



Research article

Applying DeNitrification-DeComposition model to investigate methane emission processes through nitrogen path in paddy field soil, Lampung Province, Indonesia

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Article Info

Article history:

Received 12 September 2025

Revised 25 April 2026

Accepted 2 May 2026

Available online 15 July 2026

Keywords:

DeNitrification-DeComposition (DNDC) model,
Emission,
Fertilizer,
Methane,
Paddy

Abstract

Importance of the work: Alternative methods are required for fertilizer application recommendations and irrigation schemes in paddy cultivation to mitigate CH₄ emission.

Objectives: To investigate whether CH₄ emission and its processes from the field are related to fertilizer dose and irrigation scheme.

Materials and Methods: Three doses of N fertilizer recommendations (no fertilizer, 50 kg N/ha and 100 kg of N/ha) were applied to continuous flooding and intermittent irrigation schemes in paddy fields. CH₄ flux was measured using a static closed-chamber and simulated using the DeNitrification-DeComposition (DNDC) model to investigate the processes of emissions in the soil.

Results: Soil organic carbon decreased quickly with continuous flooding at all fertilizer doses. Total N and soil organic carbon were higher in the N fertilizer application than without N. The C-to-N ratio was in the range 18–26; the mineralization rate was 0.024–0.0245 kg C/kg soil in the topsoil and the NH₄⁺ level was 16.5 parts per million (ppm). The maximum oxygen content was 10 ppm, while the soil Eh reached –300 mV. Methane emission was higher in the submerged fields. Fertilizers did not affect the amount of either methanogens or methanotrophs. Methanogens had a strong correlation to methane emission (correlation coefficient, $r = 0.7–0.8$) in all nitrogen doses under submerged soil and a weak correlation under the intermittent flooding treatment ($r = 0.48–0.71$). The DNDC methane emission simulation was lower than the observed values.

Main findings: Methane emissions from continuous flooding were 0.797–1.048 kg C/ha/d, which were higher than with intermittent irrigation (0.03–0.401 kg C/ha/d). Model simulations and crop growth showed that intermittent irrigation was effective in paddy cultivation for mitigating methane emissions.

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<https://doi.org/10.34044/j.anres.2026.60.4.03>

Introduction

Rice is one of the world's most important staple crops, but paddy cultivation is also a major source of methane (CH_4) emissions (Saha et al., 2022). CH_4 emissions from paddy fields arise due to the anaerobic decomposition of organic matter in submerged soil, with the CH_4 escaping to the atmosphere mainly via diffusive transport through the paddy, accounting for an average of 53% of total global methane (CH_4) emissions (Intergovernmental Panel on Climate Change, 1995; Rosentreter et al., 2021).

Methane (CH_4) is an important greenhouse gas. Although its atmospheric concentration is much lower than that of carbon dioxide (CO_2), CH_4 has a much higher global warming potential per unit mass (Shaidatul et al., 2018). Atmospheric methane concentration rose from about 700 parts per billion (ppb) in 1850 to 1,808 ppb in 2010, representing a 158% increase since the beginning of the industrialization period (Javadinejad et al., 2019).

Methane emissions have been studied in many countries. Previous studies reported that continuous flooding, swine manure application, and straw incorporation can increase CH_4 emissions from paddy fields (Nguyen et al., 2015; Islam et al. 2019; Jiang et al., 2019). In contrast, improved water management, such as continuous sub-irrigation with municipal wastewater, has been shown to maintain rice yield while simultaneously reducing CH_4 emissions from paddy fields (Ariani et al., 2021). Methane concentration in the atmosphere also shows a seasonal pattern related to vegetation cover, with greater vegetation cover reduces methane emissions (Javadinejad et al., 2019). In addition, cultivar selection has been suggested as a potential strategy for reducing methane emissions from rice cultivation (Gutierrez et al., 2013).

Methane emissions from paddy fields have been investigated in Indonesia, including studies on irrigation regimes, fertilizer application, rice varieties, pesticide application, mitigation strategies and methanotrophic bacteria (Nugroho et al., 1994; Setyanto et al., 2018; Najamudin, 2014; Nonci et al., 2015; Ariasandi et al., 2018; Manik et al., 2018). However, methane emission from paddy fields is a complex process, and field-based measurements often cover only limited spatial and temporal scales, which may not adequately represent the heterogeneity of paddy field ecosystems (Nguyen et al., 2015; Sibayan et al., 2018). Therefore, the current study used weather data, soil characteristics and cultivation methods data to model methane emission from paddy fields under different fertilizer

recommendations and irrigation schemes.

The model was applied to investigate methane emissions under different fertilizer recommendations and irrigation schemes, with emphasis on the role of fertilizer application and water management in Indonesian paddy fields.

Previous studies have shown that fertilizer application and water management strongly influence CH_4 emissions from rice fields. For example, midseason drainage and alternate wetting and drying (AWD) can reduce CH_4 emissions, whereas organic manure application may increase emissions (Li et al., 2002; Zou et al., 2005; Nguyen et al., 2015; Fazli et al., 2016; Sibayan et al., 2018). However, methane emissions vary substantially with location, season and environmental conditions, including water depth, soil organic matter, soil pH and other biotic or abiotic factors (Babu et al., 2006; Ariani et al., 2021). Field measurements commonly used a closed static chamber (Nguyen et al., 2015; Chidthaisong et al., 2018; Sibayan et al., 2018), which covers only a small part of a rice field and may not fully represent the spatial heterogeneity of paddy fields.

Therefore, process-based models are useful for upscaling field measurements and assessing methane emission dynamics under different management practices. The DeNitrification-DeComposition (DNDC) model (University of New Hampshire, 2012; <https://www.dndc.sr.unh.edu/model/GuideDNDC95.pdf>) predicts gas emissions from agricultural ecosystems by linking ecological drivers, soil environmental variables and biogeochemical processes. The DNDC-Rice model has been used to estimate CH_4 emissions from paddy fields under continuous flooding and AWD conditions, with satisfactory agreement with field observations in several studies (Babu et al., 2006; Katayanagi et al., 2012; Oo et al., 2020).

Therefore, the objectives of the current study were to assess: 1) the effects of fertilizer dose and water management on CH_4 emissions from paddy fields; 2) the reliability of the DNDC-Rice model in predicting CH_4 emissions under different irrigation schemes and fertilizer regimes; and 3) methane emission processes in soil using the DNDC model.

Materials and Methods

Experimental site

The field experiment was conducted during the rice-growing season from October 2021 to March 2022 on farmers' rice fields in North Rawa Jitu District, Mesuji Regency

(4.15°N, 105.63°E), Lampung Province, Indonesia. The site is characterized by a tropical humid climate, generally humid and wet, although there are months when there is low rainfall (Table 1). From soil laboratory analysis, the field texture was dominated with sand (45.2%) and clay (42.8%), the pH was 6.96, soil water retention ranged from 30.78% (field capacity) to 9.26% (wilting point), nitrogen (N-total) was 0.26%, C organic was 2.42% and potassium (K₂O) was 3.58 mg/100 g, as shown in Table 2.

