Estimating Greenhouse Gas Emissions from Irrigated Paddy Fields in Indonesia under Various Water Managements

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Abstract. Methane (CH_4) and nitrous oxide (N_2O) are two main greenhouse gasses emitted from paddy irrigated paddy fields. Their fluxes are commonly affected by water managements in the fields. However, the main problem in the study of greenhouse gas emissions in paddy fields is the instrumentation for measuring emissions. Measurements of greenhouse gas emissions are costly and complicated. The current study proposes estimating method to quantify greenhouse gas emissions by an artificial neural network (ANN) model. They are estimated based on easily measurable parameters such as soil moisture, soil temperature, soil electrical conductivity (EC), soil redox potential (Eh) and soil pH. The model was verified based on field experiments that were conducted in Bogor, West Java, Indonesia during 26 March – 24 June 2015. Here, three regimes of water management, i.e. continuous flooded (FL), moderate (MR) and dry (DR) regimes, were performed in the field. The DR regime released the lowest total greenhouse gas emissions; however, it reduced grain yield by 58% and 12% compared to the FL and MR regimes respectively. The developed model showed high accuracies for both greenhouse gasses estimation where the coefficients of determination (R^2) values were 0.84 and 0.76 for CH_4 and N_2O prediction respectively.

1. Introduction

Water management in rice production affects greenhouse gas emissions, including methane (CH_4) and nitrous oxide (N_2O). Many research findings have reported CH_4 emissions increasing under flooded water when soil is saturated [1]. On the other hand, N_2O emissions are released at a higher rate when there is limited water under aerobic soil conditions [2]. CH_4 is commonly formed during decomposition of organic materials when there is limited oxygen and sulfate in the field [3]. Organisms that play a major role in the process of forming this gas are called methanogenic bacteria. Meanwhile, N_2O gas is primarily formed by nitrification and denitrification processes in the soil [4].

Research on greenhouse gas emissions in paddy fields were first conducted in 1998 in Indonesia. The two gasses in discussion are commonly measured using a closed chamber box with specific dimensions placed over a single/multiple paddies. Then, the gas sample is collected from the chamber and it is quantified using a gas chromatograph in the lab [5]. The method is time consuming and complicated however, and uses more expensive equipment. In addition, gas sampling is usually conducted in the afternoon, which does not represent all conditions in a day.

The quantifying method for the two greenhouse gases from paddy fields comes with limitations, which need to be recognized. Greenhouse gas emissions released to the atmosphere are affected by environmental parameters including soil moisture, soil temperature and soil pH [6]. In addition, those two gasses are produced under soil reduction-oxidation (redox) processes and intermediated by the soil microbes as and fertilizer application. The fertilizer application is an important factor in influencing greenhouse gas emissions from the soils, particularly N_2O emission [7]. The environmental parameters that showed those activities are represented by soil redox potential and soil electrical conductivity.

The relationship between greenhouse gasses and the environment are complex and very difficult to develop mathematical models. Because of this limitation, artificial neural networks (ANN) would be a more appropriate method to use. It can learn and recognize the patterns of empirical data without explicit physical consideration [8]. It has been used in many agricultural aspects such as irrigation planning and application [9], especially to estimate subsurface wetting by drip irrigation [10]. The objective of this study is to propose an ANN model to estimate greenhouse gas emissions, i.e., CH_4 and N_2O based on easily measurable parameters such as soil moisture, soil temperature, soil electrical conductivity (EC), soil redox potential (Eh) and soil pH. The developed model is then validated by the empirical data.

2. Materials and Methods

2.1 Field experiment and design

The model to estimate CH_4 and N_2O emissions was developed based on field experiments that were conducted in paddy fields located in Bogor, West Java, Indonesia from 26 March to 24 June 2015. Here, three plots were supplied with different irrigation regimes with two replications. The total area for the first replication was 237 m^2, and the second was 185.2 m^2 (Figure 1), the first being under the continuous flooding regime (FL) for conventional rice farming. The water level was kept at 2 and 5 cm in depth above the soil surface from the beginning of the cultivation period until approximately 7 days before harvesting, and then the field was conditioned dry in the harvesting. For the second plot the moderate irrigation regime (MR) was used, in which the soil moisture was kept at a saturated level or water level in the soil surface at the beginning until approximately 7 days before harvesting, and then the field was conditioned dry in the harvesting. The last plot was dry irrigation regime (DR) in which the water level was kept at soil surface from the beginning to 20 days after transplanting, then the water level was drained at -5 cm water depth until approximately 7 days before harvesting, and then the field was conditioned dry in the harvesting.

