



Estimates of methane and nitrous oxide emission from a rice field in Central Java, Indonesia, based on the DeNitrification DeComposition model

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ABSTRACT

Indonesia is the world's third largest rice producer, with most rice being cultivated (estimated 3.1 million ha) in Central Java. However, one of the environmental challenges in producing rice is greenhouse gas (GHG) emissions from rice fields. Therefore, understanding the GHG emissions (methane and nitrous oxide) from the rice farming system is important for better management practices. The objective of this study is to estimate the GHG emissions supported by a satellite database, namely, the DeNitrification DeComposition (DNDC) model, at three regencies at Central Java, Indonesia, Cilacap, Karanganyar, and Pati, as well as the factors determining the emissions. The DNDC model was obtained from <https://www.dndc.sr.unh.edu>, which consists of three main submodels that worked together in simulating N₂O and N₂ emissions: (1) the soil-climate/thermal-hydraulic flux submodel, (2) the decomposition submodel, and (3) the denitrification submodel. The results showed that the N₂O emissions from rice farming in Karanganyar, Cilacap, and Pati were 19.0, 18.8, and 12.8 kg N ha⁻¹ yr⁻¹, respectively, while they were 213.7, 270.6, and 360.6 kg C ha⁻¹ yr⁻¹ for CH₄ emissions, respectively. Consecutive dry or high precipitation, which resulted in cumulative depleted or elevated soil moisture, respectively, along with warmer temperature likely promoted higher methane and nitrous oxide. Experimental fields for validating the model in accordance with various agricultural practices are suggested for further study. Overall, the DNDC model has successfully estimated the CH₄ and N₂O emissions in Central Java when incorporated with various secondary climatic and land management big data resources.

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1. INTRODUCTION

Rice is the most important staple food crop for more than 3 billion people in the world (Birla et al., 2017). World rice consumption is projected to increase from 450 million tons in 2011 to around 490 million tons in 2020 and to around 650 million tons in 2050 (Muthayya et al., 2014). Rice cultivation is a major source of atmospheric methane (CH₄) and nitrous oxide (N₂O), which are significant potential greenhouse gases (GHGs) and are responsible for approximately 11% (CH₄) and 60% (N₂O) of global anthropogenic emissions (Ciais et al., 2013). Methane emissions from rice fields are a net result of the production and oxidation of CH₄ in the soil and the transport of CH₄ gas from the soil to the atmosphere through rice plants (Minamikawa et al., 2014). Conventional

management practices of continuous inundation of irrigation in rice fields increase the anaerobic fermentation of carbon sources supplied by rice plants, add organic matter, and result in high CH₄ production.

Rice fields are also known to emit high nitrous oxide (N₂O) fluxes under nitrogen fertilization (Xu et al., 2015) and certain water management regimes (Oo et al., 2018). Most of the N₂O emissions come from the application of fertilizers and animal manure (Seitzinger & Phillips, 2017; Smith, 2017). N₂O emissions are currently increasing at a rate of 0.25% per year (Beaulieu et al., 2011), from agricultural activities, globally, namely, from Asia (63%), America (20%), Europe (13%), and Africa (3%) between 2001 and 2011 (Tubiello et al., 2014).

Therefore, measuring agricultural emissions (CH₄ and N₂O) and finding suitable mitigation measures have become important tasks in current scientific research with a focus on climatic conditions such as rainfall, soil moisture, and temperature.

The DeNitrification DeComposition (DNDC) model is a high-efficiency tool for simulating rice yields and for capturing CH₄ and N₂O emissions from different rice production systems (Zhang et al., 2021). In addition, many studies have modified and optimized the DNDC model (Han et al., 2014; Zhang et al., 2019), which can simulate soil temperature and moisture accurately. Temperature and humidity are very important for nitrification and denitrification because they determine the activity of microorganisms. In addition, soil temperature and humidity greatly affect not only the production of CH₄ and N₂O but also their diffusion into the atmosphere. In general, a decrease in moisture has an effect on N₂O emissions, while greater soil moisture has an effect on CH₄ emissions (Liu et al., 2017; Oo et al., 2018). This happens because soil moisture content is associated with microbial activity: the higher soil moisture, the higher microbial activity, and vice versa.

Chamber measurements of CH₄ and N₂O emissions provide satisfactory data on site-specific, pots, and laboratory experiments (Kim et al., 2021); however, due to soil, climate, and plant diversity, as well as soil and plant management, it is difficult to scale up these data (Abdalla et al., 2020; Li et al., 2017). Scale up techniques and simulation models that are dynamic enough to account for the spatial and temporal variability inherent in these emissions are urgently needed. The right model will increase the reliability of temporal and spatial integration and help identify knowledge gaps. Several simulation models describing the dynamics of nitrogen in the soil have been developed such as CENTURY, EXPERT-N, DAYCENT, and DNDC. The DNDC model is widely accepted and used, simulating two microbial-mediated processes, nitrification and denitrification, which are mainly processed in the soil to produce N₂O (Gilhespy et al., 2014; Zhao et al., 2020). In the DNDC model, denitrification is activated by the redox potential of the soil (Li et al., 1992a, 1992b). This model can be used for many crops and provides daily and seasonal evolution of CH₄ and N₂O from agricultural soils at a field scale, using available input data (Oo et al., 2018).