Table 1 Climate characteristics

Parameter	2021	2022
Maximum temperature (°C)	28.75–30.25	28.59–29.94
Minimum temperature (°C)	24.22–25.31	24.07–25.03
Average relative humidity (%)	84.12–88.62	85.11–89.01
Daily precipitation (mm)	7.7–15.4	3.91–7.81
Wind speed (m/s)	1.21–2.05	1.09–1.97

Table 2 Physical and chemical characteristics of soil in study area

Soil characteristic	Value
Sand (%)	45.20
Dust (%)	12.00
Clay (%)	42.80
Bulk density (g/cm ³)	1.60
Field capacity (%)	30.78
Wilting point (%)	9.26
Soil pH	6.96
Total nitrogen (%)	0.26
Available P (parts per million)	8.38
Organic C (%)	2.42
K ₂ O (mg/100 g)	3.58

Experimental design

A factorial design was used in a strip-plot design, consisting of two factors: 1) nitrogen (N) fertilization; and 2) different irrigation schemes (intermittent irrigation or flooded irrigation). The fertilization doses consisted of no nitrogen fertilization (0 kg N/ha), 50 kg N/ha nitrogen fertilization and 100 kg N/ha nitrogen fertilization, each with three replications. These treatments constituted six experimental plots, with each plot being 4 m × 2 m. Therefore, there were six treatments: FN0, FN50, FN100, IN0, IN50 and IN100, where F is flooded, I is intermittent irrigation and N is the amount of N fertilizer added in kilograms of N per hectare.

Field land management

Before land preparation, the field was sprayed with the

herbicide paraquat 2.0 liters per hectare. After the weeds had dried and died (about 6 d), the first soil cultivation process was carried out by ploughing with a rotary plough. After approximately 3 wk, the second soil cultivation was carried out and the soil was levelled using a harrow and allowed to become muddy. Each block was divided into experimental plots measuring 4 m × 2 m, with boundaries clearly demarcating each plot. In each block, trenches as water channels were created to facilitate the process of filling and reducing water. The planting process was carried out simultaneously with a planting distance of 25 cm × 25 cm, with two seedlings planted in each hole.

The source of the N fertilizer used was urea with an N content of 46%. Fertilization was divided into two applications, with the first application (50%) at 10–15 d after planting (DAP) and the second application (50%) at 30–35 DAP. There were two water regime treatments: intermittent flooding and continuous flooding. In the intermittent flooding regime, irrigation was carried out based on 10 d flooded with 2 cm water and then 3 d drained (dry) throughout the rice growth phase until just before harvest. In the continuous flooding regime, flooding with 10 cm of water was maintained throughout the growth phase until just before harvest.

Sampling and measurement of methane emission

CH₄ flux was measured using the static closed-chamber method (50 cm × 50 cm × 105 cm) at two important phases of plant growth: the vegetative phase (45–50 DAP) and the generative phase (80–90 DAP). The chamber was enclosed around the perimeter and had two small holes on the top, one for observing the temperature inside the chamber and one for taking gas samples. The chamber was also equipped with two circulating fans inside to ensure gas mixing and was placed at a random site within each plot and embedded 10 cm into the soil.

Soil temperature is known to be an important factor in affecting the activity of soil microorganisms. CH₄ formation reaches a maximum at 35°C and the rate of methane formation is very low below 20°C in waterlogged soils (Intergovernmental Panel on Climate Change, 1995). Therefore, gas samples were collected from the chamber headspace using a 100 mL plastic syringe during 1200–1400 hours at intervals of 5 min, 10 min, 15 min and 20 min. The samples were sent to the laboratory at the Rembang Agricultural Environment Research Institute, Indonesia, where the CH₄ concentration was determined using gas chromatography (Agilent 7890A; USA).

CH₄ estimation

CH₄ emission was calculated as the flux released from one unit of area in one unit of time (parts per million per minute). The CH₄ emission in milligrams of CH₄ per square meter per day was calculated using the Equation 1 (International Atomic Energy Agency, 1992):

$$\text{CH}_4 \text{ emission} = \frac{\{(\text{Slope}(\text{ppm}/\text{m} \times 265.5 \times 16 \times 60 \times 24))\}}{((224 \times (273 + T_{273})) \times 0.25 \times 1,000)} \quad (1)$$

where the Slope is rate of change of CH₄ gas concentration (measured in parts per million per minute), 265.5 L is the volume of the chamber (50 cm × 50 cm × 105 cm), 16 is the molecular weight of the CH₄ gas under standard conditions, 60 is the number of minutes in an hour, 24 is the number of hours per day, 22.4 is the volume of 1 mole of gas in 1 L at standard temperature and pressure, 273 is the standard temperature in degrees kelvin, T is the average chamber temperature during sampling (in degrees Celsius), 0.25 m² is the area occupied by the chamber and 1,000 is the number of micro grams in a milligram.

DeNitrification-DeComposition model

Model simulation began with parameterization using available data sources, including climate, soil and crop management data (Table 3). Climate data were obtained from the local climate station (maximum and minimum air temperature, solar radiation, air humidity, wind speed, rainfall). The crop management data contained several categories: (a) planting system (crop type, planting time, harvest time); (b) soil cultivation (cultivation time, method); (c) chemical and organic fertilization (fertilizer type, fertilizer application method, fertilizer amount); and (d) irrigation system (irrigation method and time, beginning and final flooding time, water amount). Soil characteristics were obtained by analyzing soil aggregate samples in the soil laboratory.

The model validation was tested based on the root mean squared error (RMSE) to evaluate the accuracy of predictive models, especially in regression analysis. RMSE quantifies the difference between predicted values (P) and observed values (O) and was calculated using Equation 2:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}} \quad (2)$$

where N is number of data

Table 3 Data input for parameterization of the DeNitrification-DeComposition model

No	Model parameter	Value or unit
1	Climate data	
	Maximum and minimum temperature	°C
	Precipitation	mm
	Wind speed at 2 m	m/s
	Radiation	MJ/m ²
	Relative humidity	%
2	Soil data	
	Land use	Rice paddy field
	Soil texture	Sandy clay
	Clay fraction	0.43
	Bulk density	1.6
	Soil pH	6.96
	Field capacity	0.38 wfps
	Wilting point	0.09 wfps
	Porosity	0.426
	Depth of water retention	0.168 m
	Drainage efficiency	0.8
	Nitrate	32.2
	Ammonium	9.075
	Microbial activity index	0.8
	Slope	41
	Soil salinity index	60
	Rainwater collection index	1
	Soil organic carbon (0–10 cm)	0.0249 kg C/kg soil
3	Crop management data (Crops data)	
	Crop type	Paddy
	Planting date	October 21
	Crop parameters (grain, leaf, stem, root)	—
	Tillage	
	Time of tilling	1 wk before planting
	Method of tilling	Flooded or intermittent
	Input date and amount of flooding	—
	Fertilization Amount of fertilization	0 kg N, 50 kg N, 100 kg N
	Method of fertilization Irrigation	Surface
	Water level control method	10 cm
	Start and end of flooding	1 wk after planting until 1 wk before harvest
	Manure amendment (organic fertilizer)	no organic fertilizer amendment
	Film mulch	no mulch
	Grazing or cutting	no grazing/cutting

Note: wfps = Water-Filled Pore Space

Fixed universal thresholds for a good RMSE are not available—whether the value of RMSE is “good” depends entirely on the context. Therefore, RMSE should be used alongside other metrics such as the coefficient of determination (R²), which is a measure used in statistics to indicate how well

the independent variable predicts or explains the changes in the dependent variable. It was calculated using Equation 3:

$$R^2 = 1 - \frac{SS_{RES}}{SS_{TOT}} \quad (3)$$

where SSres is the sum of squares of residuals (the difference between the observed and predicted values) and SStot is the total sum of squares (the difference between the observed values and their mean).