The soil texture was identical in all plots and there was no significant difference between them, it was classified as clayey, having a clay content of 46.1 ± 3.0%, silt of 29.7 ± 2.3% and sand of 24.2 ± 4.8%. One day before planting, compost (manure) was sown to the field with doses of 5 ton/ha, then Phonska and Urea fertilizers in identical doses of 75 kg/ha were sown 20 days after transplanting to the fields. Silica fertilizer was then sown 30 days after transplanting with a dose of 100 kg/ha. Finally, Phonska and Urea fertilizers were sown again 40 days after transplanting with each dose of 75 kg/ha.

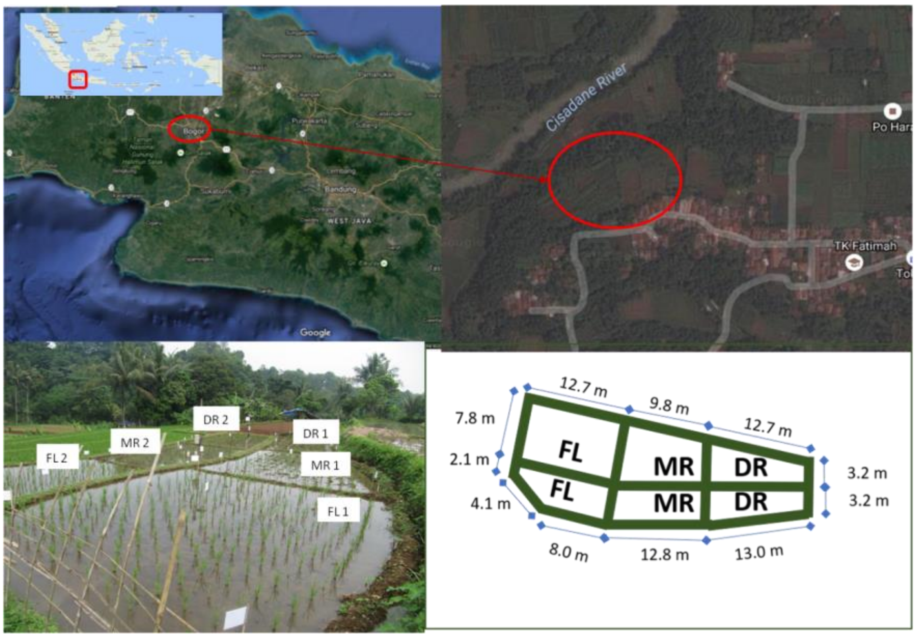

Figure 1. Experimental design and field location in West Java, Indonesia.

2.2 Environmental parameters measurements

Soil parameters consisted of soil moisture, soil temperature, soil EC, soil redox potential (Eh) and soil pH. Soil moisture, soil temperature and soil EC were measured by a 5-TE sensor from Decagon Device Corp at 5 cm soil depth, while soil pH and Eh were measured by pHmeter (pH 3310 SET 2 incl. SenTix® 41), and ORP meter (WTW Sentix), respectively. In particular for soil Eh measurement, the output of ORP meter is first converted by normalizing the redox value according to a SHE (*Standard Hydrogen Electrode*) reference electrode on the redox observed by the instrument. Soil Eh values range from -300 mV to 700 mV, in which 300 mV is border of aerobic and anaerobic conditions [11].

Meanwhile, greenhouse gas emissions were measured manually using a closed chamber box. The size of the chamber was 30 x 30 x 120 cm and equipped with a fan to circulate air inside the box. There are four samples were taken on 0, 10, 20, 30 minutes after the chamber is placed in the fields. Then, the sampling gas was quantified using a GC (Micro GC CP 4900) with flame ionization detector (FID) in the lab.

2.3 Artificial Neural Network (ANN) Model

CH_4 and N_2O emissions were estimated by using the ANN, a computational mode that learns the dataset given to produce a model that represents the nature of the data. It behaves like a black box that receives input, and produces an output. The ANN model only suggested system modeling where high complexity or uncertainty occurs. It will provide a good prediction, even if the nonlinearity of the system being predicted is high [12]. Since ANN is a learning data model, the more data provided for training, the more accurate the result of prediction is. However, nearly a hundred-percent-accurate modeling dataset should also be avoided, as it is over-fitting phenomena that damage the generalization [13].