Indonesia is the third largest rice producer in the world and the world's largest rice consumer. The total area of rice fields reached around 13.8 million ha in 2016 (BPS, 2021), with Java being the second largest rice field area in Indonesia, which contributes to national rice productivity (Susilawati et al., 2015) and contributes to the average emission from rice fields in Indonesia of 0.18 t CH₄ ha⁻¹, with Java 1,146 Gg CH₄ yr⁻¹, 691 Gg CH₄ yr⁻¹ for Sumatra, 324 Gg CH₄ yr⁻¹ for Sulawesi, 206 Gg CH₄ yr⁻¹ for Kalimantan, 103 Gg CH₄ yr⁻¹ for Nusa Tenggara, 25 Gg CH₄ yr⁻¹ for Bali, and 10 Gg CH₄ yr⁻¹ for Papua (Ariani et al., 2021). These CH₄ emission values are based on field measurements without studies of specific duration that are not well documented in peer-reviewed publications (Ariani et al., 2021).

Furthermore, researchers focus more on studies of CH₄ and N₂O emissions using the chamber method at a laboratory-field scale with various factors such as organic

matter (Nungkat et al., 2015) and irrigation practices (Setyanto et al., 2018). This makes research on GHG emissions in rice fields still limited to large areas. Yet, to the best of our knowledge, the studies on CH₄ and N₂O emissions in rice fields using the DNDC model with large areas are still limited. There are many challenges for application in Indonesia, particularly sparse data and data infrastructure is not the same for all provinces. Therefore, starting from Java Islands, where the data infrastructure is better than other provinces, and Central Java, as one of the national rice baskets of Indonesia, the aim of this study was to estimate the CH₄ and N₂O emissions with a focus on precipitation, soil moisture, temperature, and rice production in Central Java. The estimation and monitoring of GHG emissions in rice fields can contribute to hunger reduction (Sustainable Development Goal—SDG2), ensure a climate safety net for food production (SDG 13), and sustainably manage forests from land degradation (SDG 15).

2. MATERIALS AND METHODS

2.1 Study sites

Since 1980, Indonesia's national rice yield has been the highest in tropical Asia (GRiSP, 2013). Also, Indonesia has one of the largest rice consumers in the world, averaging more than 200 kg per head each year (Connor et al., 2021). Rice is grown across the major islands of Indonesia, but most rice is cultivated on the island of Java on an estimated 3.1 million ha of land (Ministry of Agriculture, 2018). The study was conducted in Central Java, in Cilacap (7.45°S, 109.01°E), Karanganyar (7.36°S, 110.05°E), and Pati (6.46°S, 111.07°E), from 2005 to 2010, as shown in Figure 2.

2.2 Calculation using the DNDC model

The DNDC model was obtained from <https://www.dndc.sr.unh.edu>, which consists of three main submodels (Figure 1) that work together in simulating N₂O and N₂ emissions: (1) soil-climate/thermal-hydraulic flux submodel, (2) decomposition submodel, and (3) denitrification submodel.

2.2.1. Thermohydraulic submodel

The thermohydraulic submodel calculates hourly and daily mean soil temperatures and soil moisture profiles. To do so, DNDC uses a cascade model approach in which the soil is divided into a series of horizontal layers, assuming that each layer has uniform temperature and humidity. Both temperature and humidity calculations are gradient-driven equations. This flux is created by the average daily air temperature and the temperature of the soil layer at a certain depth (Li et al., 1992a). To calculate the temperature, it is assumed that there is a simplified heat flux between the ground surface and the atmosphere (see also equations 1–3). In soil moisture simulation, evapotranspiration is used as the output, while rainfall and irrigation are combined as the inputs. The water input is always calculated as if the input starts at midnight and the intensity is constant, and thus, the duration varies. At the beginning of each time step, the water input fills the soil layer by layer. So, excess water from one layer fills the next deeper layer. Surface runoff and water intercepted from vegetation are not taken into account in this initial version (as shown by Equation 4).

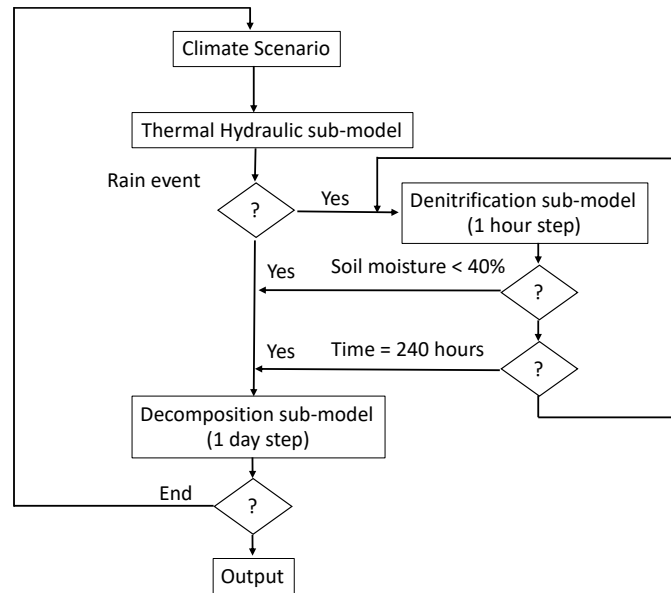


Figure 1. Structure of the DNDC model incorporating three submodels (Li et al., 1992a).