Results

The weather at the field site was generally fair (Fig. 1). Based on the precipitation amounts during the study period, it could be classified as being in a wet year. This was also reflected in the radiation data, as there were periods when

it was relatively low. The daily average temperature was in the range 26–29°C, with most days in the range 26–27°C. The soil surface temperature was slightly higher than the air temperature (27.7°C). The relative humidity remained high (73.62–93.44%), even though occasionally there were drier days. The evaporation rate was moderate (0.17–4.90 mm/d) with some days having a very low value. Overall, the study was conducted under relatively normal weather conditions.

With field agrometeorological data (Table 1, Fig. 1), soil characteristics (Table 2) and average inside chamber temperature (Table 4), the methane flux is presented in Table 5. The conversion procedures for methane emission, grain weight and biomass are described in the Materials and Methods section.

The DNDC model simulated methane emissions, grain weight and crop biomass, as shown in Table 6. The RMSE values were 37.63 kg C/ha/year for methane emission, 671.69

Table 4 Inside chamber temperature (°C) at different days after planting (DAP)

35 DAP												
Treatments	Rep 1				Rep 2				Rep 3			
	5'	10'	15'	20'	5'	10'	15'	20'	5	10'	15'	20
FN0	34	35	35	35.2	36.2	38	38	37	34	35	36	36
FN50	35	35.7	35.7	36	36	37	37.1	37.2	36	36	36.5	36
FN100	35	35	35	36	35	35	35.5	35	36.5	37	37.5	37
IN0	35.5	36	36	36.2	36.1	36.8	37	37.1	35	35.5	36	36
IN50	35	35.1	35.2	35.2	36	36	36.5	37	34.5	35	36	36
IN100	35.5	37	37	37	35.2	36	36.3	36.5	35	35	36	36
65 DAP												
Treatments	Rep 1				Rep 2				Rep 3			
	5'	10'	15'	20'	5'	10'	15'	20'	5	10'	15'	20
FN0	37	37.5	38	38.5	38	40.5	42	42.5	34	34.5	34.5	34
FN50	37	37.8	38	38.7	37	37	37	37	34.5	35	35	35.5
FN100	37	38	38	38.5	37	37	37.5	37	37	37.5	37	37
IN0	37.2	38.2	39	39.2	36.2	36	35.3	35	34	35	35	35.5
IN50	36.5	37	37	38	38	40.1	41.8	42.2	33	34	34	35
IN100	39.2	40	41	41.5	39	39	38.5	37	33	34	34.5	35
90 DAP												
Treatments	Rep 1				Rep 2				Rep 3			
	5'	10'	15'	20'	5'	10'	15'	20'	5	10'	15'	20
FN0	35	38	39	39.5	41	41	42	41	42	42.5	42	43
FN50	33	34	36	40	40	42	43	42	41	42	42	42
FN100	34	34.5	37	40	41	41	42	41	42.5	43	43	43
IN0	36	37	39	36	39	40	40	40	41	42	43	43
IN50	34	38	36	35	40	41	41	40	42	42.5	42	42
IN100	36	36	39	36	40	41	40	41	42.5	43	43	43

Rep = replicate; 5' = 5 min; 10' = 10 min; 15' = 15 min; 20' = 20 min. Treatments: FN0 = flooded with 0 kg/ha N fertilizer, FN50 = flooded with 50 kg/ha N fertilizer, FN100 = flooded with 100 kg/ha N fertilizer; IN0 = Intermittent with 0 kg/ha N fertilizer, IN50 = Intermittent with 50 kg/ha N fertilizer, IN1000 = Intermittent with 100 kg/ha N fertilizer

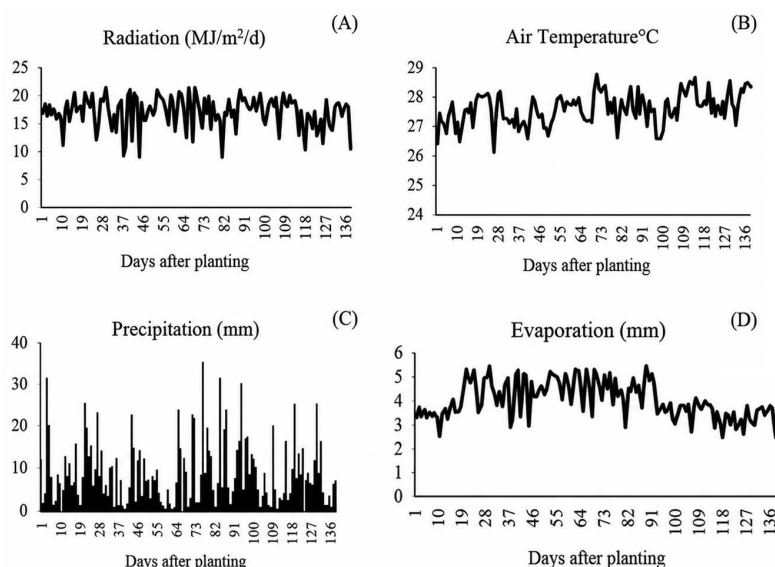


Fig. 1 Climate details of study area (2021)

Table 5 CH₄ emission field measurements at different days after planting (DAP)

35 DAP			
Treatment	Temperature (°C)	Slope	CH ₄ flux (mg/m²/day)
FN0	35.78	8.79	268.37
FN50	36.18	11.61	350.43
FN100	35.79	10.88	331.93
IN0	36.10	11.34	343.22
IN50	35.63	12.40	380.23
IN100	36.04	10.01	303.23
65 DAP			
Treatment	Temperature (°C)	Slope	CH ₄ flux (mg/m²/day)
FN0	37.58	8.41	244.34
FN50	36.63	9.30	277.29
FN100	37.38	9.81	286.83
IN0	36.30	20.42	614.62
IN50	37.22	12.75	374.34
IN100	37.64	13.85	401.97
90 DAP			
Treatment	Temperature (°C)	Slope	CH ₄ flux (mg/m²/day)
FN0	40.50	0.37	10.11
FN50	39.75	0.66	18.16
FN100	40.25	0.47	12.74
IN0	39.67	1.22	33.56
IN50	39.46	1.29	35.82
IN100	39.88	1.05	28.76

Treatments: FN0 = flooded with 0 kg/ha N fertilizer, FN50 = flooded with 50 kg/ha N fertilizer, FN100 = flooded with 100 kg/ha N fertilizer; IN0 = Intermittent with 0 kg/ha N fertilizer, IN50 = Intermittent with 50 kg/ha N fertilizer, IN1000 = Intermittent with 100 kg/ha N fertilizer

kg C/ha for grain weight and 704.75 kg C/ha for crop biomass. The model underestimated methane emission in all treatments and crop biomass in most treatments, while simulated grain weight was higher than the observed values in all treatments.

