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Genetic Algorithms Optimization for Water Management in Irrigated Paddy Fields

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Abstract. Water management in paddy fields is main key to produce more yield and mitigate greenhouse gas (GHG) emissions at the same time. Commonly, Indonesian farmers apply continuous flooding irrigation to combat weed growth and gain maximum yield as well. However, this method is less efficient in water use and releases more GHG emissions as represented by Global Warming Potential (GWP) value. The System of Rice Intensification (SRI), as alternative rice farming, applies intermittent irrigation that has possibility produce more yields with minimum GHG emissions. However, optimum water management for these purposes is not clear yet. The objective of this study was to search optimal soil moisture and water depth in each growth stage using genetic algorithms (GA) model for SRI rice farming. GA model was developed based on one rice season experiment that was conducted during January to May 2018 with three water management regimes, i.e., flooded (FL), moderate (MD) and dry (DR) regimes, respectively. Based on the experiment, MD regime produced highest yield by 5.26% and 10.89% higher than those FL and DR regimes, respectively. So this was the best regime among others. However, this regime release more GHG emissions than that DR regime in which its GWP value was 87.85% higher than that DR regime. So, the GA model was used to find the better regime than that MD regime. Based on those empirical data, GA model found optimal soil moisture and water depth in four growth stages. Based on GA optimal scenario, the yield can be increased up to 1.31% higher than that MD regime and GWP can be reduced up to 8.62% lower than that MD regime. More field experiments are needed to validate the model under various climate conditions.

Keywords: genetic algorithms, water management, paddy fields, system of rice intensification

1. Introduction

In the tropical paddy fields such as in Indonesia, most farmers used more water irrigation to cultivate rice by keeping water depth 2-5 cm above soil surface continuously until the late season growth stage. This anaerobic condition will promote more activities of methanogens bacteria in reducing CO_2 and produce more methane emission during soil organic matter decomposition [1]. Thus, paddy field with

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flooded water is known as major source of methane emission. Methane is one of greenhouse gas that has contribution in global warming of 25 times higher than that carbon dioxide (CO_2) [2]. In addition, flooded water is less efficient in water use since more water is loss through deep percolation, seepage and runoff [3].

The two main reasons adopted flooded waters are to combat weed growth and avoid lack water when water resource is limited during cultivation period. Also, sometime it can reduce nitrous oxide (N_2O) emission during nitrification and denitrification process in the soil [4] or even absorb nitrous oxide [5]. Nitrous oxide is also one of greenhouse gas that has paying attention since it effect to global warming is 298 times higher than that carbon dioxide [2] However, flooded water continuously is not always associated with higher yield or even reduce yield [6]. The possibility of reducing yield in flooded water is less tiller numbers developments in vegetative stage and then following by less panicles development in the next stage [7].

The System of Rice Intensification (SRI) is wished as alternative rice cultivation with possibility produces more rice by less water and low greenhouse gas emission in total that is represented by global warming potential (GWP) value [8]. The SRI has at least six basic components that basically different with ordinary rice farming in Indonesia. The components are application of young seed while 2-3 leaf developed during 7-14 days, single transplanted seed in one hill, wider spacing between the hill, intermittent irrigation application, weeding regularly and compost/organic fertilizers application as much as possible to enhance soil organic matter [9]. Regarding application of intermittent irrigation, saturated soil or thin water layer depth is applied during particular time and then water is drained in others particular time. Following Arif et al. 2014 [10], it has been recommended that optimal water management for SRI is by maintained saturated soil (wet condition) during initial and vegetative/crop development growth stages, and then water level can be reduced by kept soil moisture at medium level in mid-season growth stage and finally drained water in late season growth stage to conditioned soil moisture at dry level. This scenario can increase yield 4.4% and save water input up to 12.28% compared to continuously saturated soil condition water regime.

However, that optimal water management didn’t consider greenhouse gas emission effect. Thus, optimization water management in paddy fields by considering greenhouse gas emission is important especially to minimize GWP from paddy fields. Sometimes in the developing optimization model for irrigation application, there are some constraints in integrating many aspects such as weather conditions, plant growth condition and soil condition as well [11]. Here, Genetic Algorithms (GA) model can be proposed as alternative optimization method since it can search optimum global value by searching the entire population instead of moving from one point to the next as the traditional methods [12].

