

Mitigation Potential of Nitrous Oxide Emissions from Irrigated Rice Fields by the DNDC-Rice Model

Kruamas Smakgahn

Abstract—The DNDC-Rice model was used to obtain mitigation potential of N₂O emission from flooded rice fields under various water management regimes in central Thailand. The alternative water management (midseason drainage, multiple drainage, and local method) emitted approximately 61% of N₂O emissions higher than conventional water management (continuously flooded). The short drainage period (local method) emitted the lowest emission compared to other treatments. There was no difference in crop carbon, harvest part, shoot and root portion among 4 treatments. Also, the efficiency of nitrogen uptake by the crop of all treatments was not different. The continuously flooded and short drainage period is an interesting candidate for mitigating N₂O emissions from irrigated rice cultivation. However, multiple drainages are a remarkable effective practice to reduce greenhouse gases (CH₄ and N₂O) emissions from the rice field.

Index Terms—Alternative water regime, field drainage, greenhouse gas, nitrous oxide, mitigation.

I. INTRODUCTION

Nitrous oxide (N₂O) contributes to the global warming of the atmosphere because it traps part of the thermal radiation from the earth's surface. On a per molecule basis, nitrous oxide is 310 times more potent than carbon dioxide [1]. Nitrous oxide is produced in the soil through nitrification and denitrification processes. Bacterial and chemical denitrification processes affect nitrate (NO₃⁻) and nitrite (NO₂⁻) under strictly anaerobic conditions. The nitrification process is the biological oxidation of ammonium (NH₄⁺) resulting in nitrite or nitrate, which is then reduced to N₂O and nitrogen gas through denitrification. Denitrification is an anaerobic process where nitrate is reduced to N₂ via NO and N₂O. NO, and N₂O are emitted if denitrification is incomplete. NO₃⁻, NO, and N₂O act as electron acceptors when there is not enough oxygen. Denitrification is a function of oxygen supply, carbon availability, temperature, pH, water content and concentration of NO₃⁻, NO and N₂O. High concentrations of available organic carbon, pH between 6 and 8, temperature above 10 °C and water content of more than 80% support denitrification [2]. In addition, N₂O is produced from the nitrifier denitrification process, the pathway of nitrification. In this process, the oxidation of NH₃ to NO₂⁻ is followed by the reduction of NO₂⁻ to N₂O.

In rice fields, N₂O emissions mainly occurred during non-flooding/fallow periods [3] or drainage period [4], [5], when the soil exposed the air a very long time [6]. High N₂O

emission was observed from intermittent irrigation [5], [7]. N₂O emissions derived from agriculture are > 75% of anthropogenic sources, but the prediction of N₂O emissions is not yet reliable. If some combination of agricultural management practices, such as matching N supply with crop demand, tightening N flow cycles, using advanced fertilization techniques and optimizing tillage irrigation and drainage were adopted, the emission could decrease by almost 20% [8].

The objective of this study is to obtain the mitigation potential of N₂O emission under various water management regimes by the DNDC-Rice model.

II. MATERIALS AND METHODS

DNDC-Rice model [9] was validated for N₂O emissions against field observations data in 2002 from irrigated rice field at Samutsakorn province in the central plain of Thailand (see [5] for details of field observation). This field experiment was investigated with four different water management under the same cultivar type and soil properties in the wet season. Four different field drainage regimes were conducted: the local method (LM), continuous flooding (CF), mid-season drainage (MSD) and multiple aerations or multiple drainages (MTD). LM treatment in this area consists of flooding with flexible short drainage during a growing period. MSD treatment was conducted at 64 days after planting (flowering stage) for 6 days. MTD consisted of two intermittent drainage periods of three days duration conducted at 21 days and 64 days after initial flooding. The final drainage was applied for all treatment at 15 days before harvesting. This field experiment was planted after rice straw from the previous growing season was burned therefore rice was planted without rice straw incorporation. The AP fertilizer was applied at 20 days after planting as the basal fertilizer (25 kg N ha⁻¹). Nitrogen as urea fertilizer was applied as the top dressing fertilizer at 29 days after planting (DAP). The AP fertilizer was applied again at 47 DAP as the top-dressing fertilizer. The photoperiod insensitive non-jasmine rice cultivar Suphanburi1 (Sp1) was used. Wet seeding with 187.5 kg ha⁻¹ was applied on August 12, 2002. The fields were flooded 7 DAP and the water level in each field was controlled (5-10 cm), except for during drainage periods. Rice soil in this field experiment was Bangkok (Bk) soil series and the soil was classified as *Typic Tropaquepts*. This soil contained 1.31% of organic carbon and 0.06 % nitrogen content under an initial soil pH of 6.10. Soil texture was classified as clay with a percentage composition of sand: silt: clay of 22: 24: 54 (Table I). (see [5] for the characteristic of the agriculture management).

