grown in the region of interest.

3.2. Soil Redox Status and Methane Emissions

The field observation results showed that the soil Eh was as low as –150 mV during the early growth period of the summer season, and then it showed an increasing trend toward the end of the growing period (Figure 2). After the start of AWD irrigation, the soil Eh value showed an increasing trend and was always higher than that of CF treatment. The model predicted the season pattern of the soil Eh value well in CF, but it failed for AWD irrigation due to the overresponse of the model to the drying period during the alternate wetting and drying period.

When soil contains O_2, DNDC-Rice simulates soil Eh (mV) as a function of the soil O_2 concentration, (O_2) (mol kg^{-1} soil), according to the formula,

$$Eh = \max\left(0,\ 1230 + 200\left(\log_{10}[O_2] - 1\right)\right)$$

When soil O_2 has been depleted, in turn, soil Eh is simulated using empirical functions that relate soil Eh to reduction of soil Fe and S [17]. To analyze the behavior of simulated soil Eh, we examined simulated (O_2) (at the depth of 5 cm) during the AWD irrigation in the summer season of 2016 and found that it was mostly zero during the wetting periods, but increased to about 0.2–0.9 mmol kg^{-1} soil during the drying periods, which was about 4–20% of the (O_2) level during the most aerobic period between rice-growing seasons. Consequently, simulated soil Eh jumped up to around 400 mV during the drying periods, according to the above formula. If the simulated (O_2) is reasonable, therefore, it is suggested that the above function of (O_2) is not appropriate for simulating soil Eh during AWD irrigation. Unlike earlier versions of DNDC (e.g., Babu et al. [13]), however, soil Eh does not directly affect CH_4 production in DNDC-Rice, where CH_4 production is explicitly limited by the availability of electron donors (H_2 and dissolved organic carbons) in competition with the alternative electron acceptors (Fe, Mn, and S) [17], instead of applying simulated soil Eh as the threshold for CH_4 production. We expect, therefore, that the over-responding soil Eh did not affect the simulated CH_4 emissions, even though it did not match the observed soil Eh.

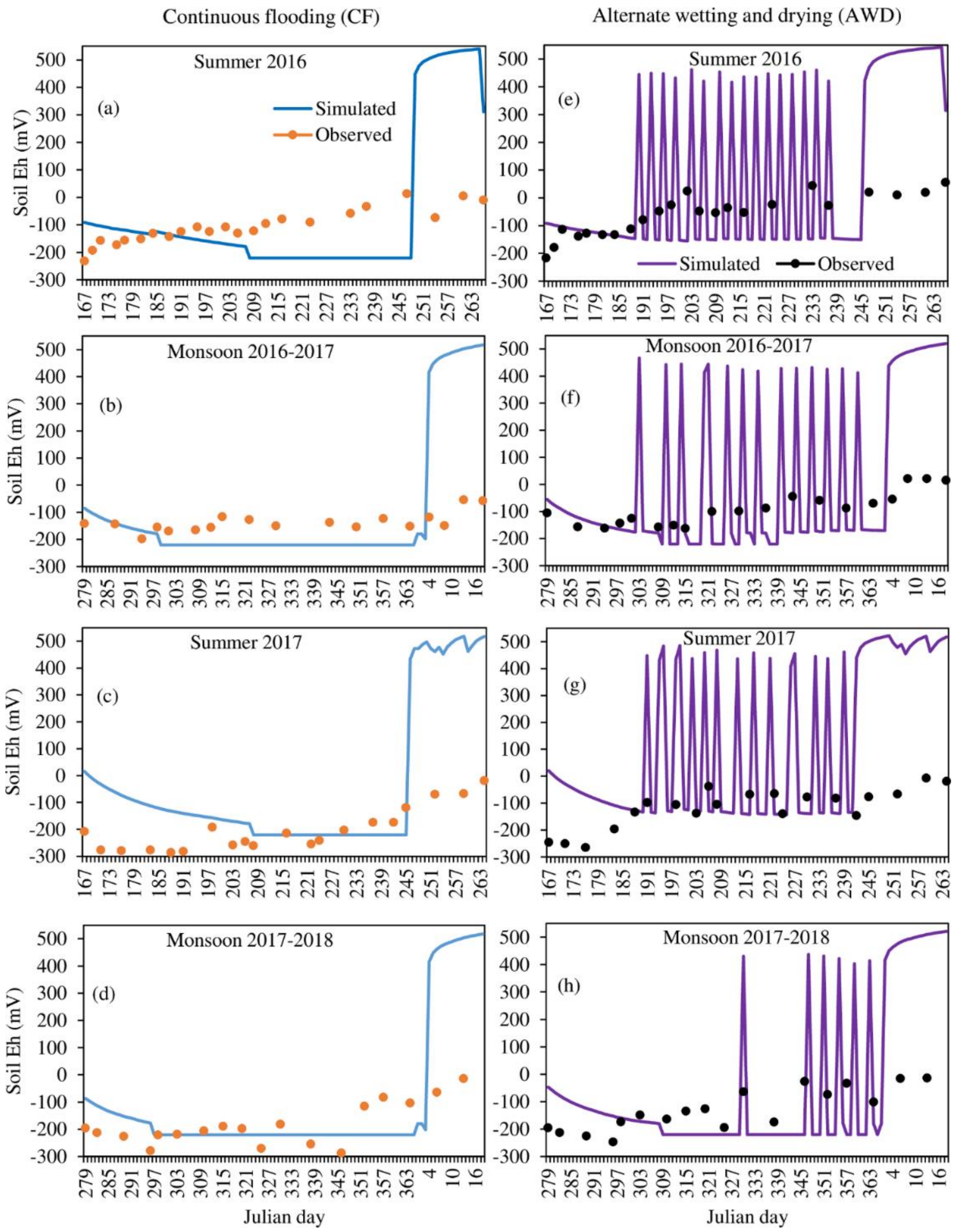

Figure 2. Observed and simulated soil redox potential under continuous flooding (**a**–**d**) and alternate wetting and drying conditions (**e**–**h**) during different rice-growing seasons.