The current model consisted of three layers, i.e. input, hidden and output layer. As input, there were five nodes consisting of soil moisture, soil temperature, soil EC, soil Eh and soil pH respectively. Those parameters were selected because of their effects on greenhouse gas emissions from paddy fields. CH_4

and N_2O gasses were set as output nodes (Figure 2). Each layer was connected to a hidden layer that was represented by weight values, which are the output of the model that will be used to estimate greenhouse gas emission. Finding optimal weight values, the learning method is back propagation that has two main steps. The first step is propagation (forward and backward propagation), and the second is weight updated by minimizing the errors. Here, for the activation, a sigmoid function was used with the following equations:

$$f(y) = \frac{1}{1+e^{-gy}}, \tag{1}$$

$$y = \sum_{i=0}^{n} x_i w_i \tag{2}$$

where f(y), xi, wi, n, y, g are activation values, the inputs, weights, number of inputs, total signal input and gain parameter, respectively.

The algorithm was developed by Visual Basic Application in MS. Excel 2007. The performance was evaluated by comparing observed and estimated data that was represented by a coefficient of determination (R^2). The R^2 value ranged 0 to 1. Higher R^2 and its score closer to 1 indicated that the model was accurate.

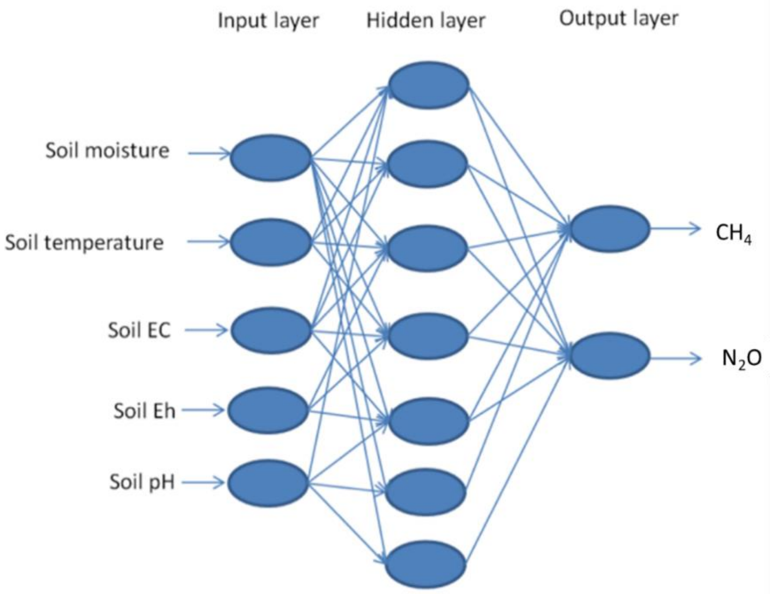

Figure 2. The ANN model to estimate greenhouse gas emission from paddy fields.

3. Results and Discussion

3.1 Greenhouse Gas Emissions and Environmental Parameters

Figure 3 shows seasonal variations of greenhouse gas emissions under different water levels, soil moisture and soil Eh. The FL regime released more CH_4 emission, particularly during 0-21 days after transplanting and reached its peak on 35 days after transplanting. It occurred when standing water materialized in the field, with an average of 2.1 cm above soil surface, the soil moisture was 0.631 m^3/m^3 caused by an anaerobic condition that was presented by soil Eh value (<300 mV) with its interval being 129.9 – 171.9 mV. This condition promotes more methanogen activities during organic matter decomposition, resulting in more CH_4 emissions when oxygen and sulfate were limited [14]. On the other hand, when average water level reached 0.3 cm below soil surface and the average soil moisture was 0.542 m^3/m^3 during that period in the DR regime, the flux of CH_4 was negative, which indicated an oxidative process in aerobic condition (soil Eh > 300 mV) had occurred in the fields.