Manuscript received August 13, 2019; revised January 8, 2020.

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The database component for the regional mode of DNDC-Rice model simulation contained daily weather data in the planted year for all cases. Soil properties (Land development department), farming practices (such as fertilizer application, planting data, tillage data), and water management in study area derived from governmental agencies were used for simulations. The fraction of the above-ground litter or crop residue returned to the field after harvest was assumed to 25 %. The water leaking problem has been defined as moderate ($2\text{--}10\text{ mm day}^{-1}$). Default of the model has been applied if lack of information from field observations included climate data (N concentration in rainfall, atmospheric background of NH_3 and CO_2 concentration), soil data (soil wilting point, field capacity, soil bypass flow, initial soil NO_3^- , NH_4^+ concentration), crop data (initial photosynthesis efficiency, maximum photosynthesis rate, development rate in vegetative stage, development rate in reproductive stage).

The essential data input for the DNDC-rice model is that the reduction of electron acceptors such as Fe^{3+} , Mn^{4+} , and SO_4^{2-} affects the CH_4 production rate. Hence, the DNDC-rice model requires data on soil concentrations of Fe^{3+} , Mn^{4+} , and SO_4^{2-} as input parameters. These data were derived from previous field observations in Thailand. The manure amendment information was not concerned in this study because no organic amendment and manure as organic fertilizer were applied before or during the growing season. In addition, weeding and grazing information were not concerned with the simulations.

TABLE I: SOIL PROPERTY IN THE STUDY SITE [5]

Soil property	Unit	
pH		6.1
Organic matter	%	2.3
Organic carbon	%	1.31
Nitrogen (N)	%	0.06
Potassium (K)	ppm	800
Phosphorus (P)	ppm	7
Magnesium (Mg)	ppm	504
$\text{NH}_4^+\text{-N}$ (ppm N)	ppm N	19.6

III. RESULTS AND DISCUSSION

A. Total Nitrous Oxide Emissions

Total seasonal N_2O emissions estimated by the DNDC-Rice model were underestimated compared with field observation in most cases. Lowest seasonal N_2O emissions were observed from the local method (0.033 g ha^{-1}) and the highest emission was observed from the midseason drainage treatment (0.051 g ha^{-1}). Multiple drainages emitted almost equal N_2O emission from continuously flooded; 0.037 and 0.038 g ha^{-1} , respectively. Validated N_2O emission by the DNDC-Rice model shown more than 50% underestimation compared to field observation data in all cases. But the lowest emission derived from continuously flooded and about 10 times lower than higher than alternative water management. The multiple drainage treatment and the local method emitted almost the same level as midseason drainage but the midseason drainage treatment emitted $\sim 30\%$ higher than from the local method. While the multiple drainages and continuously flooded treatments emitted almost the same

level and $\sim 10\%$ higher than the local method (Fig. 1).

B. Seasonal Pattern of Nitrous Oxide Emissions

The results from the DNDC-Rice model validation agree with field observations, that N_2O emission from the drainage treatments (midseason drainages and multiple drainages) were high. Validated data and field measurements indicated that midseason drainage and multiple drainages can be used to predict N_2O flux patterns. The low amount of N_2O emitted during the flooding period but it began increasing gradually during the drainage period and then decreased when the fields were re-flooded (Fig. 2). However, the simulation data by the DNDC-Rice model showed that the model could not predict all pulses of N_2O including the presented timing of pulses. The results of this study coincide with the research of [4] that the high N_2O pulses both timing and magnitude could not be predicted by the model. The reason for underprediction may cause of the inaccuracy of rice growth. The higher simulated rice growth showed that the nitrogen in the soil was used by the plant and fewer nitrogen contents remain for microbial activity in soil [4]. Even though the observation data presented N_2O emissions but the model cannot predict. These are because the flooded condition does not induce the nitrification process and less NO_3^- for denitrification under flooded conditions [4].