The field observation results showed that the seasonal variations of CH_4 fluxes were significantly lower in AWD compared to CF treatment in all rice-growing seasons (Figure 3). Under AWD irrigation, reduction in the irrigation water volume led to a lower surface standing water depth and even no standing water above the surface of the soil, which increased oxygen penetration into the soil and led to soil organic carbon being oxidized and suppressed CH_4 emissions [26].

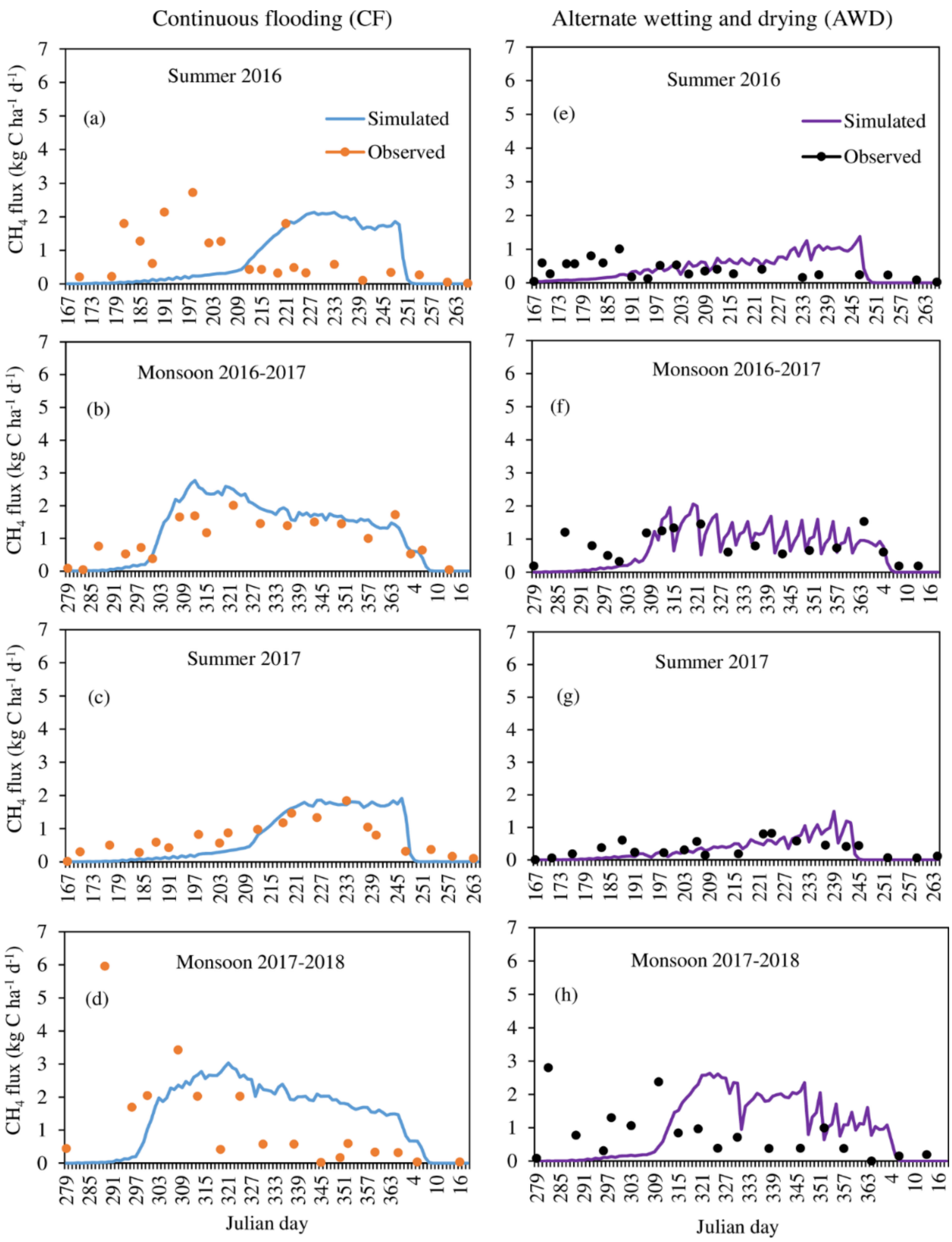

Figure 3. Observed and simulated CH_4 emissions from rice fields under continuous flooding (**a**–**d**) and alternate wetting and drying conditions (**e**–**h**) during different rice-growing seasons.