Soil organic matter

The DNDC model simulation of the SOM at the study field is presented in Table 7. The field soil contained similar total SOM, in the range 4.33–4.35%. After 1 yr, the SOM had declined slightly to 4.28–4.30% in the flooded area and to 4.30–4.31% in the intermittent irrigation fields.

Carbon-to-nitrogen ratio in soil

In the current study, the C:N ratio ranged from 18 to 26 in the flooded field and from 19 to 21 in the intermittent irrigation field. In the current study, the mineralization rate was 0.024–0.0245 kg C/kg soil in the topsoil (0–10 cm), decreasing to 0.0186–0.213 kg C/kg soil and finally only around 0.046 kg C/kg soil at 50 cm depth (Table 8). Treatments of irrigation scheme and fertilizer doses did not substantially differ in soil mineralization, with all values declining below the topsoil depth.

Soil inorganic nitrogen pools

The simulated changes during 2 yr in soil inorganic N pools in the study field are presented in Table 9.

Table 6 Comparison between measured/observed and simulated values for methane emission, grain weight and crop biomass

Treatment	Methane emission (kg C/ha/year)		Grain weight (kg C/ha)		Crop biomass (kg C/ha)	
	Measured	Simulated	Observed	Simulated	Observed	Simulated
FN0	117.04	65.85	1158.75	1736.33	2844	2594
FN50	95.09	60.11	1417.50	2101.29	3202	2959
FN100	88.88	54.22	1255.50	2152.32	4030	3010
IN0	63.69	37.76	1473.75	1708.44	2441	2566
IN50	77.86	53.27	1642.50	2585.16	3390	4482
IN100	75.48	28.88	1755.00	2152.32	3791	3010

Treatments: FN0 = flooded with 0 kg/ha N fertilizer, FN50 = flooded with 50 kg/ha N fertilizer, FN100 = flooded with 100 kg/ha N fertilizer; IN0 = Intermittent with 0 kg/ha N fertilizer, IN50 = Intermittent with 50 kg/ha N fertilizer, IN1000 = Intermittent with 100 kg/ha N fertilizer

Table 7 Total soil organic matter (%)

Treatment	Day 1 (C)	Day 1 (N)	Day 365 (C)	Day 365 (N)
FN0	4.35	0.43	4.30	0.43
FN50	4.33	0.43	4.28	0.43
FN100	4.35	0.43	4.30	0.43
IN0	4.35	0.43	4.31	0.43
IN50	4.33	0.43	4.30	0.43
IN100	—	—	4.31	0.43

C = carbon; N= nitrogen

Treatments: FN0 = flooded with 0 kg/ha N fertilizer, FN50 = flooded with 50 kg/ha N fertilizer, FN100 = flooded with 100 kg/ha N fertilizer; IN0 = Intermittent with 0 kg/ha N fertilizer, IN50 = Intermittent with 50 kg/ha N fertilizer, IN1000 = Intermittent with 100 kg/ha N fertilizer

The N sources traced were NO_3^- , NH_4^+ , clay NH_4 and $\text{N}_2\text{O}+\text{N}_2$. Of the total, N fertilizer affected the soil N source but declined over a longer time (2 yr) with the no fertilizer and 50 kg/ha application and only increased with the 100 kg N

application. Both treatments commenced with similar values (66.79 kg N/ha) and ended with 5.17 kg N/ha in FN0, 22.64 kg N/ha in FN50 and 73.04 kg N/ha in FN100. There were slight differences with the intermittent irrigation with 5.07 kg N/ha in IN0, 22.17 kg N/ha in IN50 and 75.69 kg N/ha in IN100.

Soil oxygen and soil redox potential

Fig. 2 shows that in the submerged field, there was zero oxygen, while during the dry period under the intermittent scheme, oxygen was present. The Eh was negative when water was present (under submerged conditions) and positive when the field was dry.

Soil methanogens and methanotrophs

The number of these bacteria in each treatment is presented

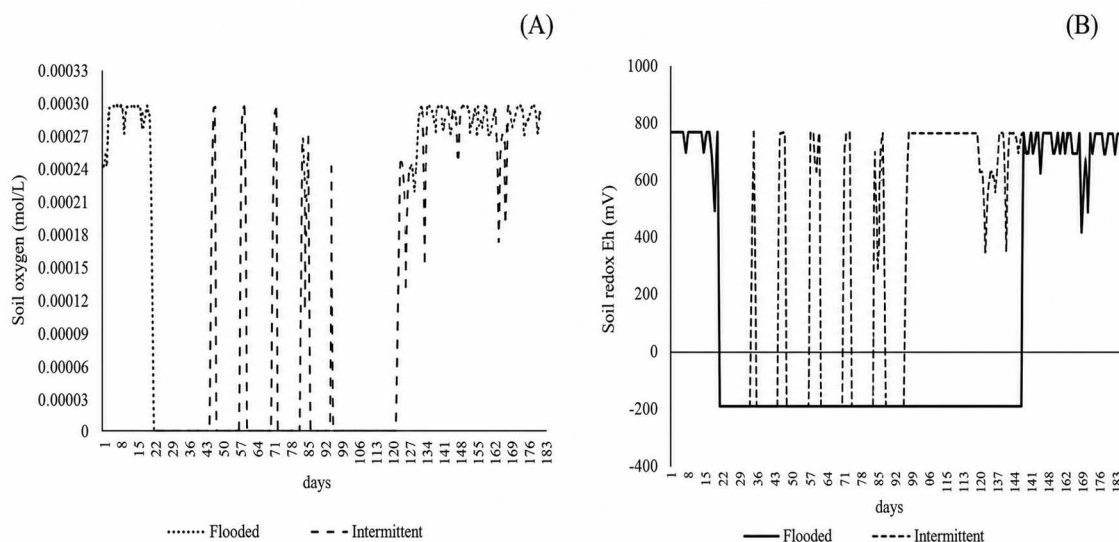
**Fig. 2** Soil oxygen and soil redox potential (Eh) reflecting water presence in field

Table 8 Soil C:N ratio and soil mineralization (kg-C/kg soil)

Treatment	Soil C (kg C/ha)	Soil N (kg N/ha)	C:N ratio	Soil Depth (cm)			
				10–20	20–30	30–40	40–50
FN0	675.3	26.3	26	0.0244	0.0212	0.0117	0.0053
FN50	483.6	26.6	18	0.0244	0.0186	0.0095	0.0045
FN100	490.1	26.8	18	0.0244	0.0213	0.0118	0.0053
IN0	532.9	27.5	19	0.0245	0.0213	0.0118	0.0054
IN50	585.1	28.3	21	0.0245	0.0186	0.0095	0.0046
IN100	594.8	28.3	21	0.0245	0.0213	0.0118	0.0054