$$q_s = \frac{(T_1 - T_{air})}{(z_1 - 0)} \times -k_1, \text{ Soil heat flux at the surface} \quad [1]$$

$$q_{i,i-1} = \frac{(T_i - T_{i-1})}{(Z_i - Z_{i-1})} \times -k_{i,i-1}, \text{ Soil heat flux (layer } i - 1 \rightarrow \text{layer } i) \quad [2]$$

$$q_b = (T_{bl} - T_{mean}) (Z_{bl} - Z_{deep}) \times k_{bl}, \text{ Soil heat flux at the bottom of the profile} \quad [3]$$

$$E_0 = DAY_1 * \left(\frac{1,6}{NM}\right) * \left(10 * \frac{T_n'}{I}\right)^a, \text{ Potential evapotranspiration} \quad [4]$$

where q_s is the heat flux at the soil surface ($J s^{-1}$), $q_{i,i-1}$ is the heat flux from layer $i - 1$ down to layer i ($J s^{-1}$), q_b is the heat flux at the bottom of the profile ($J s^{-1}$), K_1 is the soil thermal conductivity of layer 1 (soil surface) ($J cm g^{-1} °C^{-1}$), $K_{i,i-1}$ is the average thermal conductivity of layers I and $i - 1$ ($J cm g^{-1} °C^{-1}$), K_{bl} is the average thermal conductivity at the bottom of the profile ($J cm g^{-1} °C^{-1}$), T_1 is the temperature of layer 1 (soil surface) ($°C$), T_i is the temperature for level i ($°C$), T_{bl} is the temperature at the bottom of the profile ($°C$), T_{air} is the air temperature ($°C$), T_{mean} is the mean annual air temperature ($°C$), Z_{bl} is the depth at the bottom of the profile (cm), and Z_{deep} is the depth where temperature variation is assumed to be negligible (500 cm). E_0 is the potential evapotranspiration ($cm d^{-1}$), DAY_1 equals 1/12 of the day's hours of daylight, NM is the

number of days in the month, T_n' is the mean monthly air temperature of month n ($°C$), $a = 0,49 + (0,079 \times I) - (7,71e^{-5} \times I^2) + (6,75e^{-7} \times I^3)$ where $I = \sum_{n=1}^{12} \frac{T_n^{1,5}}{5}$. E_0 is zero for months where the mean air temperature is below $0° C$.

2.2.2. Soil decomposition submodel

The soil decomposition submodel alternated with the soil denitrification submodel, depending on the simulated soil oxygen content. In the soil decomposition model, the soil profile was divided into uniform horizontal layers with a typical thickness of 2 cm. Counting layer by layer in daily time steps, the three organic assemblages are determined (decomposable plant material residues, microbial and humid biomass), and their corresponding labile and resistant compartments decompose via first-order kinetics, as shown in Equations 5, 6, and 7.

$$\frac{dc}{dt} = \mu_{CLAY} \times \mu_{CN} \times \mu_{tn} \times (S \times k_1 + (1 - S) \times k_r) \quad [5]$$

$$\mu_{CLAY} = \log \frac{0.14}{CLAY} + 1 \quad [6]$$

$$\mu_{CN} = 0.2 + \frac{7.2}{CP/NP} \quad [7]$$

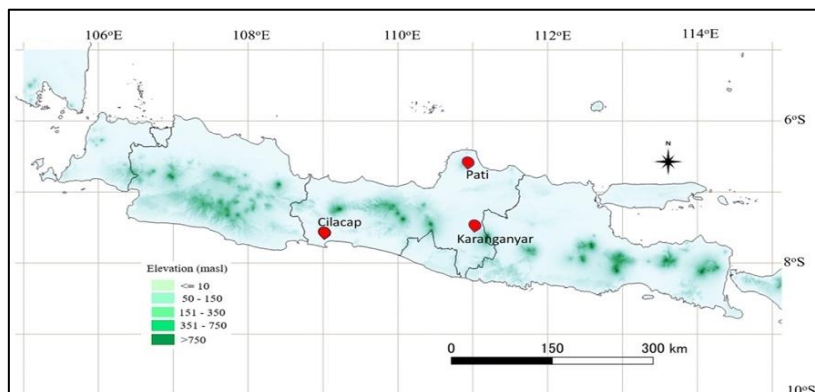


Figure 2. Study sites for CH₄ and N₂O estimation.

where μ_{CLAY} is the clay content reduction factor, μ_{CN} is the C/N ratio reduction factor, μ_{tn} is the temperature reduction factor for nitrification, S is the labile fraction of organic C compounds in the pool, K_1 is the specific decomposition rate (SDR) of labile fraction (d^{-1}), K_r is the SDR of the resistant fraction (d^{-1}), CLAY is the soil clay fractional content, CP is the carbon produced by potential residue decomposition ($kg\ C\ ha^{-1}\ d^{-1}$), and NP is the nitrogen produced by potential residue decomposition plus free NH_4^+ and NO_3^- in the soil ($kg\ N\ ha^{-1}$).