With respect to the seasonal variability of CH_4 fluxes, high flux was often observed during the early growth stage under both the CF and AWD treatments (Figure 3). The higher CH_4 emissions during the early rice-growing season were attributed to high soil temperature and low soil redox potential during that period [3,27]. However, the DNDC-Rice model tended to underestimate the CH_4 fluxes during the early growth stage. Presumably, this was caused because the model failed to predict the reductive soil conditions at the early growth stage, as indicated by comparing observed and simulated soil Eh (Figure 2). Minamikawa et al. [6] also reported that the underestimates by the model during the early growing season were mainly due to the unsuccessful prediction of the development of reductive conditions at the early growth stage since soil redox status before cultivation is important in determining the subsequent CH_4 emission in the model.

Under CF conditions, the average rate of observed and simulated CH_4 fluxes was 0.75 and 0.70 kg C ha^{-1} d^{-1} in the summer and 1.17 and 1.29 kg C ha^{-1} d^{-1} in the monsoon season, respectively (Table 3). The RMSE values for the simulated CH_4 fluxes in the CF were 0.81 and 1.23 kg C ha^{-1} d^{-1} in the summer and monsoon season, respectively. The average observed daily CH_4 fluxes and RMSE values in this study fall within the simulated flux range from 0.09 to 1.4 kg C ha^{-1} d^{-1} and RMSE values from 0.16 to 1.17 kg C ha^{-1} d^{-1} from paddy fields in Japan and China [17]. Although the model underestimated the early seasonal emissions, the agreement between the average daily observed and simulated CH_4 fluxes was good under CF conditions in all rice-growing seasons (Table 3, Figure 3).

Table 3. Observed and simulated mean CH_4 and N_2O fluxes from rice fields under continuous flooding (CF) and alternate wetting and drying (AWD) conditions during different rice-growing seasons. *n*—number of samples, SD—standard deviation, RMSE—root mean square error.

		CH_4 (kg ha^{-1} d^{-1})				N_2O (g ha^{-1} d^{-1})			
		n	Mean	SD	RMSE	*n*	Mean	SD	RMSE
Summer 2016									
CF	Observed	21	0.79	0.77		21	7.1	18.8	
	Simulated	101	0.73	0.82	1.14	101	5.9	11.1	19.1
AWD	Observed	21	0.37	0.25		21	20.1	27.0	
	Simulated	101	0.42	0.37	0.49	101	25.7	27.3	25.2
Monsoon 2016–2017									
CF	Observed	19	1.12	0.58		19	4.3	5.7	
	Simulated	105	1.19	0.92	0.60	105	1.7	4.4	7.4
AWD	Observed	19	0.78	0.45		19	8.9	14.1	
	Simulated	105	0.70	0.61	0.54	105	45.6	89.3	97.0
Summer 2017									
CF	Observed	20	0.70	0.49		20	5.5	11.0	
	Simulated	98	0.66	0.75	0.47	98	10.2	20.2	18.3
AWD	Observed	20	0.33	0.25		20	10.5	16.6	
	Simulated	98	0.29	0.34	0.30	98	52.4	89.3	96.1
Monsoon 2017–2018									
CF	Observed	18	1.21	1.03		18	12.1	36.5	
	Simulated	105	1.38	1.02	1.85	105	5.7	15.0	41.1
AWD	Observed	18	0.79	0.76		18	10.5	19.9	
	Simulated	105	0.96	0.91	1.31	105	8.0	11.9	22.2

The DNDC-Rice model reproduced the suppressive effect of AWD treatment on CH_4 emission well in all rice-growing seasons (Table 3, Figure 3). Under AWD conditions, the average rate of observed and simulated CH_4 fluxes was 0.35 and 0.36 kg C ha^{-1} d^{-1} in the summer and 0.79 and 0.83 kg C ha^{-1} d^{-1} in the monsoon season, respectively. The RMSE values for the simulated CH_4 fluxes in the AWD were 0.40 and 0.93 kg C ha^{-1} d^{-1} in the summer and monsoon season, respectively. According to our knowledge, this is the first report of validation of the DNDC-Rice model under water-saving AWD irrigation in double-cropping paddy rice under field conditions, although other studies have used the DNDC-Rice model to estimate CH_4 emissions under mid-season drainage and intermittent irrigation [6,17,19,20]. The results of their studies stated that the DNDC-Rice model represents a valuable tool for estimating CH_4 emission from paddy rice soil under mid-season drainage and intermittent irrigation.

The previous study, conducted by Katayanagi et al. [21], validated the DNDC-Rice model for tropical rice paddies in Philippine under AWD irrigation management in a pot experiment. Their result showed that the model simulated the temporal variability of CH_4 fluxes for CF and AWD pots well with the average observed daily CH_4 fluxes of 4.49 and 1.22 kg C ha^{-1} d^{-1}, respectively, and the RMSE values of 1.76 and 1.86 kg C ha^{-1} d^{-1}. The simulated RMSE values for the simulated CH_4 fluxes under CF and AWD irrigation practices in this study were comparable to the values from rice soil in the Philippines. The results highlighted that the DNDC-Rice model is suitable for estimation of CH_4 fluxes not only for conventional water management techniques also for water saving conditions in double-cropping paddy rice in major rice growing areas in the tropical region.