The overall results of emissions prediction consisted of other research that zero N_2O emissions were simulated by the DNDC model under continuously flooded rice fields [10], low N_2O fluxes that were observed [5] during permanent flooding, were probably due to the reduction of N_2O to N_2 under low soil Eh [11], [12] and also due to less availability of NO_3^- for denitrification [13].

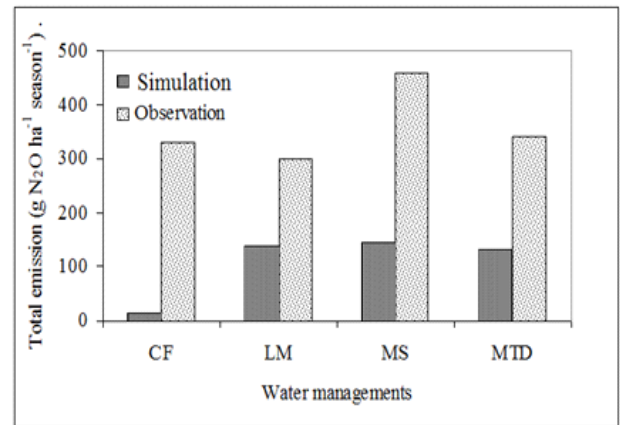


Fig. 1. Nitrous oxide emissions from field observations and the DNDC-Rice model Validated under different water management regimes.

The results from measurements at Samutsakorn experiment and predictions by the DNDC-Rice model were in agreement with previous research, suggesting that N_2O emissions mainly occurred during non-flooding periods or fallow periods [14] and no emission of N_2O was detected in the rice paddy field under anaerobic conditions [7]. Emissions of N_2O were influenced by water content and soil Eh [15], [16] and the peak of N_2O in paddy soils during midseason aeration could be attributed to the occurrence of optimum soil moisture under sufficient N availability, favorable for the production and accumulation of N_2O [14]. The use of nitrification inhibitor under wet irrigation reduced

N_2O emission [17]. Subsequent delayed flooding or intermittent irrigation can contribute to significantly reduce the global warming potential of rice cropping systems concerning continuous flooding [18], [19].

In general, draining the rice fields may create a suitable O_2 availability in the soil for N_2O production as an intermediate product in either nitrification or denitrification. While maintaining flooded conditions may create strict anaerobic conditions and restrict N_2O formation and emission [14]. In the case of multiple drainages (despite two short drainage times (3 days) being employed), the N_2O emissions were lower than in the midseason drainage treatment with a one-time drainage of 6 days. Shorter drainage time might not be sufficient for N_2O to develop. Therefore, multiple drainages showed lower N_2O emissions compared to midseason drainage. In contrast, the long draining period (6 days) lead to lower CH_4 emissions compared to the 3-days draining period.

Field observation data from South India reported that the alternate wetting and drying irrigation-induced N_2O emissions [20], and field observation in Vietnam also reported that multiple aerations increased N_2O emissions by 1.5% [21]. The intermittent irrigation increases N_2O emission by 23.72% respected continuously flood [22]. Even though continuously flooded trends to reduce N_2O emission compared to alternative water management but it promoted anaerobic conditions suitable for CH_4 emission [5], [23]. The intermittent irrigation reduced total seasonal CH_4 emission by 24.22% compared to continuously flooded [22]. Modeling tests agree with previous research that trade-off daily N_2O flux and daily CH_4 flux occurred in rice fields (Fig. 3) and indicate that field drainage induced N_2O fluxes.

The result concluded that multiple drainages (two intermittent drainage periods of three days duration) in the flooded rice field is an interesting option for N_2O mitigation. In addition, multiple drainages is a remarkable effective practice to reduce greenhouse gases (CH_4 and N_2O) emissions from the rice field.

C. Rice Growth and Yield

Simulated rice grain yield or harvest part by DNDC-Rice model from continuously flooded, local method, and mid-season drainage were almost similar, but the multiple drainage treatment reduced approximately 1% compared to others (Table II). However, a field experiment in Thailand at Samutsakorn province [5] reported rice yield under midseason drainage and multiple drainages were reduced by 6.86 to 11.43%, respective concerning conventional water management. Multiple drainages decreased panicle number but the DNDC-Rice model calculates just the tiller number but not panicle number, which is importance parameter for grain yield calculation. Thus, rice grain yield calculation may not be accurate.