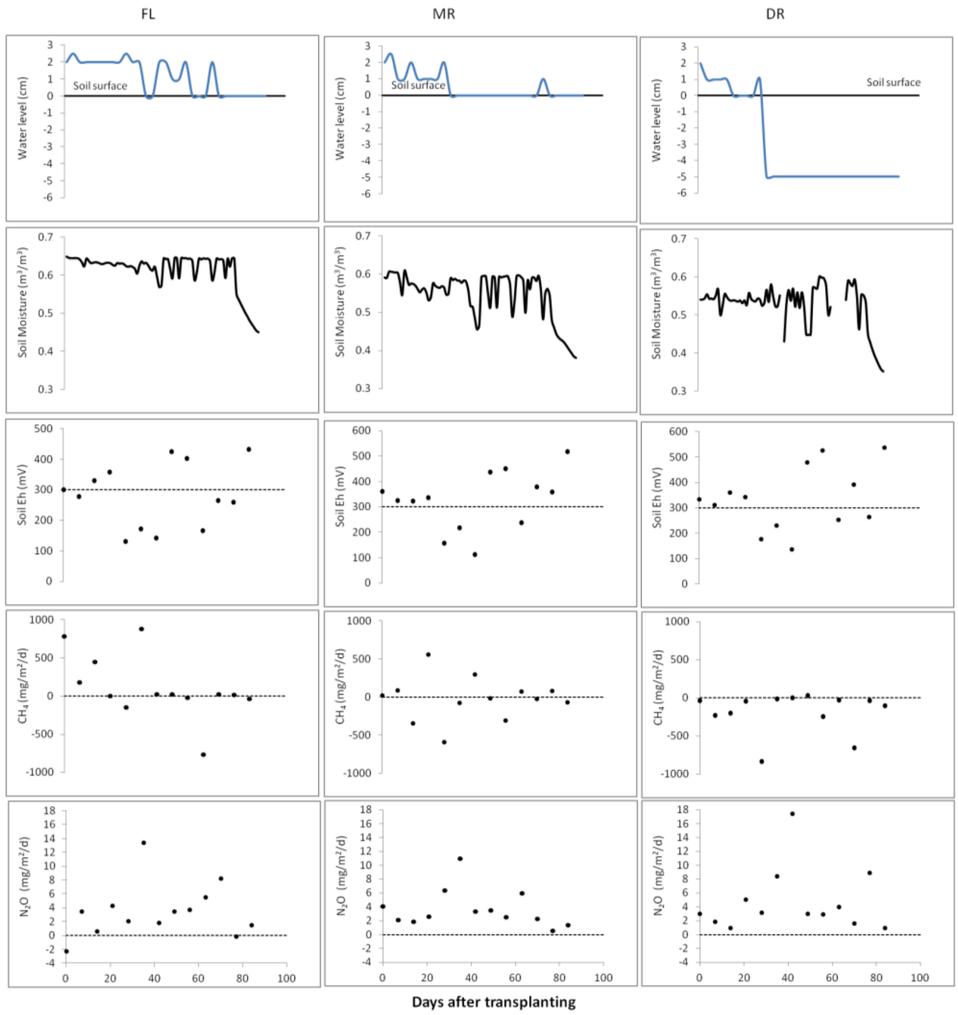

Figure 3. Seasonal variations of greenhouse gas emission, water level and soil moisture

For N_2O emission, the flux was comparable and there was no significant difference among the regimes, particularly during the first 28 days after transplanting. The average of N_2O emission in this period was 2.0, 2.9 and 2.9 $mg/m^2/d$ for FL, MR and DR, respectively. N_2O emission had different characteristics with CH_4 emission; it mainly being affected by fertilizer application [14, 28]. 28 days after transplanting, fertilizer was sown at regular doses for all plots, soil EC had no significant difference among regimes. N_2O is a byproduct of nitrification and denitrification from biological processes. In aerobic soil where O_2 level is relatively high, N_2O is mainly formed by nitrification process [15]. This probably occurred during the DR regime, when the water level was dropped after 31 days after transplanting became 5 cm below soil surface and soil Eh was 342.1 mV, the N_2O emission increased significantly. It was revealed that aerobic conditions under DR treatment promotes more microbial processes, i.e. nitrification and denitrification in soil, producing N_2O. This result was similar with previous finding that stated its flux is limited in the flooded, on the other hand the flux reaches maximum at the beginning of the disappearance of flooding water in the soils. Also, when N fertilizer is supplied to the field, N_2O flux rises dramatically [16].

Table 1. Total greenhouse gas emissions and rice productivity in each water regime.

	Irrigation Regimes		
Parameters	**FL**	**MR**	**DR**
CH_4 (kg/ha)	65.3	-16.7	-163.4
N_2O (kg/ha)	3.2	3.1	4.2
GWP* (kg $CO_{2\text{-eqv}}$)	2591.7	516.2	-2821.8
Grain yield (ton/ha)	4.16 + 0.68	2.96 + 1.02	2.64 + 1.02
Biomass yield (ton/ha)	12.96 + 1.81	10.4 + 0.91	13.36 + 0.57
Irrigation water (mm)	510.4	447.3	434.6

* GWP: Global Warming Potential at the 100-year time horizon of 25 and 298 for CH_4 and N_2O, respectively (IPCC 2007).