3.3. Nitrous Oxide Emissions

The field observation results showed that the seasonal variations of N_2O fluxes were relatively higher in AWD compared to CF treatment in all rice-growing seasons (Figure 4). Under continuously flooded conditions, the consistently low soil Eh (Figure 2) resulted in complete denitrification, and consequently reduced N_2O emission [3]. Ussiri and Lal [28] 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. The increase in N_2O emissions from AWD treatments under N fertilization was due to the abundant N supply and the suitable soil moisture conditions due to successive moist and dry periods during the rice-growing season.

Under CF conditions, the seasonal variability of N_2O fluxes was simulated reasonably by the DNDC-Rice model in all rice-growing seasons (Figure 4). The DNDC-Rice model simulated near zero N_2O emission from the flooded rice soils throughout the rice-growing season and peak emission was observed towards the maturity of the crop after water was drained from the field. Babu et al. [13] tested the DNDC model in wide regions of India. They discussed that the influence of the rhizosphere on the ecological drivers is not yet incorporated in the model, so the model simulates flooded anoxic soils with suppressed rates of nitrification, leading to zero N_2O emissions in continuously flooded rice fields. The average rates of observed and simulated N_2O fluxes in CF were 6.3 and 8.1 g N ha^{-1} d^{-1} in the summer and 8.2 and 7.4 g N ha^{-1} d^{-1} in the monsoon season, respectively (Table 3). The RMSE values for the simulated N_2O fluxes in the CF were 18.7 and 24.3 g N ha^{-1} d^{-1} in the summer and monsoon season, respectively.

Although the seasonal variability of N_2O fluxes was simulated reasonably under AWD, the model overestimated N_2O emissions after the additional nitrogen fertilization in all rice-growing seasons (Figure 4). When the soil is well aerated under AWD irrigation, the oxidation, i.e., nitrification, of available nitrogen dominates and NO is the most common gas emitted from the soil instead of N_2O [29], and therefore the observed emission peaks after additional fertilization were lower compared with the simulated one. Moreover, frequent aeration under AWD significantly increased soil redox conditions up to +485, which might be overestimated by the model. Under actual field conditions, although an increase in soil redox potential was observed after introducing the drying period in AWD, the soil was still saturated, and therefore the soil redox potential did not reach positive values (Figure 2). As a result, the model overestimated soil N_2O emissions compared to observed ones. The average rates of observed and simulated N_2O fluxes were 15.3 and 39.1 g N ha^{-1} d^{-1} in the summer and 9.7 and 26.8 g N ha^{-1} d^{-1} in the monsoon season, respectively (Table 2). High RMSE values of 60.7 and 59.6 g N ha^{-1} d^{-1} in the summer and monsoon season, respectively, stated that the model poorly predicted N_2O emissions under AWD irrigation.

In previous applications of the DNDC-Rice model to tropical rice soil in The Philippines [21], the simulated and observed N_2O emissions from the AWD pots were higher than those from the CF pots, but the DNDC-Rice model could not predict the timing and magnitude of the high N_2O pulses which created a higher RMSE for AWD irrigation (124 g N ha^{-1} d^{-1}) than for CF (2.23 g N ha^{-1} d^{-1}). In this study, the DNDC-Rice model predicted high magnitude N_2O peaks after additional nitrogen fertilization in AWD treatment in all rice-growing seasons. This might be due to overestimation of soil nitrification under frequent soil aeration in AWD-related high soil redox values (Figure 4), since N_2O production in paddy rice soils was mainly regulated by nitrification [21].