Treatments: FN0 = flooded with 0 kg/ha N fertilizer, FN50 = flooded with 50 kg/ha N fertilizer, FN100 = flooded with 100 kg/ha N fertilizer; IN0 = Intermittent with 0 kg/ha N fertilizer, IN50 = Intermittent with 50 kg/ha N fertilizer, IN1000 = Intermittent with 100 kg/ha N fertilizer

Table 9 Changes of soil inorganic N pools (kg N/ha) in 1 yr

Continuous flooding			NO ₃ ⁻	NH ₄ ⁺	Clay-NH ₄	N ₂ O+N ₂	Total
F0	Year 1	Day 1	4.64	37.32	24.83	0	66.79
		Day 365	0	0.19	5.97	0.01	6.16
F0	Year 2	Day 1	0	0.19	5.97	0.01	6.16
		Day 365	0	0.14	5.03	0	5.17
F50	Year 1	Day 1	4.63	37.17	24.96	0	66.75
		Day 365	0	0.33	12.78	9.5	22.61
F50	Year 2	Day 1	0	0.33	12.78	9.5	22.61
		Day 365	0	0.28	11.94	10.41	22.64
F100	Year 1	Day 1	4.64	37.32	24.83	0	66.79
		Day 365	18.17	19.72	15.42	18.07	71.39
F100	Year 2	Day 1	18.17	19.72	15.42	18.07	71.39
		Day 365	13.01	14.67	15.39	29.96	73.04
Intermittent	flooding						
IN0	Year 1	Day 1	4.64	37.32	24.83	0	66.79
		Day 365	0	0.20	5.61	0	5.81
IN0	Year 2	Day 1	0	0.20	5.61	0	5.81
		Day 365	0	0.15	4.92	0	5.07
IN50	Year 1	Day 1	4.63	37.17	24.96	0	66.75
		Day 365	0	0.32	11.55	9.6	21.47
IN50	Year 2	Day 1	0	0.32	11.55	9.6	21.47
		Day 365	0	0.27	10.80	11.10	22.17
IN100	Year 1	Day 1	4.64	37.32	24.83	0	66.79
		Day 365	13.05	19.26	15.42	31.42	79.16
IN100	Year 2	Day 1	13.05	19.26	15.42	31.42	79.16
		Day 365	12.54	14.03	15.39	33.73	75.69

Treatments: FN0 = flooded with 0 kg/ha N fertilizer, FN50 = flooded with 50 kg/ha N fertilizer, FN100 = flooded with 100 kg/ha N fertilizer; IN0 = Intermittent with 0 kg/ha N fertilizer, IN50 = Intermittent with 50 kg/ha N fertilizer, IN1000 = Intermittent with 100 kg/ha N fertilizer

in Table 10. The table showed that methanogen was higher in flooded irrigation scheme compared to the intermittent scheme (7.64 kg C/ha in FN0 compared to 5.16 kg C/ha in IN0; and 8.12 kg C/ha in FN50 compared to 6.01 kg C/ha in IN50, 7.76 kg C/ha in FN100 and the much lower 1.78 kg C/ha in IN100).

Methanotroph, which oxidizes methane, had a similar pattern but with lower amounts (5.64 kg C/ha in FN0 compared to 3.41 kg C/ha in IN0; and 5.87 kg C/ha in FN50 compared to 4.24 kg C/ha in IN50, 5.70 kg C/ha in FN100 and 1.36 kg C/ha in IN100).

Daily CH₄ production and flux

The final CH₄ emission from each treatment is presented in Table 11 and the relationships between the methanogenic and methanotrophic bacteria and methane emissions are presented in Table 12. Based on the bacteria present, the CH₄ emission was higher in the flooded field than in the intermittent one for all fertilizer doses.

Table 12 shows that methanogens had a fairly strong correlation with CH₄ emission across all three nitrogen doses ($r = 0.7$ – 0.8) under the flooded water scheme and a weaker

correlation under the intermittent scheme ($r = 0.48$ – 0.71). On the other hand, methanotrophic bacteria had little to no correlation with methane emission ($r = -0.07$ – 0.41). Table 12 and Fig. 5 show that the daily methane emission was in the ranges 0.797–1.048 kg C/ha/day under continuous flooding irrigation and 0.03–0.401 kg C/ha/day under intermittent irrigation.

Crop production

Crop production by treatment was represented by the grain weight per paddy clump, grain production and biomass per experimental plot (Table 13). Except for the biomass weight, the weight of grains per clump and production per experimental plot were affected by irrigation. Intermittent irrigation resulted in higher grain weights per clump and production per experimental plot (70.8 g/clump and 6.54 kg/plot, respectively), than for continuous flooding irrigation (59.4 g/clump and 5.64 kg/plot, respectively). Application of 100 kg N/ha produced the highest grain weight per clump and production per experimental plot. In addition, intermittent irrigation resulted in a higher biomass weight, though this was not significantly different from continuous irrigation. The application of 100 kg N/ha resulted in the highest biomass weight (260.7 g/plot).

Table 10 Methanogen and methanotroph bacteria in field soil (kg C/ha)

Treatment	Methanogen	Methanotroph
FN0	7.64	5.64
FN50	8.12	5.87
FN100	7.76	5.70
IN0	5.16	3.41
IN50	6.01	4.24
IN100	1.38	1.36

Treatments: FN0 = flooded with 0 kg/ha N fertilizer, FN50 = flooded with 50 kg/ha N fertilizer, FN100 = flooded with 100 kg/ha N fertilizer; IN0 = Intermittent with 0 kg/ha N fertilizer, IN50 = Intermittent with 50 kg/ha N fertilizer, IN100 = Intermittent with 100 kg/ha N fertilizer

Table 11 Daily C pools and CH₄ flux

Treatment	CH ₄ production (kg C/ha)	CH ₄ flux (kg C/ha/day)
FN0	947.6127	0.796617
FN50	1,006.523	1.038469
FN100	962.287	0.930803
IN0	640.0905	0.339496
IN50	745.2352	0.401046
IN100	171.6157	0.026623

Treatments: FN0 = flooded with 0 kg/ha N fertilizer, FN50 = flooded with 50 kg/ha N fertilizer, FN100 = flooded with 100 kg/ha N fertilizer; IN0 = Intermittent with 0 kg/ha N fertilizer, IN50 = Intermittent with 50 kg/ha N fertilizer, IN100 = Intermittent with 100 kg/ha N fertilizer

Table 12 Correlation coefficients of methanogen and methanotroph with CH₄ emission

Treatment	Methanogen (r)	Methanotroph (r)
FN0	0.70	0.29
IN0	0.66	0.024
FN50	0.69	0.156
IN50	0.47	-0.07
FN100	0.801	0.13
IN100	0.71	0.41

Treatments: FN0 = flooded with 0 kg/ha N fertilizer, FN50 = flooded with 50 kg/ha N fertilizer, FN100 = flooded with 100 kg/ha N fertilizer; IN0 = Intermittent with 0 kg/ha N fertilizer, IN50 = Intermittent with 50 kg/ha N fertilizer, IN100 = Intermittent with 100 kg/ha N fertilizer

Table 13 Grain weight per paddy clump, grain production and biomass per experimental plot

Treatment	Grain weight per clump (g)	Grain production (kg/plot)	Biomass weight (g)
Irrigation method			
Intermittent	70.795 ^a	6.54 ^a	223.911 ^a
Submerged	59.357 ^b	5.64 ^b	213.822 ^a
LSD 5%	1.40	0.18	34.43
CV (%)	2.4%	1.49%	17.34%
Nitrogen fertilizer			
Without N	57.013 ^c	5.16 ^c	176.167 ^c
50 kg N/ha	64.340 ^b	6.02 ^b	219.733 ^b
100 kg N/ha	73.877 ^a	7.12 ^a	260.700 ^a

LSD = least significant difference; CV = coefficient of variation

The same column followed by different lowercase superscript letters are significantly different ($p < 0.05$).