Oxidation of organic C causes the release of NH_4^+ , which is nitrified or evaporated. In nitrification, the rate of nitrification potential is related to available NH_4^+ , soil temperature, and soil moisture (see Equation 8). The model calculations simulate the nitrification rate as a function of these three factors, assuming an optimal rate at 35°C and 90% soil moisture. In model calculations, N_2O emission from nitrification (Equation 9) is controlled directly by soil ammonium concentration, temperature being the rate-determining factor (Li et al., 1992a). During nitrification, the amount of N_2O emitted in the soil correlates with the amount of N that can be nitrified in the soil. In DNDC, NH_4^+ is the direct factor controlling N_2O emission under aerobic conditions. The N_2O emission from the nitrification process was modeled as a function of soil temperature and soil ammonium concentration.

$$dNNO = NH_4(t) \times [1 - \exp(-K_{35} \times \mu_{t,n} \times dt)] \times \mu_{m,n},$$

Nitrification rate [8]

$$N_2O = (0.0014 \times \frac{NH_4}{30.0}) \times \frac{(0.54 + 0.51 \times T)}{15.8},$$

[9]

where dNNO is the NH_4^+ converted to NO_3^- ($kg\ N\ ha^{-1}\ d^{-1}$), $NH_4(t)$ is the available NH_4^+ at time t ($kg\ N\ ha^{-1}$), K_{35} is the nitrification rate at 35°C (25) ($mg\ kg^{-1}\ soil\ d^{-1}$), $\mu_{t,n}$ is the temperature reduction factor for nitrification, and $\mu_{m,n}$ is the moisture reduction factor for nitrification. N_2O is the daily emission of N_2O , NH_4 is the NH_4^+ concentration in the liquid phase ($mol\ cm^{-3}$), and T is the temperature (°C).

2.2.3. Denitrification submodel

The denitrification submodel was activated at each rainfall, and here, the soil was divided into layers 2 cm thick, with corresponding uniform properties. Rainfall events take place as long as the relative humidity (the fraction of pores filled with water) was above 40%. Denitrification begins as soon as the layer is saturated with water, and at this time, only the denitrifier is considered active. In addition, temperature and pH conditions are also affected by denitrification. The growth of denitrifying bacteria is proportional to their respective biomass. Regarding the emissions of N_2 and N_2O , the emission is modeled as a function of both the adsorption coefficient and the air-filled porosity, as shown in Equations 10 and 11. Thus, during rain, when the soil layer is saturated, the diffusion of N_2 , and N_2O is neglected because the expected diffusion rate is low. The effect of soil depth is not taken into account because denitrification is concentrated at the soil surface (Li et al., 1992b).

$$N_2 = 0.017 + ((0.025 - 0.0013 \times AD) \times PA) \quad [10]$$

$$N_2O = (0.0006 + 0.0013 \times AD) + (0.013 - 0.005 \times AD) \times PA \quad [11]$$

Where: N_2 and N_2O are emissions from soil; $P(N_2)$ is the emitted fraction of the total N_2 evolved in a day, AD is the adsorption factor depending on clay content in the soil (range = 0–2), PA is the air-filled fraction of the total porosity, $P(N_2O)$ is the emitted fraction of the total N_2O evolved in a day, AD is the adsorption factor depending on clay content in the soil (range = 0–2), and PA is the air-filled fraction of the total porosity.

2.3. DNDC input parameters

The DNDC model by (Li et al., 1992a, 1992b) provides daily and seasonal N_2O evolution from agricultural soils at the field scale using readily available input data. In this study, inputs are required in three different areas. First, climate files consisting of daily precipitation and air temperatures were collected from APHRODITE (<http://aphrodite.st.hirosaki-u.ac.jp/>). Second, soil surface properties including texture, bulk density, pH, and total organic carbon were collected from the WoSIS database (<https://data.isric.org/geonetwork/srv/eng/catalog.search#/home>) and a previous study in the study site. Last, pertinent management variables such as crop selection, timing and the amount of fertilizer N, and manure applications were determined based on the Policy of Agriculture Ministry about recommendation for paddy fertilization in Indonesia (Husnain et al., 2020). The rice yield data were obtained based on The Indonesia Statistical Institute (BPS, 2021) from year 2005–2010 over the study sites.

Furthermore, weeds and irrigation can also be included. Outputs include annual and daily fluxes of C including CO_2 , CH_4 , dissolved organic carbon, and labile and resistant pools of soil organic carbon. Similarly, annual and daily fluxes of N, including N_2O , N_2 , NO, and NH_3 , are the outputs.

2.4 Statistical analysis

Two-way ANOVA was conducted with the R software. The mean values were compared with least significant difference tests at the 0.05 level of probability. Linear regression and correlation analyses were conducted to evaluate relationships between response variables.

3. RESULTS

3.1. Climate, soil moisture, and rice production

The characteristics climate, soil moisture, and rice production were analyzed at each study site. In study site, the rainy season occurred in December, January, and February, where most of the precipitation falls. Dry season occurred in June, July, and August, where precipitation is less than 50 mm for 20 consecutive days; meteorological drought may occur (BMKG, 2019). Figure 3 shows that the total annual rainfall ($mm\ yr^{-1}$) and average annual temperature (°C) was 2724.3 and 26.89; 2471.2 and 22.24; 2395.61 and 28.27 for Cilacap, Karanganyar, and Pati, respectively. The highest precipitation was 34.38 $mm\ day^{-1}$ that occurred in Pati during the period of 2005–2010.