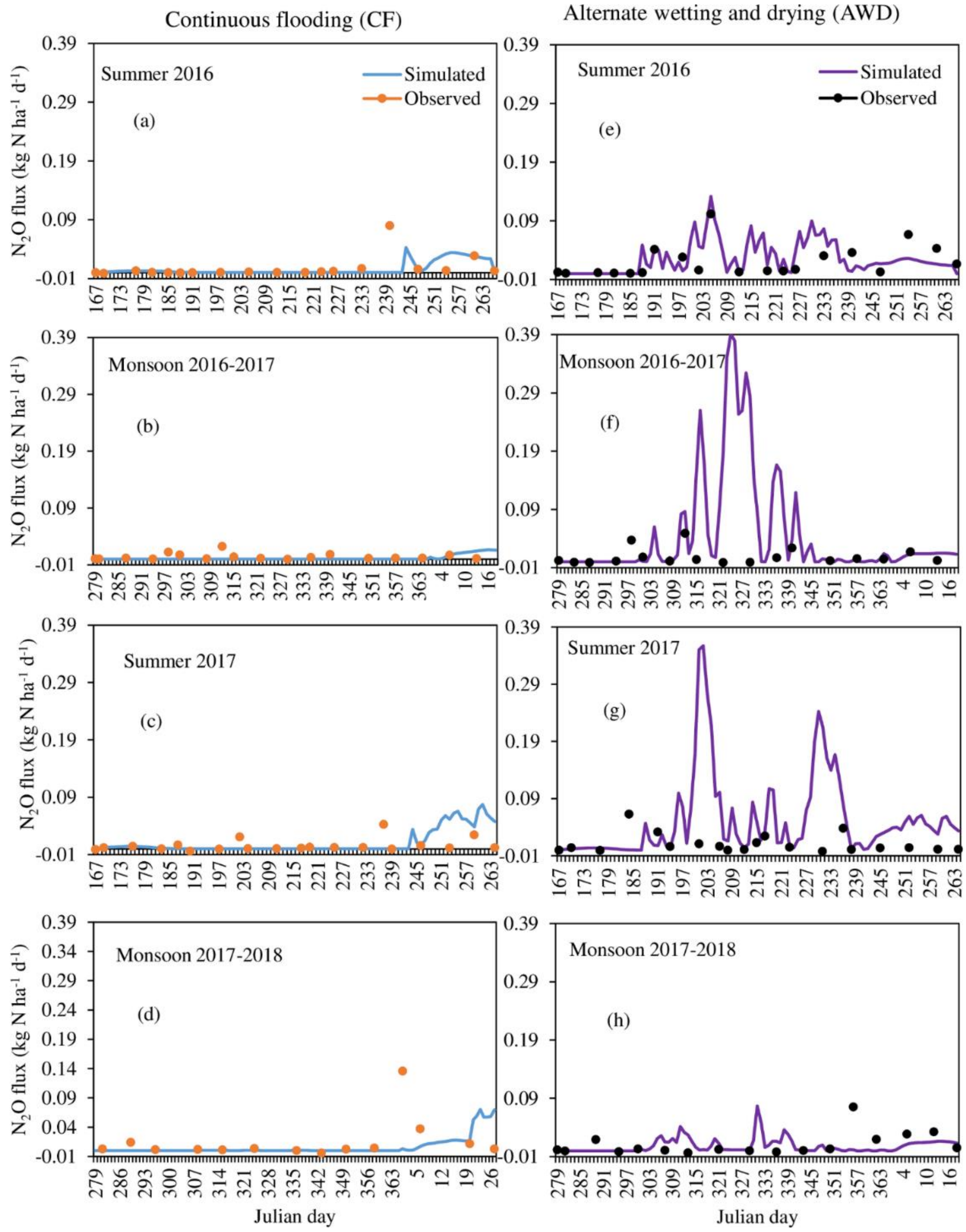

Figure 4. Observed and simulated N_2O emissions from rice fields under continuous flooding (**a**–**d**) and alternate wetting and drying conditions (**e**–**h**) during different rice-growing seasons.

3.4. Cumulative Emissions and Total Global Warming Potential

The average observed and simulated cumulative CH_4 emissions in CF were 73.7 and 69.0 kg C ha^{-1}, respectively, with a relative variation of −6.5% during the summer season and 131.0 and 135.6 kg C ha^{-1} with the variation of 4.2% during the monsoon season (Table 4). The simulated emissions for CF were 6.4% lower in the summer season and 3.5% higher in the monsoon season than the corresponding observed values.

The average observed and simulated cumulative CH_4 emissions in AWD were 38.5 and 35.2 kg C ha^{-1}, respectively, with the variation of −9.3% during the summer season and 99.4 and 87.3 kg C ha^{-1} with the variation of −12.7% during the monsoon season (Table 4). The simulated emissions for AWD were 8.6% and 12.2% lower than the observed ones in the summer and monsoon, respectively. Overall, the DNDC-Rice model reasonably estimated the total CH_4 emission in CF and reproduced the suppressive effect of AWD treatment on CH_4 emission well (Figure 5a).

Table 4. Observed and simulated cumulative emissions and global warming potential (GWP) from rice fields under continuous flooding (CF) and alternate wetting and drying (AWD) conditions during different rice-growing seasons.

		Cumulative Emissions (kg C or N ha^{-1})		GWP (kg CO_2 eq ha^{-1})		
		CH_4	N_2O	CH_4	N_2O	Total GWP
Summer 2016						
CF	Observed	74.2	0.92	3363.7	430.8	3794.6
	Simulated	72.9	0.59	3304.8	276.3	3581.1
Relative variation (%)		−1.8	−35.9			−5.6
AWD	Observed	44.9	1.23	2035.5	576.0	2611.5
	Simulated	42.3	2.57	1917.6	1203.5	3121.1
	Variation (%)	−5.8	108.9			19.5
Monsoon 2016–2017						
CF	Observed	115.3	0.39	5226.9	182.6	5409.6
	Simulated	125.9	0.18	5707.5	84.3	5791.8
Relative variation (%)		9.2	−53.85			7.1
AWD	Observed	89.6	0.78	4061.9	365.3	4427.1
	Simulated	73.9	4.79	3350.1	2243.1	5593.2
Relative variation (%)		−17.5	514.1			26.3
Summer 2017						
CF	Observed	73.2	0.52	3318.4	243.5	3561.9
	Simulated	65.1	0.99	2951.2	463.6	3414.8
Relative variation (%)		−11.1	90.4			−4.1
AWD	Observed	32.1	0.97	1455.2	454.2	1909.4
	Simulated	28.0	5.10	1269.3	2388.3	3657.6
Relative variation (%)		−12.8	425.8			91.6
Monsoon 2017–2018						
CF	Observed	146.6	0.78	6645.9	365.3	7011.1
	Simulated	145.3	0.65	6586.9	304.4	6891.3
Relative variation (%)		−0.9	−16.7			−1.7
AWD	Observed	109.2	1.57	4950.4	735.2	5685.6
	Simulated	100.6	0.84	4560.5	393.4	4953.9
Relative variation (%)		−7.9	−46.5			−12.9

Katayanagi et al. [21] tested the DNDC-Rice model by using the data from The Philippines under CF and AWD conditions. They observed that the simulated emissions for CF and AWD were 9.8% lower and 0.76% higher, respectively, than the observed values. In this study, low variations between the observed and simulation values for CF and AWD indicated that the DNDC-Rice model simulated CH_4 emission well. Thus, the model can be used for the estimation of CH_4 emissions under both water management conditions in the double-cropping paddy rice system in the tropical regions. Previous studies also demonstrated the advantage of using DNDC-Rice for estimating the general effect of midseason drainage or intermittent drainage on CH_4 reduction instead of conducting the corresponding long-term field experiments [6,30].