Discussion

Similar research in Tamil Nadu, India, revealed that the simulated CH₄ emissions were 6.4% lower and 4.2% higher

than the observation under continuous flooding irrigation and 9.3% and 12.7% lower on an intermittent irrigation scheme (Oo et al., 2020). DNDC validation was also studied in 11 different sites in India, yielding various relative deviations. At some sites, the model predicted lower emissions (from -0.03 to -12.3%), while at others it was higher by 1.1–56% (Babu et al., 2006). In the current study, the DNDC model underestimated methane emissions in all treatments. The RMSE for methane emission was 37.63 kg C/ha/year and the R^2 value was 0.67, indicating that the model simulation explained about 70% of the observed value. These results were lower than the RMSE of a similar study by Gong (2023), which was 0.85 kg C/ha or 76.5 kg C/ha/year (in two paddy planting periods), with slightly higher R^2 values (0.67–0.6). This result indicates moderate agreement between simulated and measured methane emission, although the model still underestimated the field observations.

The discrepancies in the DNDC model Notably apprehensive regarding the stability of the soil ecosystem (Babu et al., 2006; Fumoto et al., 2008; Gong et al., 2023). One important factor that has a direct influence on GHG emissions is soil temperature, because it influences soil moisture, microbial activity and evaporation (Macharia et al., 2021; Shah et al., 2024). In the present study, direct soil temperature measurements were not available, but air temperature was. Since soil temperature has a close relation with air temperature, to investigate whether the model could estimate the soil temperature closely, air temperature could be used. The coefficient correlation (r) and RMSE between modelled air temperature and observed air temperature was calculated (Table 14). It is obvious that the modelled air temperature did not estimate the air temperature well ($r = -0.3$) and no correlation to soil temperature ($r = -0.1$). On the other hand, the highest correlation and smallest RMSE occurred between observed air temperature to modelled soil temperature ($r = 0.718$, RMSE 0.778). Indirectly, it is suspected that since the model was inaccurate in estimating soil temperature, the methane emission estimated by this model was affected. Therefore, uncertainty in soil temperature simulation may have contributed to differences between simulated and observed methane emissions.

Soil organic carbon and nitrogen conditions

Assuming a soil weight of 2 t/ha, the field soil contained approximately 6.33% soil carbon on the first day of planting. This percentage is high for agricultural soil in Indonesia (Edwin, 2016). Soil organic carbon (SOC) decreased more quickly in the continuous flooding field than in the intermittent one at all fertilizer doses (Fig. 3). This result suggests that irrigation

regime influenced SOC dynamics during the simulation period. Total N and SOC contents were higher in the treatments with N application than in the treatments without N. Similar results were reported by Jinshun et al. (2020) and Ali et al. (2021) in the Red Soil Region of China, where N fertilizer application increased SOC. Therefore, the higher SOC and total N under fertilized treatments may partly reflect the contribution of N fertilization to soil nutrient status during paddy cultivation.

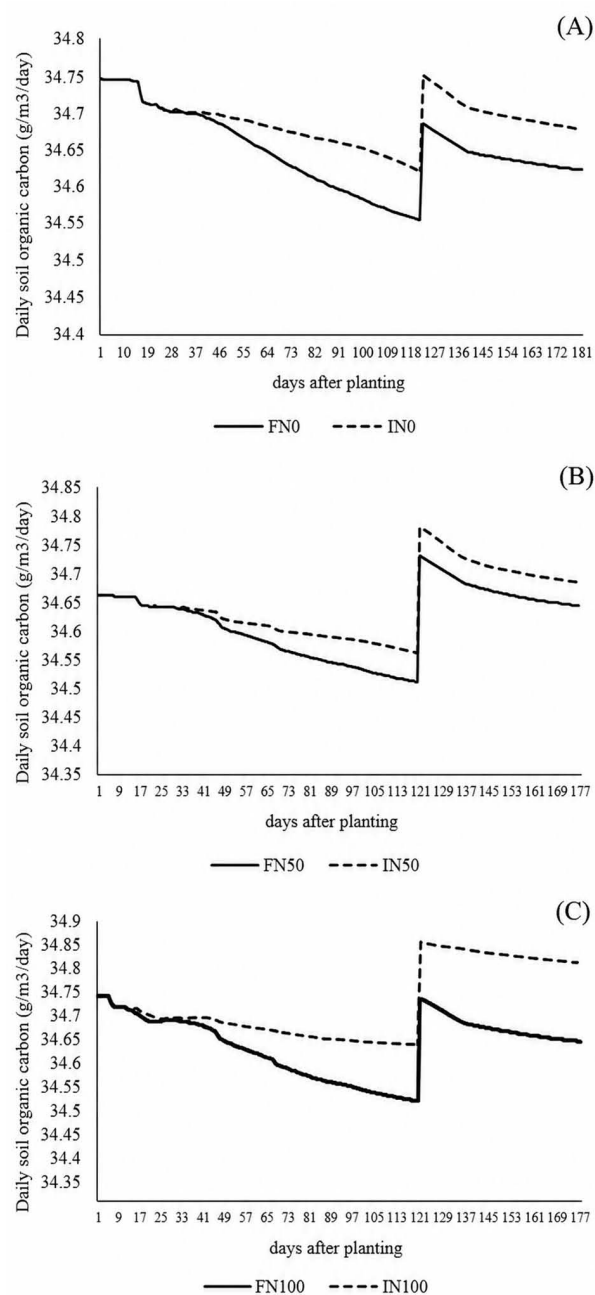


Fig. 3 Soil organic carbon content of the field soil during planting period. Treatments: FN0 = flooded with 0 kg/ha N fertilizer, FN50 = flooded with 50 kg/ha N fertilizer, FN100 = flooded with 100 kg/ha N fertilizer; IN0 = Intermittent with 0 kg/ha N fertilizer, IN50 = Intermittent with 50 kg/ha N fertilizer, IN1000 = Intermittent with 100 kg/ha N fertilizer

Table 14 Statistical correlation (root mean squared error, RMSE) of modelled temperature (T) of air and of observed and simulated soil temperature