Furthermore, the model does not calculate photosynthesis in the vegetative period to the panicle period but just calculates only for tiller number but photosynthesis does not limit by the panicle or tiller number, therefore, the model unable to predict rice grain yield from drainage treatments, especially for multiple drainages. The observation data [5] reported shoot and root dry weight from 4 treatments were

not significantly different. However, multiple drainages reduced of 3.52% of shoot dry weight compared to continuously flooded, while, mid-season drainage induced of 3.35% of shoot dry weight over continuously flooded.

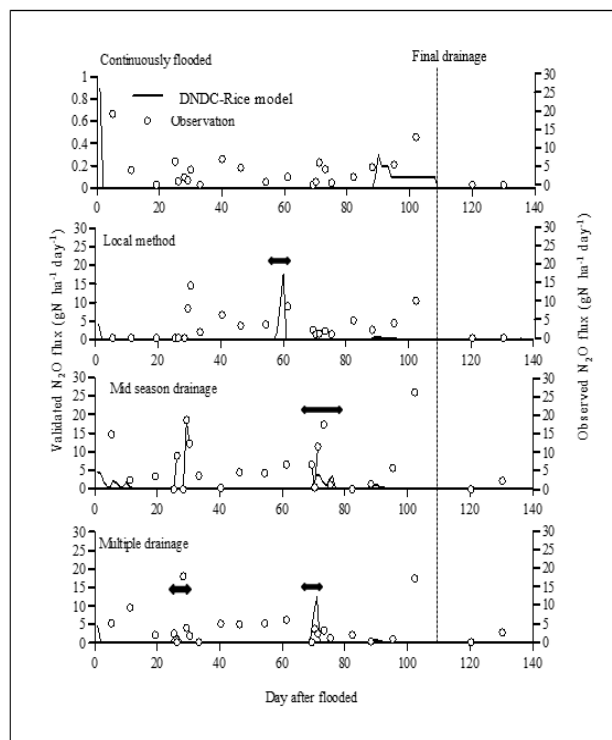


Fig. 2. Comparison of observed daily nitrous oxide fluxes and simulated by the DNDC-Rice model under different water management regimes at Samutsakorn rice field. (Dark two-way arrow indicated drainage duration).

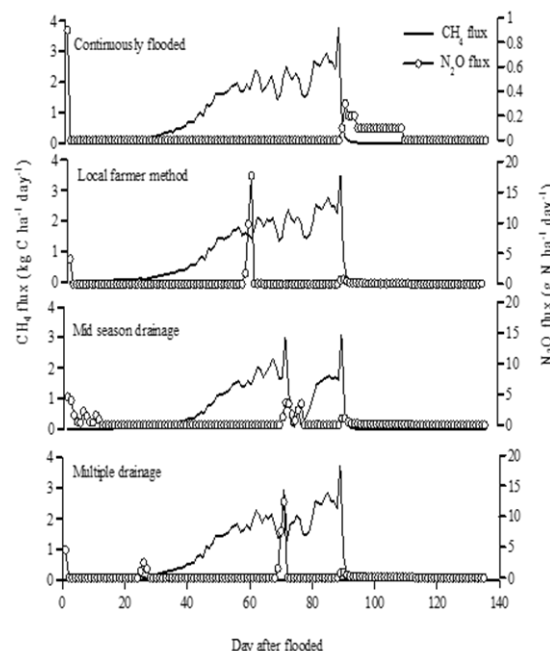


Fig. 3. Simulated seasonal variation of nitrous oxide and methane emission from Samutsakorn rice field under different water management regimes.

The DNDC-Rice model agreed with field observation that multiple drainages reduced shoot weight but only 0.2% respect to continuously flooded. While mid-season drainage induced shoot weight of 0.2% higher than continuously flooded. The root weight was increased by 0.40% over the continuously flooded by model simulation but increased by more than 11% when obtained from field observed. And the

observation data reported multiple drainage management increased root weight but the model simulation showed the opposite result. However, the model simulation data was not shown the large difference in shoots and root portion among four treatments.