The averaged observed and simulated cumulative N_2O emissions in CF were 0.72 and 0.79 kg N ha^{-1}, respectively, with the relative variation of 27.3% during the summer and 0.59 and 0.42 kg N ha^{-1} with the relative variation of −35.3% during the monsoon season (Table 4). The simulated emissions for CF were 9.7% higher in the summer and 28.8% lower than the observed value in the monsoon season.

The average observed and simulated cumulative N_2O emissions in AWD were 1.1 and 3.8 kg N ha^{-1}, respectively, with the variation of 267.4% during the summer season and 1.18 and 2.82 kg N ha^{-1} with the variance of 233.8% during the monsoon season (Table 4). The simulated emissions for N_2O were 245.5% and 139.0% higher in the summer and monsoon season, respectively, than the observed values. The result showed that a negative or positive effect of CF and AWD irrigations on

N_2O emissions observed in the measurement was not adequately reproduced by the model (Figure 4). This result was also supported by the correlation analysis (Figure 5b). Katayanagi et al. [21] observed that the simulated N_2O emissions for CF and AWD were 87% and 29% lower, respectively, than the observed values. High range of estimation error value in this study (−35.9% to +514.1%) was comparable to the error values that ranged from −220% to +28.6% [13] and from −66% to +265% [19] and it was hypothesized that these errors were caused by inaccurate estimation of nitrogen release rates from fertilizers, including coated urea.

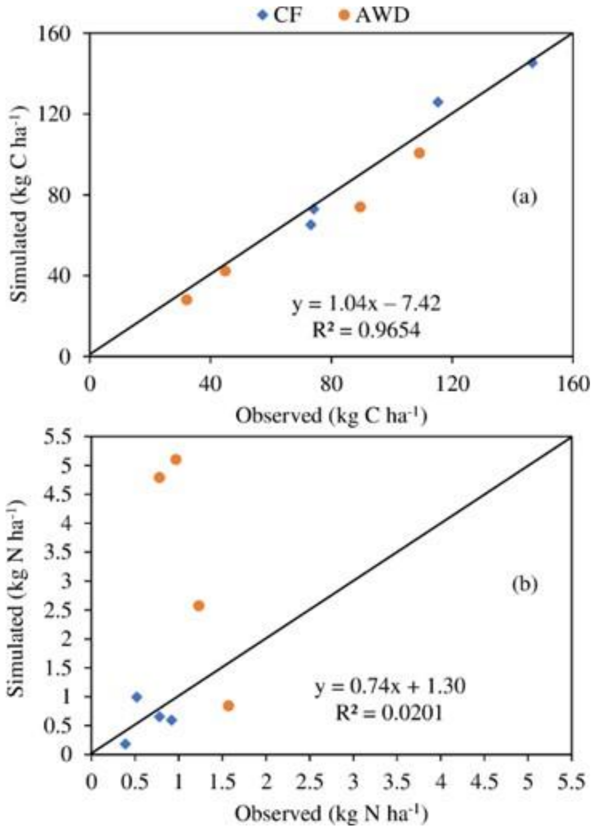

Figure 5. Relationship between observed and simulated cumulative CH_4 (**a**) and N_2O emissions (**b**). CF—Continuous flooding, AWD—Alternate wetting and drying.

The average observed and simulated total GWP in CF were 3678 and 3498 kg CO_2 eq ha^{-1} in the summer season and 6210 and 6342 kg CO_2 eq ha^{-1} in the monsoon season, respectively (Table 4). The simulated emissions for CF were 4.9% lower in the summer season and 2.1% higher than the observed values in the monsoon season. The average observed and simulated total GWP in AWD were 2260 and 3389 kg CO_2 eq ha^{-1}, respectively, in the summer season and 5056 and 5274 kg CO_2 eq ha^{-1} in the monsoon season (Table 4). The simulated emissions for total GWP were 49.9% and 4.3% higher than the observed values in the summer and monsoon season, respectively.

Generally, the simulated results of the GWP for different rice-growing seasons indicated that the model predicted the suppressive effect of AWD irrigation well (Table 4). However, a high estimation error of total GWP in both summer seasons and the monsoon season from 2016–2017 was due to the overestimation of N_2O emissions after additional nitrogen fertilization by the model under high soil redox values due to AWD irrigation. Therefore, the DNDC-Rice model will require further improvements to reasonably estimate N_2O emission from paddy rice soil under water-saving irrigation. However, in terms of GWP, the contribution of N_2O to total GWP was considerably smaller than that of CH_4 in both irrigation practices under observed field conditions and also in the simulated results in most of the rice-growing seasons. Katayanagi et al. [21] discussed that due to the smaller contribution of N_2O to the GWP compared with that of CH_4, it is less important to modify the model to account for N_2O emission from paddy rice fields for estimation of total GWP.