	Modelled				
	T max	T min	T average	T soil	T (observed)
Average	30.160	27.559	24.959	27.594	26.995
Standard deviation	1.467	0.834	0.708	0.971	0.971
Correlation to observed temperature	0.340	0.298	0.384	0.718	1.000
Correlation of air to soil temperature	-0.037	0.108	0.018	1.000	0.718
RMSE for observed temperature	3.458	2.234	1.110	0.778	-

The C:N ratio in healthy soil is generally around 10:1, signifying a balanced state with a good balance between C and Nitrogen, which is crucial for plant growth and microbial activity. A ratio of 20-30:1 results in an equilibrium state between mineralization (nitrogen is released for plant uptake) and immobilization (microbes utilize and tie up N for the plant), according to In the current study, a balanced C:N ratio was around 18–26:1, which is optimal for efficient nutrient cycling and healthy soil (Gaffer et al., 2015). However, it might not be sufficient for plant uptake. The soil mineralization values in the current study were consistent with the study by Gan, et al. (2019) in eastern China, which reported a rate of 0.025 kg C/kg soil. The SOC results are relevant because organic carbon provides substrate for microbial processes associated with methane production in flooded paddy soil.

Soil inorganic nitrogen pools

The simulated inorganic N pools showed that the 100 kg N/ha treatment maintained higher total inorganic N than the 0 kg N/ha and 50 kg N/ha treatments under both irrigation schemes. Other research has reported that in paddy soil, weakly fixed ammonium (NH_4^+) can reach 66 mg/kg, while exchangeable N can reach 29.7 mg/kg (Matsuoka and Moritsuka, 2011). In comparison, the current recorded lower values, indicating that the soil had a relatively low N source. The addition of 100 kg N/ha increased the simulated N pool, particularly through higher NH_4^+ and $\text{N}_2\text{O}+\text{N}_2$ components. Fig. 4 describes the effect of increasing N fertilizer to the inorganic source of soil. Both in flooding and intermittent irrigation scheme applying more fertilizer would increase the inorganic soil. A significant increase appeared in applying 100 kg N as a result in increasing NH_4^+ . The intermittent scheme gave more inorganic Nitrogen because of higher $\text{N}_2\text{O}+\text{N}_2$

Soil redox condition and methane-related microbial activity

Oxygen (O_2) participates in carbon and nitrogen transformations through its influence on redox potential (Liptzin et al., 2011). GHGs, such as CO_2 , N_2O and CH_4 ,

are produced and consumed in soils through redox-related microbial processes. At this site, the maximum oxygen content was 10 ppm.

Redox potential is a measure of the tendency of an environment to oxidize or reduce substrates. According to Pezeshki (2001), aerated soils have an Eh greater than +400 mV; moderately reduced soils have an Eh between +100 and +400 mV; reduced soils have an Eh between -100 and +100 mV; and highly reduced soils have an Eh between -100 and -300 mV. Cultivated soils most frequently fall within the range +300 and +500 mV under aerobic conditions (Macías and Arbestain, 2010). However, the Eh can reach +750 mV in podzols (Husson, 2013). In the current study, the soil Eh reached -300 mV when the field was submerged, indicating highly reduced soil conditions.

Nitrogen availability and microorganism activity are related to soil redox conditions. Under submerged conditions, low Eh coincided with higher methanogen activity. Fig. 5 shows that N pools increased during low Eh and then became relatively stable at higher Eh, while methanogens were present mainly during low Eh conditions.

Methanogens produce methane in anoxic conditions, whereas methanotrophs oxidize methane using oxygen or alternative electron acceptors (Nonci, 2015). Table 11 shows that methane production and flux were higher in the flooded fields than in the intermittent irrigation fields. Fertilizer application did not show a consistent increase in methanogens or methanotrophs values across irrigation scheme. These results indicate that irrigation regime had a stronger influence than fertilizer dose on methane-related microbial activity and CH_4 emission. Fig. 5 clearly shows that irrigation scheme effects the existence of methanogen and methanotroph rather than the dose of fertilizer. The effect of fertilizer dose and irrigation scheme on N cycles in soil is that in flooded soil, methane-producing bacteria generate more than was consumed. In the intermittent scheme, as long as the water was present, methanogens were produced but more methane was consumed than produced. The bacteria amount ultimately determines gas emission from the paddy field, as showed in Fig 6.

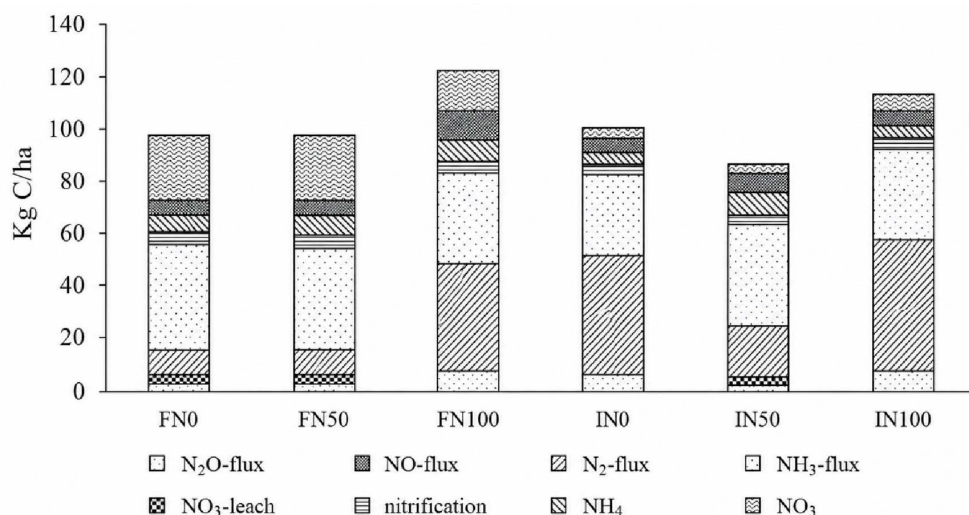


Fig. 4 The effect of increasing N fertilizer on soil inorganic N sources. In both the flooded and intermittent irrigation schemes, applying more fertilizer increased the soil inorganic N pool. A substantial increase appeared with 100 kg N/ha.

Treatments: FN0 = flooded with 0 kg/ha N fertilizer, FN50 = flooded with 50 kg/ha N fertilizer, FN100 = flooded with 100 kg/ha N fertilizer; IN0 = Intermittent with 0 kg/ha N fertilizer, IN50 = Intermittent with 50 kg/ha N fertilizer, IN1000 = Intermittent with 100 kg/ha N fertilizer

Implications for methane mitigation and crop production

The CH_4 fluxes in the current study were compared with findings from Jiangxi Province, China. Zou et al. (2005) reported seasonal average CH_4 fluxes of 0.25–0.72 kg/ha/d

under flooding and managed water regimes without residue application, and 1.19–1.86 kg/ha/d when wheat straw was applied. In the current study, where no straw residue was applied, CH_4 flux ranged from 0.8 to 1.04 kg/ha/d under continuous flooding and from 0.03 to 0.34 kg/ha/d under intermittent irrigation.