Consider that agricultural (rice) productivity is directly related to climatic conditions. The results showed that rice

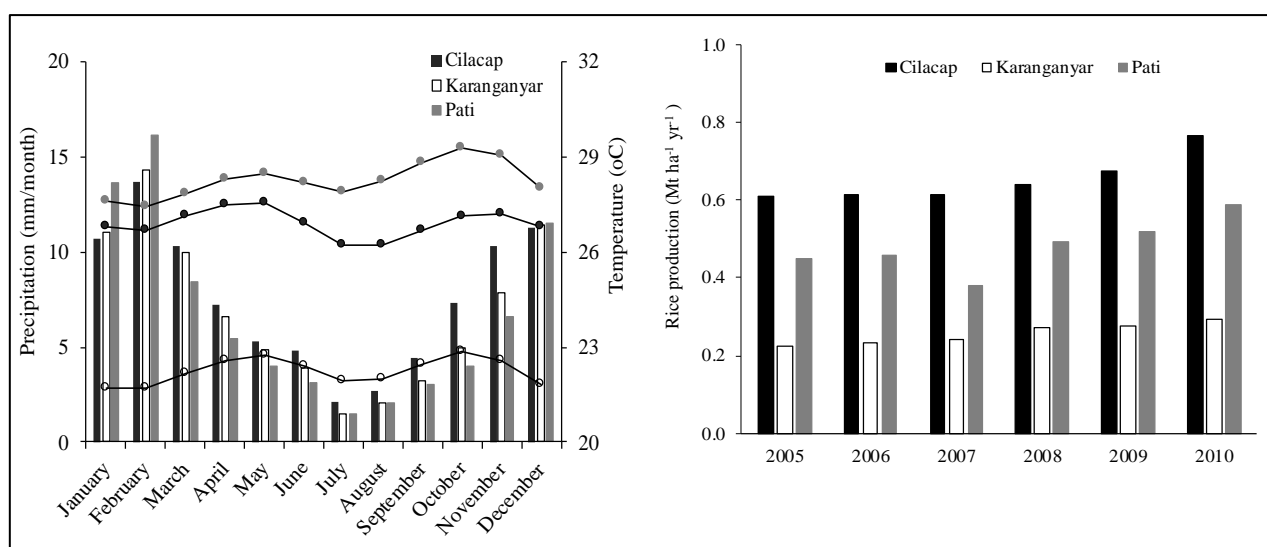


Figure 3. Climate (left) and rice production (right) over study sites.

production ($\text{Mt ha}^{-1} \text{ yr}^{-1}$) increased significantly during the period of 2005–2010, that is, 0.61–0.77 $\text{Mt ha}^{-1} \text{ yr}^{-1}$ for Cilacap, 0.22–0.29 $\text{Mt ha}^{-1} \text{ yr}^{-1}$ for Karanganyar, and 0.45–0.59 $\text{Mt ha}^{-1} \text{ yr}^{-1}$ for Pati (Figure 3).

3.2. Seasonal variability of CH₄ uptake and N₂O emission

Figure 4 shows the seasonal variability of CH₄ and N₂O fluxes with climate and soil moisture over the study sites throughout the period of rice growth from 2005 to 2010. The large N₂O emissions occurred under dry conditions when the soil moisture ranged 30%–40%, where statistical analysis showed that there is a high correlation between precipitation and soil moisture to N₂O emission in rice fields. Meanwhile, large CH₄ emissions occurred under wet conditions. A validation of soil water content estimation was analyzed, where the average soil moisture values over the study sites from 2005 to 2010 are 75.1%, 79.6%, and 82.6% for Karanganyar, Cilacap, and Pati, respectively.

Karanganyar Regency was found to have lower soil moisture causing the highest total N₂O emission up to 19 kg N $\text{ha}^{-1} \text{ yr}^{-1}$ than Cilacap and Pati (18.8 and 12.8 kg N $\text{ha}^{-1} \text{ yr}^{-1}$, respectively). Meanwhile, Pati has the higher average soil moisture (82.6%) causing enhanced CH₄ emission (360 kg C

$\text{ha}^{-1} \text{ yr}^{-1}$) compared with Cilacap (270.6 kg C $\text{ha}^{-1} \text{ yr}^{-1}$) and Karanganyar (213.7 kg C $\text{ha}^{-1} \text{ yr}^{-1}$), as shown in Table 1.

The results showed that the temperature was significantly correlated with CH₄ emission, with Cilacap having $R^2 = 0.34$. In contrast, statistical analysis showed that temperature did not significantly affect N₂O in the rice field in this study site. Table 2 shows that the temperature was significantly correlated with CH₄ emission (Cilacap (0.58), Karanganyar (–0.18), and Pati (0.05)). In contrast, statistical analysis showed that the temperature did not significantly affect the N₂O emission, for Karanganyar only.