4. Conclusions

This study is the first attempt for field validation of the DNDC-Rice model by using the observed CH_4 and N_2O emissions data from double-cropping paddy rice under continuous flooding and water-saving irrigation in Tamil Nadu, India. The model predicted cumulative CH_4 emissions and total GWP for CF and AWD treatments for all rice-growing seasons well. However, there were some discrepancies between observed and simulated daily CH_4 fluxes at the beginning of the growing season, indicating that the model was less successful in predicting seasonal pattern of emissions during the rice-growing season. Due to high fluctuation in the soil Eh value during the drying period of AWD irrigation, the model needs to be improved for calculation of soil Eh in response to soil aeration, though soil Eh does not directly influence CH_4 emissions in simulation by this model. Moreover, further modification of the nitrification and denitrification rates under AWD irrigation will be needed for reasonable prediction of N_2O emissions from double-cropping paddy rice under frequent soil aeration in tropical rice production.

Author Contributions: Conceive and design the experiments: A.Z.O., S.S., K.I., K.O., A.Y., C.U., K.V., P.E., V.R., and V.A. Perform the experiments: A.Z.O., S.S., C.U., K.V., and P.E. Analyze the data: A.Z.O., K.T.W., S.S., and T.F. Supervision: S.S., K.I., V.R. Write the paper: A.Z.O., S.S., and T.F. Review the paper: S.D.B.-K., K.T.W., K.S.B., and M.R. All authors have read and agreed to the published version of the manuscript.

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References

1. IPCC (Intergovernmental Panel on Climate Change). *Climate Change 2013: The Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013; 1535p. [CrossRef]
2. Xu, Y.; Ge, J.; Tian, S.; Li, S.; Nguy-Robertson, A.L.; Zhan, M.; Cao, C. Effects of water-saving irrigation practices and drought resistant rice variety on greenhouse gas emissions from a no-till paddy in the central lowlands of China. *Sci. Total Environ.* **2015**, *505*, 1043. [CrossRef] [PubMed]
3. Oo, A.Z.; Sudo, S.; Inubushi, K.; Mano, M.; Yamamoto, A.; Ono, K.; Osawa, T.; Hayashida, S.; Patra, P.K.; Terao, Y.; et al. Methane and nitrous oxide emissions from conventional and modified rice cultivation systems in South India. *Agric. Ecosyst. Environ.* **2018**, *252*, 148–158. [CrossRef]
4. Kruger, M.; Frenzel, P.; Conrad, R. Microbial processes influencing methane emission from rice fields. *Global Chang. Biol.* **2001**, *7*, 49–63. [CrossRef]
5. Itoh, M.; Sudo, S.; Mori, S.; Saito, H.; Yoshida, T.; Shiratori, Y.; Suga, S.; Yoshikawa, N.; Suzue, Y.; Mizukami, H.; et al. Mitigation of methane emissions from paddy fields by prolonging midseason drainage. *Agric. Ecosyst. Environ.* **2011**, *141*, 359–372. [CrossRef]
6. Minamikawa, K.; Fumoto, T.; Itoh, M.; Hayano, M.; Sudo, S.; Yagi, K. Potential of prolonged midseason drainage for reducing methane emission from rice paddies in Japan: A long-term simulation using the DNDC-Rice model. *Biol. Fertil. Soils.* **2014**, *50*, 879–889. [CrossRef]
7. Setyanto, P.; Pramono, A.; Adriany, T.A.; Susilawati, H.L.; Tokida, T.; Agnes, T.; Padre, A.T.; Minamikawa, K. Alternate wetting and drying reduces methane emission from a rice paddy in Central Java, Indonesia without yield loss. *Soil Sci. Plant Nutr.* **2018**, *1*, 23–30. [CrossRef]