A study from the Philippines, with similar agroclimatic conditions but lower rainfall than the current trail, reported seasonal CH_4 emission during the dry season of 69.9 kg CH_4 /ha, equivalent to 52.43 kg C/ha, under continuous flooding and 42.2 kg CH_4 /ha, equivalent to 31.65 kg C/ha under alternate wetting and drying irrigation. During the wet season, emissions were 328 kg CH_4 /ha, equivalent to 246.68 kg C/ha under continuous flooding and 350.1 kg CH_4 /ha, equivalent to 262.5 kg C/ha under an alternate wetting and drying irrigation (Sibayan, 2018). These values were lower than the CH_4 production in the current study, which ranged from 947.61 to 1,006.52 kg C/ha under continuous flooding and from 171.75 to 745.24 kg C/ha under the intermittent irrigation. (Fig. 7). The difference could be due to Indonesia wetter condition where paddy field are submerged up to 20 cm deep compared to only 5 cm in The Philippines.

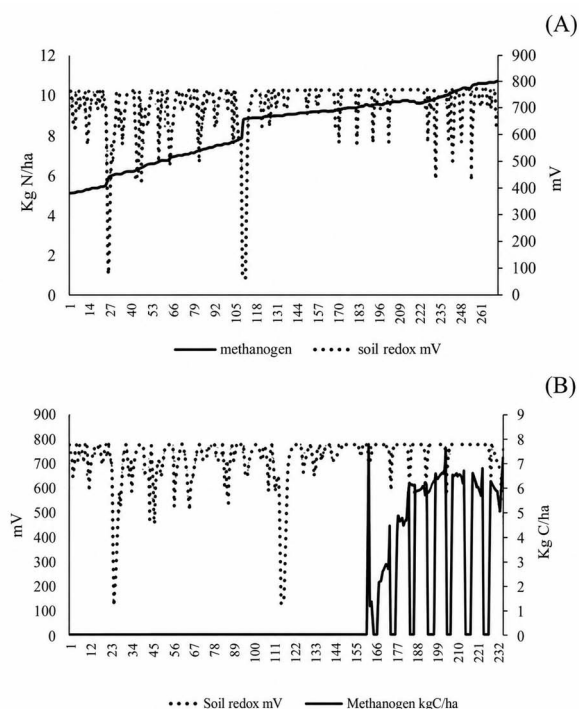


Fig. 5 Relationship between soil redox potential (Eh), nitrogen pools and methanogen activity

Conclusions

The DNDC model was applied to simulate CH_4 emissions from paddy fields under different irrigation schemes and

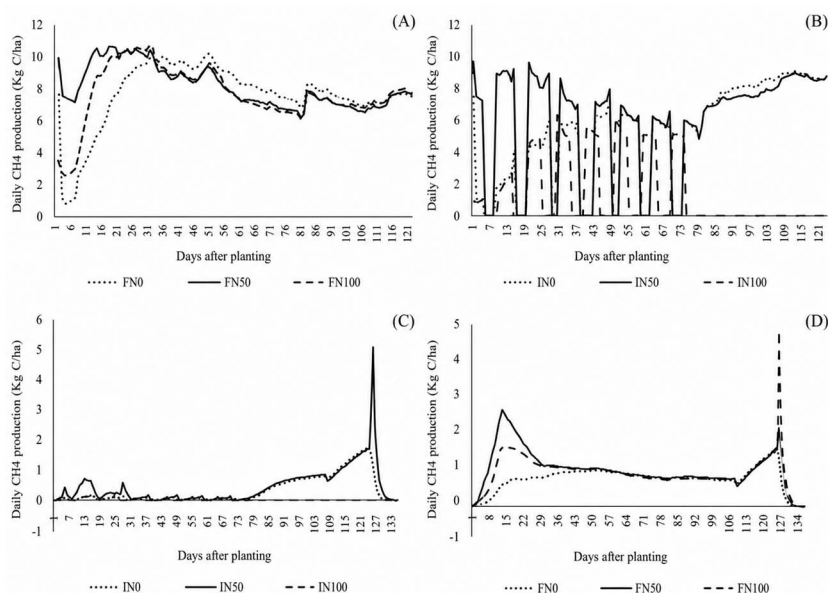


Fig. 6 Daily CH_4 production and flux from paddy field under different fertilizer doses and irrigation schemes, Treatments: FN0 = flooded with 0 kg/ha N fertilizer, FN50 = flooded with 50 kg/ha N fertilizer, FN100 = flooded with 100 kg/ha N fertilizer; IN0 = Intermittent with 0 kg/ha N fertilizer, IN50 = Intermittent with 50 kg/ha N fertilizer, IN1000 = Intermittent with 100 kg/ha N fertilizer

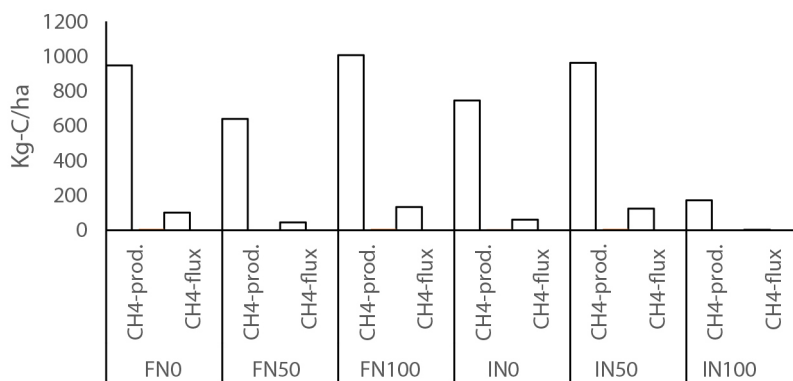


Fig. 7 Total CH_4 pools and fluxes at study site during planting period, Treatments: FN0 = loaded with 0 kg/ha N fertilizer, FN50 = flooded with 50 kg/ha N fertilizer, FN100 = flooded with 100 kg/ha N fertilizer; IN0 = Intermittent with 0 kg/ha N fertilizer, IN50 = Intermittent with 50 kg/ha N fertilizer, IN1000 = Intermittent with 100 kg/ha N fertilizer

N fertilizer doses. The model under estimated the field observations, with an RMSE of 37.63 kg C/ha/year. However, the simulation results showed the same trend as the field observations, indicating that CH_4 emission was higher under continuous flooding than under intermittent irrigation. Intermittent irrigation consistently reduced CH_4 emissions compared with continuous flooding. In addition, intermittent irrigation did not reduce paddy yield under the conditions of this study. Therefore, intermittent irrigation can be recommended as a potential water-management strategy

for mitigating CH_4 emissions from paddy cultivation. Further model validation using multi-season field data and basic environmental parameters, including air and soil temperatures, is needed to improve the reliability of DNDC simulations.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

This research project was facilitated by the Graduate Study Program of Agronomy, Faculty of Agriculture, Lampung University and the Community Development Office of North Rawa Jitu District, Mesuji Regency Lampung Province, Indonesia.

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