3.3. Correlation between climate, soil moisture, rice production, and N₂O and CH₄ emissions

Climate change is a vital environmental issue that significantly affects rice productivity. Rice paddy fields are one of the greatest anthropogenic sources of N₂O and CH₄ emissions. The results showed that the annual rice production significantly ($R^2 = 0.81$) affected the CH₄ emissions in Cilacap, only. Meanwhile, the annual rice production significantly affected the N₂O emission in Cilacap and Karanganyar (0.36), while Pati (0.34) as shown in Table 2. In addition, soil moisture has affected CH₄ and N₂O emissions over study sites, as shown in Figure 5.

Table 1. Flux rates of CH₄ and N₂O from 2005 to 2010 in the study sites.

Year	CH ₄ [kg C ha ⁻¹ yr ⁻¹]			N ₂ O [kg N ha ⁻¹ yr ⁻¹]		
	Cilacap	Karanganyar	Pati	Cilacap	Karanganyar	Pati
2005	280.15	186.06	374.04	20.11	18.68	13.66
2006	269.95	173.37	359.28	17.65	16.13	11.51
2007	272.20	227.84	363.60	17.89	19.65	11.85
2008	267.84	224.88	360.06	20.08	22.04	15.02
2009	259.40	232.42	342.67	15.60	14.89	9.62
2010	274.32	237.59	363.86	21.42	22.62	15.27
Average	270.65	213.69	360.58	18.79	19.00	12.82

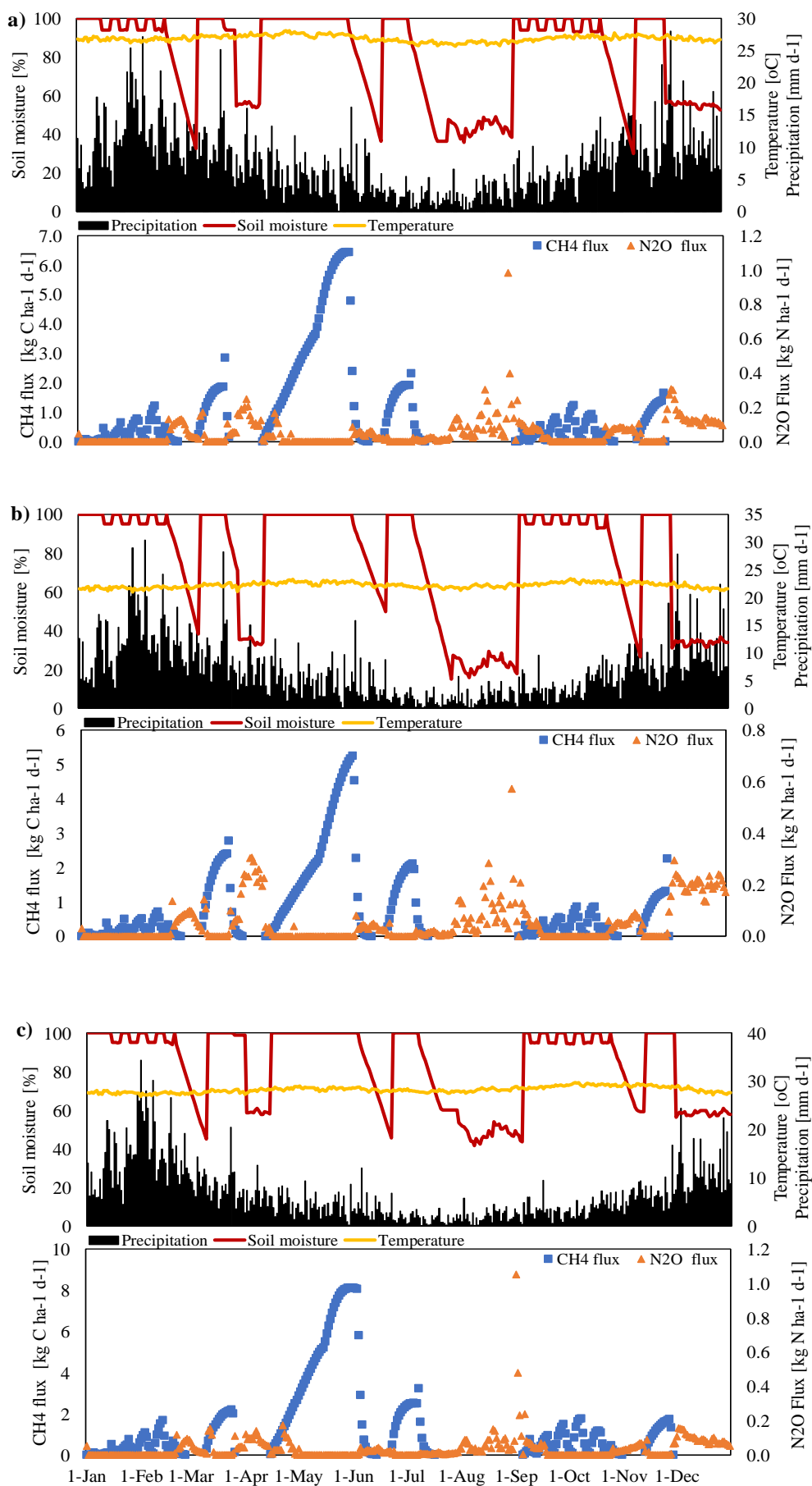


Figure 4. Seasonal variability of daily average precipitation, temperature, and soil moisture as well as of soil nitrous oxide and methane fluxes at (a) Cilacap, (b) Karanganyar, and (c) Pati sites in 2005–2010.