8. Win, E.P.; Win, K.K.; Kimura, S.D.; Oo, A.Z. Greenhouse gas emissions, grain yield and water productivity: a paddy rice field case study based in Myanmar. *Greenh. Gas Sci. Technol.* **2020**. [CrossRef]
9. Oo, A.Z.; Sudo, S.; Inubushi, K.; Chellappan, U.; Yamamoto, A.; Ono, K.; Mano, M.; Hayashida, S.; Koothan, V.; Osawa, T.; et al. Mitigation Potential and Yield-Scaled Global Warming Potential of Early-Season Drainage from a Rice Paddy in Tamil Nadu, India. *Agronomy* **2018**, *8*, 202. [CrossRef]
10. Peyron, M.; Bertora, C.; Pelissetti, S.; Said-Pullicino, D.; Celi, L.; Miniotti, E.; Romani, M.; Sacco, D. Greenhouse gas emissions as affected by different water management practices in temperate rice paddies. *Agric. Ecosyst. Environ.* **2016**, *232*, 17–28. [CrossRef]
11. Zou, J.; Huang, Y.; Zheng, X.; Wang, Y. Quantifying direct N_2O emissions in paddy fields during rice growing season in mainland China: Dependence on water regime. *Atmos. Environ.* **2007**, *41*, 8032–8042. [CrossRef]
12. Wang, J.; Jia, J.; Xiong, Z.; Khalil, M.A.K.; Xing, G. Water regime-nitrogen fertilizer-straw incorporation interaction: Field study on nitrous oxide emissions from a rice agroecosystem in Nanjing, China. *Agric. Ecosyst. Environ.* **2011**, *141*, 437–446. [CrossRef]
13. Babu, Y.J.; Li, C.; Frolking, S.; Nayak, D.R.; Adhya, T.K. Field validation of DNDC model for methane and nitrous oxide emissions from rice-based production systems of India. *Nutr. Cycl. Agroecosyst.* **2006**, *74*, 157–174. [CrossRef]
14. Li, C. Modeling trace gas emissions from agricultural ecosystems. *Nutr. Cycl. Agroecosyst.* **2000**, *58*, 259–276. [CrossRef]
15. Li, C.; Aber, J.; Stange, F.; Butterbach-Bhal, K.; Papen, H. A process-oriented model of N2O and NO emissions from forest soils: Model development. *J. Geophys. Res.* **2000**, *105*, 4369–4384. [CrossRef]
16. Li, C.; Frolking, S.; Harriss, R. Modeling carbon biogeochemistry in agricultural soils. *Glob. Biogeochem. Cycles* **1994**, *8*, 237–254. [CrossRef]
17. Fumoto, T.; Kobayashi, K.; Li, C.; Yagi, K.; Hasegawa, T. Revising a process-based biogeochemistry model DNDC to simulate methane emission from paddy fields under various residue managements. *Glob. Chang. Biol.* **2008**, *14*, 382–402. [CrossRef]
18. Smakgahn, K.; Fumoto, T.; Yagi, K. Validation of revised DNDC model for methane emissions from irrigated rice fields in Thailand and sensitivity analysis of key factors. *J. Geophys. Res.-Biogeosci.* **2009**, *114*, G02017. [CrossRef]
19. Fumoto, T.; Yanagihara, T.; Saito, T.; Yagi, K. Assessment of the methane mitigation potentials of alternative water regimes in rice fields using a process-based biogeochemistry model. *Glob. Chang. Biol.* **2010**, *16*, 1847–1859. [CrossRef]
20. Minamikawa, K.; Fumoto, T.; Iizumi, T.; Cha-un, N.; Pimple, U.; Nishimori, M.; Ishigooka, Y.; Kuwagata, T. Prediction of future methane emission from irrigated rice paddies in central Thailand under different water management practices. *Sci. Total Environ.* **2016**, *566–567*, 641–651. [CrossRef]
21. Katayanagi, N.; Furukawa, Y.; Fumoto, T.; Hosen, Y. Validation of the DNDC-Rice model by using CH_4 and N_2O flux data from rice cultivated in pots under alternate wetting and drying irrigation management. *Soil Sci. Plant Nutr.* **2012**, *58*, 360–372. [CrossRef]
22. Inubushi, K.; Takeuchi, D.; Mano, M.; Sudo, S.; Oo, A.Z.; Ono, K.; Yamamoto, A.; Hayashida, S.; Ravi, V. Greenhouse-gasses emission and their influencing factors in paddy fields in South India. *Res. Trop. Agric.* **2017**, *10*, 15. (In Japanese)
23. Penning de Vries, F.W.T.; Jansen, D.M.; Ten Berge, H.F.M.; Bakema, A. *Simulation of Ecophysiological Processes of Growth in Several Annual Crops*; Pudoc: Wageningen, The Netherlands; IRRI: Los Baños, Philippines, 1989; 271p.
24. Farquhar, G.; Von Caemmerer, S. Modelling of photosynthetic response to environmental conditions. In *Physiological Plant Ecology II*; Lange, O.L., Nobel, P.S., Osmond, C.B., Ziegler, H., Eds.; Springer: Berlin/Heidelberg, Germany, 1982; pp. 549–587.
25. Kato, Y.; Okami, M. Root growth dynamics and stomatal behavior of rice (*Oryza sativa* L.) grown under aerobic and flooded conditions. *Field Crops Res.* **2010**, *117*, 9–17. [CrossRef]
26. Sun, H.; Zhou, S.; Fu, Z.; Chen, G.; Zou, G.; Song, X. A two-year field measurement of methane and nitrous oxide fluxes from rice paddies under contrasting climate conditions. *Sci. Rep.* **2016**, *6*, 28255. [CrossRef] [PubMed]
27. Oo, A.Z.; Nguyen, L.; Win, K.T.; Cadisch, G.; Bellingrath-Kimura, S.D. Toposequential variation in methane emissions from double-cropping paddy rice in Northwest Vietnam. *Geoderma* **2013**, *209–210*, 41–49. [CrossRef]

28. Ussiri, D.; Lal, R. Nitrous oxide emissions from rice fields. In *Soil Emission of Nitrous Oxide and Its Mitigation*; Ussiri, D., Lal, R., Eds.; Springer: Cham, The Netherlands, 2013; pp. 213–242.
29. Davidson, E.A.; Keller, M.; Erickson, H.E.; Verchot, L.V.; Veldkamp, E. Testing a conceptual model of soil emissions of nitrous and nitric oxides: Using two functions based on soil nitrogen availability and soil water content, the hole-in-the-pipe model characterizes a large fraction of the observed variation of nitric oxide and nitrous oxide emissions from soils. *Bioscience* **2000**, *50*, 667–680.
30. Katayanagi, N.; Fumoto, Y.; Hayano, M.; Shirato, Y.; Takata, Y.; Leon, A.; Yagi, K. Estimation of total CH_4 emission from Japanese rice paddies using a new estimation method based on the DNDC-Rice simulation model. *Sci. Total Environ.* **2017**, *601–602*, 346–355. [CrossRef]