In total, greenhouse gases were emitted at different levels under three water management regimes (Table 1). The FL regime with maintaining higher water levels released more CH_4 emissions, particularly in the early growth stage to mid-season stage. CH_4 emissions were released to the atmosphere during flooding conditions when soil moisture was at a saturated level. Meanwhile, the DR regime released the highest N_2O emission when drought conditions occurred by maintaining water levels at -5 cm below the soil surface, starting from 20 days after transplanting. This result indicated that CH_4 and N_2O emissions have an opposite trend. global warming potential (GWP) is therefore used as an indicator to represent total greenhouse gas emissions. Table 1 shows that DR regime has the lowest GWP, but it significantly decreases the rice yield. The grain yield of DR regime was 58% and 12% lower than that FL and MR regimes, respectively. It was indicated that under limited water, more spikelet sterility occurred, particularly around flowering time. FL regime produced the highest yield of 29% and 37% higher than that of the MR and DR regimes. It was revealed that to obtain optimal grain yield, water stress should be avoided. Meanwhile, the MR regime released greenhouse gas emission at a lower rate of 80% than that of the FL. In addition, it saved more water irrigation, by being 12.4% lower than the FL regime, also decreasing rice yield by 29%. Therefore, the MR regime may be the most effective option for water management in Indonesia for mitigating greenhouse gas emissions.

3.2 Model Validation

The ANN model has the ability to capture the non-linearity of a system, including as a solution to making a model of CH_4 and N_2O flux emissions form paddy fields that have a complex relationship with the soil parameters. Figure 4 shows validation results of the developed model, with high accuracies for both greenhouse gas predictions where the coefficients of determination (R^2) values for CH_4 and N_2O were 0.84 and 0.76. The values, nearly 1 ($R^2 \approx 1$), indicated a good relationship between the model and the observed data, thus the developed model is acceptable [17]. N_2O emissions were estimated less accurate than CH_4 emission, most likely caused by overestimation since insignificant differences of N_2O emission were observed in a previous study [18].

The model was accurate in predicting greenhouse gas emissions from a paddy field. Since the field experiments were conducted under certain soil and climatic conditions, we recommend conducting more field measurements that represented any soil and climatic conditions to enrich the observed data, so the model can be trained under a wider interval of soil and climatic conditions.

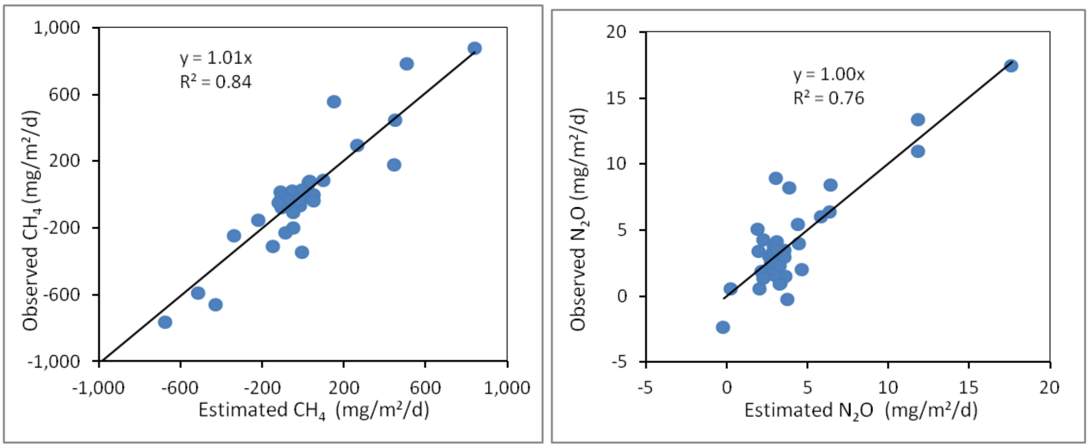

Figure 4. Validation results of the developed ANN model.

4. Conclusion

Based on our experiments, water management was correlated to rice productivity and greenhouse gas emissions. Maximum grain yield can be obtained under sufficient water supply as represented by the FL. However, this regime released more greenhouse gas emissions as indicated by the highest amount of GWP. MR may be an effective option for water management in Indonesia for mitigating greenhouse gas emissions without losing significant yield. The developed ANN model was effective to predict greenhouse gas emissions, i.e. CH_4 and N_2O, using easily measurable inputs such as soil moisture, temperature, electrical conductivity, Eh and pH. The developed model showed excellent accuracies for both greenhouse gas predictions where the R^2 values for CH_4 and N_2O were 0.84 and 0.76. To conclude, this model can be applied to other rice cultivation systems with similar soil and climate characteristics. For wider application, it is recommended that more field experiments be conducted to better train the model under a wider interval of soil and climatic conditions.

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