Table 2. Pearson’s correlation (r) between climate, soil moisture, and rice production on CH₄ and N₂O emissions.

Variables	CH ₄			N ₂ O		
	Cilacap	Karanganyar	Pati	Cilacap	Karanganyar	Pati
Precipitation	0.280*	0.692*	0.081*	0.593*	0.661*	0.228*
Temperature	0.580*	-0.182*	0.052*	-0.097*	0.175ns	-0.521*
Soil moisture	0.748*	0.323*	0.810*	0.973*	0.981*	0.810*
Rice production	-0.102*	0.810*	-0.289*	0.364*	0.365*	0.344*

Notes: α = 0.05; *: significant; ns: no significant.

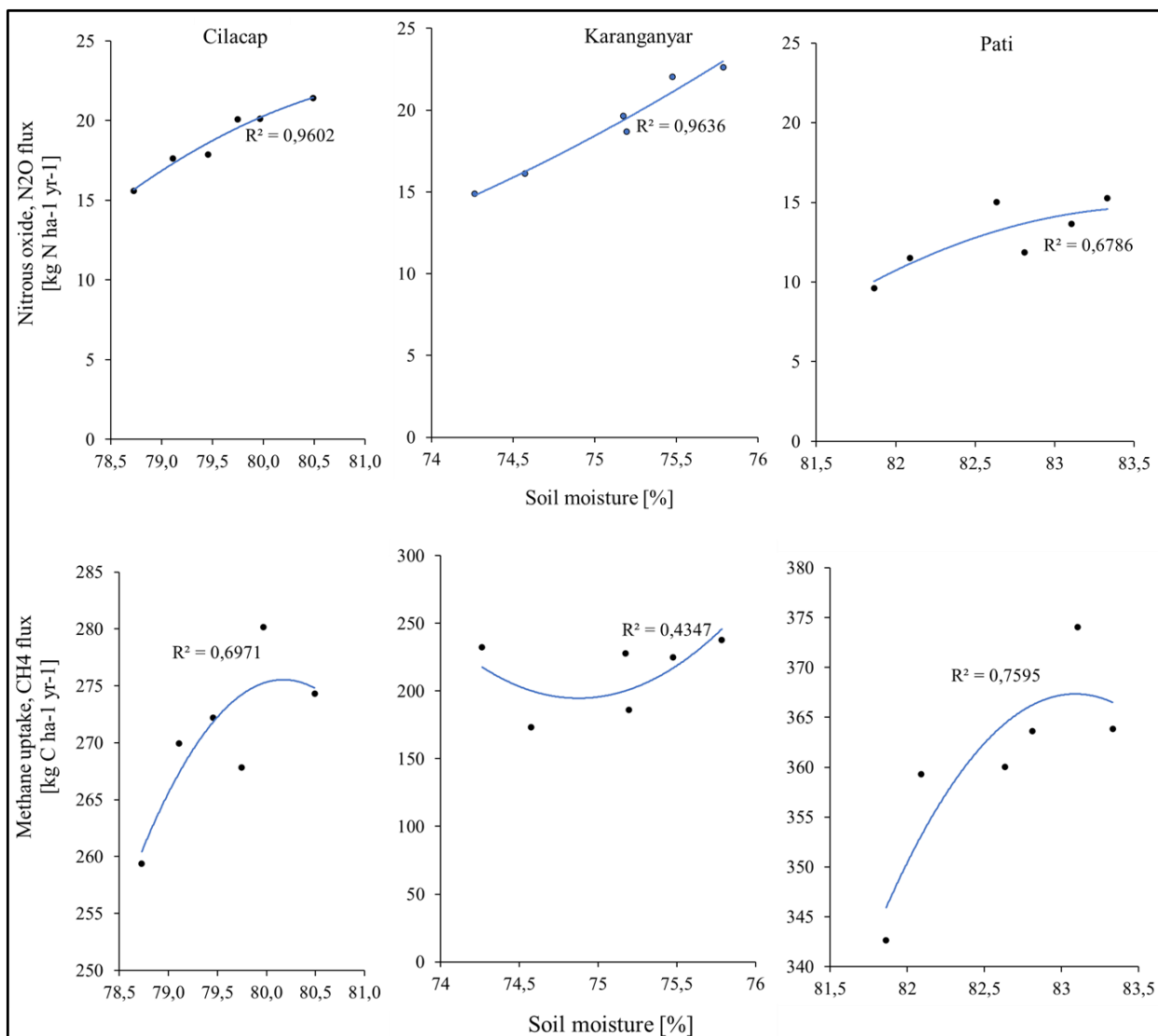


Figure 5. Regression of soil moisture and greenhouse gas fluxes in the study sites in the period of 2005–2010.

Figure 5 shows that increasing soil moisture consistently enhanced the N₂O flux at all areas, with a linear regression pattern. However, the pattern of CH₄ flux increases was parabolic, which means that the increasing soil moisture would enhance the CH₄ emission but at a certain point (peak) it would decrease. However, the pattern of CH₄ emission related to soil moisture was inconsistent in the Karanganyar District, which shows a decline along with a soil moisture increase but enhanced after a particular point.