TABLE II: SIMULATED VALUE OF CROP CARBON, HARVEST PART, SHOOT, ROOT WEIGHT, N UPTAKE BY CROP, AND OBSERVED VALUE OF GRAIN YIELD

Parameters	YIELD			
	CF	LM	MS	MTD
Crop C (kg C ha ⁻¹)	2,259	2,267	2,265	2,253
Harvest part (kg C ha ⁻¹)	791	793	793	789
Shoot (kg C ha ⁻¹)	971	975	974	969
Root (kg C ha ⁻¹)	497	499	498	496
N uptake by crop (kg N ha ⁻¹)	160.6	162.18	162.39	160.38
Observed grain yield (kg ha ⁻¹) [5]	4,350	4,375	4,075	3,875

Remarks: CF: continuously flooded, LM: local method, MS: midseason drainage, MTD: multiple drainages.

Simulated N uptake by crop among four treatments were not large differences, and it is related to the weight and root weight of plants (Table II). The multiple drainages reduced 0.14% of N uptake by crop compared to continuously flood but the local method and mid-season drainage induced 0.98% and 1.11% over continuously flooded, respectively. The higher simulated rice growth from local method and mid-season drainage results in higher nitrogen uptake by the plants [4].

D. Global Warming Potential

This study calculated the GWP values of N₂O and CH₄ emissions from the simulated results compare to the observation data. The N₂O emissions (kg N ha⁻¹) and CH₄ were converted to the equivalent CO₂ emission (kg CO₂ eq ha⁻¹) by multiplying these values by 21 and 310, then considering the GWPs for a 100 year time horizon [24]. The GWP of simulated N₂O and the observation is shown in Table III.

TABLE III: GLOBAL WARMING POTENTIAL

Treatments	Observed value [5]			Simulated value		
	CH ₄	N ₂ O	N ₂ O/ Total (%)	CH ₄	N ₂ O	N ₂ O/ Total (%)
CF	5,115.59	115.16	2.20	6,972	15.5	0.22
LM	5,030.54	102.43	1.99	6,846	18.6	0.27
MS	3,646.12	159.28	4.19	6,090	15.5	0.25
MTD	3,292.49	119.30	3.50	6,888	18.6	0.27

Remarks: CF: continuously flooded, LM: local method, MS: midseason drainage, MTD: multiple drainages.

The simulated net global warming potentials (GWPs) were higher than that of the observation data but not large differences among the four treatments. While net GWPs from field observations were large differences between conventional (continuously flooded and local method) and alternatives water management (Mid-season drainage and multiple drainages). The observed GWP of N₂O was about 1.99-4.19% of the total, but the simulated value was only 0.22-0.27% of total GWPs. The highest GWP of N₂O was observed from mid-season drainage, however, the highest

predicted value derived from the local method and multiple drainages. The GWP of N₂O under mid-season drainage from field observation increased by 90.45% compared to continuously flood but increased only by 13.63% when predicted by the model. Therefore, model modification of the process of nitrification and denitrification of the model simulation is required to more accuracy of calculation of N₂O emission.

IV. CONCLUSION

The data prediction by the DNDC-Rice model was agreed with field observations that N₂O emissions from alternative water management regimes were higher than continuously flooded (conventional water management regime). Alternative water management induced ~60% of N₂O emissions compared to conventional water management regimes. The results from field observed and the DNDC-Rice model simulation was in agreement with previous research, suggesting that N₂O emissions mainly occurred during non-flooding periods or drainage period. Therefore, water management in a rice field during the growing period played an important role in N₂O emissions under the same soil condition. The outcomes of this study suggest that controlled water supplied in flooded rice soil as continuously flooded conditions and short wet-dry conditions are a reasonable way to mitigate N₂O emission from irrigated rice fields. The result also suggested that the modifications of the DNDC-Rice model's feature of N₂O calculation in case of drainage management, the feature of photosynthesis, panicle number, and grain yield prediction are required to obtained better prediction accuracy of N₂O emission and grain yield.

CONFLICT OF INTEREST

"The author declares no conflict of interest".

AUTHOR CONTRIBUTIONS

K. Smakgahn conducted the research, analyzed the data, prepared the manuscript and approved the final version.

ACKNOWLEDGMENT

Thank you, Dr. Kazuyuki Yagi and Dr. Tamon Fumoto National Institute for Agro-Environmental Sciences, 3-1-3 Kannondai Road, Tsukuba, Ibaraki 305-8604, Japan for their kind suggestions and the DNDC-Rice model. Thanks, Dr. Chitnucha Buddhagoon (IRRI Thailand) for his kind suggestions on rice crop data for simulation.

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