4. DISCUSSION

In the Karanganyar, Cilacap, and Pati Districts, the N₂O emissions from rice farming were 19.0, 18.8, and 12.8 kg N ha⁻¹ yr⁻¹ and the CH₄ emissions were 213.7, 270.6, and 360.6

kg C ha⁻¹ yr⁻¹, respectively. The N₂O and CH₄ emissions in the surroundings were due to precipitation, temperature, soil moisture, and rice productivity (Table 2). The climate variables influence the biogeochemical processes, which in turn influence the soil GHG fluxes (Timilsina et al., 2020).

Overall, the temperature significantly correlated with nitrous oxide emission and the changing of methane emission over study area (Figure 3). However, the temperature at Karanganyar Regency was not correlated with N₂O emissions, probably due to lower air temperature and precipitation in Karanganyar Regency than in Cilacap and Pati Regencies. In other words, lower temperature and precipitation promote a smaller influence on nitrous oxide emissions because warmer and wetter weather enhances nitrous oxide emissions (Griffis

et al., 2017). Further, the increasing temperature affects the availability of soil moisture, which can change the flux of N from the soil as N₂O emissions (Liu et al., 2017; Liu et al., 2015). In addition, the three major processes that cause methane emissions from rice fields, namely, production, oxidation, and transport (Wang et al., 2018). The rate at which bacteria can degrade organic matter is a chain of steps, and each step is temperature-dependent, thereby causing variability in the system; Similarly, methanotrophic bacteria that oxidize methane are also stimulated by an increase in temperature (Lu et al., 2015). Therefore, temperature, along with soil moisture, is one of the most influential environmental factors affecting the rate of nutrient cycling and the production of greenhouse gases in the soil such as CH₄ and N₂O, contributing to global warming and in turn being almost influenced by climate change (Liu et al., 2017).

CH₄ and N₂O emissions tended to increase during rather longer rainy days (Figure 4), which significantly correlated with soil moisture, values of which were 0.559 and 0.946; 0.104 and 0.961; 0.656 and 0.655, for Cilacap, Karanganyar, and Pati. This is in line with a previous report (D'Imperio et al., 2017) that soil moisture was the crucial factor influencing CH₄ and N₂O emissions from soils. When there is precipitation for some consecutive days, soil moisture will increase, thus instantaneously influencing the soil microbes, soil pH, bulk density, and soil pore space, hence releasing the GHG fluxes (Li et al., 2020). In addition, the N₂O emissions increase under successive moist and dry periods (Zhang & Niu, 2016). Moreover, the soil drying and wetting cycles caused by precipitation stimulated the mineralization of soil organic matter, resulting in rapid soil carbon losses; such a phenomenon is called the "Birch effect" (Birch, 1964).

This study found the significant correlation of rice production with the N₂O emissions in Central Java, Indonesia. The main reason for N₂O emissions from agricultural soils is the application of inorganic fertilizers and/or manure when plants cannot absorb all of the nitrogen (N) provided because the growth stage does not require all of them (Wang et al., 2021), making the zones of N₂O formation more potential. Similar findings were also reported where the application of N fertilization (Zhao et al., 2019) and irrigation management practices (Jiang et al., 2019) contributed to N₂O emissions. Because the global demand for rice production increases with population growth (FAO, 2017) and higher atmospheric N₂O concentrations (global average 1875 ppb) raise concerns about global warming (Tian et al., 2016), an effective management strategy is needed to reduce GHG emissions while maintaining high rice yields (Islam et al., 2018).

Because Indonesia is the third largest rice producer and as the fourth most populous country in the world, and also one of the world's main rice consumers (GRISP, 2013), rice is grown in the major islands of Indonesia, but most rice is cultivated in Java on an estimated land area of 3.1 million ha (Ministry of Agriculture, 2018). However, because agricultural land is a major contributor to CH₄ and N₂O emissions (Zhou et al., 2014), it is very important to have a comprehensive understanding of the feedback between agricultural soils (that is, rice) and the ongoing climate change crisis (that is, GHG emissions) in Indonesia. Monitoring the CH₄ and N₂O

emissions will contribute to support decision-making toward sustainable agriculture for the Indonesian government and relevant stakeholders. This study proves that the DNDC model can possibly predict the CH₄ and N₂O emissions in Central Java when incorporated with various secondary climatic and land management big data resources.

5. CONCLUSIONS

The DNDC model estimated that the N₂O and CH₄ emissions in Central Java, Indonesia, from 2005 to 2010 reached 18.8 and 270.6; 19.0 and 213.7; and 12.8 and 360.6 kg N/C ha⁻¹ yr⁻¹ in the Cilacap, Karanganyar, and Pati regions, respectively. The major factors influencing the emissions were precipitation, temperature, soil moisture, and rice productivity in each region. Since fertilizer input and irrigation practices may contribute to the N₂O and CH₄ emissions, further studies on agricultural practices on the emissions are suggested.

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Declaration of Competing Interest

The authors declare no competing financial or personal interests that may appear and influence the work reported in this paper.

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