The main objective of this research is to find optimal irrigation water for the SRI that is represented by optimal soil moisture and water depth in four growth stages, i.e., initial, crop development, mid-season and late season stages to maximize yield and minimize GWP value. In addition, land productivity and water use efficiency are also considered in the developed model.

2. Materials and Methods

2.1 Field experiments and water regime applications

Achieving the objectives, one rice planting season was conducted during 20 Jan to 13 May 2018 in wet-dry season in the field laboratory of Dept. of Civil and Environmental Engineering, West Java Indonesia. Here, rice (*Oriza sativa* L) variety of *Pertiwi* by SRI components are single transplanting, young seed (14 days after sowing), single planting in one hill with 30 cm x 30 cm interval were used.

However, chemical fertilizers with doses of 275 kg/ha for urea, 100 kg for SP-36 and 150 kg/ha for KCl, respectively were used instead of organic fertilizers. Soil properties both chemical and physical properties can be shown in Table 1. Crop growth stages were divided into four stages, i.e., initial (0-27 days after transplanting (DAT)), crop development (28-72 DAT), mid-season (73-96 DAT) and late season stages (97-112 DAT) based on FAO's standard [13].

Table 1. Soil properties of field location

Soil properties	Parameters	Value
Chemical	pH (H_2O)	7.5
	C (%)	3.84
	N (%)	0.2
	C/N	19
Physical	Soil texture:	
	Sand (%)	23
	Silt (%)	34
	Clay (%)	43
	Permeability (cm/h)	8.17
	Bulk Density (g/cm^3)	1.98

For water management, there were three regimes, i.e., flooded (FL), moderate (MD), and dry (DR) regimes. We prepared 2 m x 2 m plot for each water regime. In FL regime, water depth 2-5 cm above soil surface was expected in kept during first to third growth stages, and then water was drained in the last stage. MD regime was set as moderate application in which water depth at nearly soil surface (0 cm water depth) was expected during first to third growth stages, and then water was drained in the last stage. The last regime, DR regime, was set as extreme water application with water stress condition in which water depth at nearly soil surface was expected only during 0-20 days after transplanting (DAT), after root developed well then water depth was set at 5 cm below soil surface until the end of third growth stage, and then in the last stage water was drained as the same two regimes before.

2.2 Field Measurement Parameters

To perform optimization model, some parameters in the fields consisted of plant growth performance, meteorological and soil parameters were measured as well as greenhouse gas emissions using some instrumentations. For growth performance, plant height, tiller and panicle numbers were measured manually every 3 days in which 5 hill samples were selected in each plot. For meteorological parameters, air temperature, relative humidity, precipitation, solar radiation, wind speed and direction were measured using automatic weather station (AWS) equipped with particular sensors with 30 minutes interval. The meteorological were used to determine crop evapotranspiration and water analysis.

Soil parameters were measured using specific sensors consisted of 5-TE sensor (Decagon Device Ltd) to measure soil moisture, soil temperature and soil Electrical Conductivity (EC) with 30 minutes interval, pHmeter (pH 3310 SET 2 incl. SenTix® 41) to measure soil pH and ORP meter (WTW Sentix) to measure soil redox potential (Eh) once a week. In particular soil Eh measurement, the output of ORP meter should be converted first by adding the redox value according to a SHE (*Standard Hydrogen Electrode*) reference electrode on the redox value measured by the instrument. Soil Eh values range from -300 mV to 700 mV, in which its value lower than 300 mV shows an anaerobic condition [14].

Greenhouse gas emissions were measured using a static closed chamber method [15] with the modification. This method was widely applied in greenhouse gas emission studies such as Kudo et al. 2014 [16]. The chamber was rectangular acrylic with size was 30 cm length x 30 cm width x 120 cm height equipped with mini fan to circulate air during measurement (Figure 1). The gas samples were collected at noon time using syringe four times at 0, 10, 20 and 30 minutes after the chamber placed over the single plant. Gas sample in the syringe was immediately transferred into 200-ml tedlar bag, and then collect 10-ml gas sample from that tedlar bag and transferred into 10-ml vial bottle. Each gas sample in the vial bottle then was analyzed using a gas chromatograph (Micro GC CP 4900) with flame ionization detector (FID) in the lab. From four samples, four different concentration of greenhouse gas were collected and then the flux was calculated by the following equation:

$$E = \frac{\delta C}{\delta t} \times \frac{V_{ch}}{A_{ch}} \times \frac{mW}{mV} \times \frac{273.2}{273.2+T}, \quad (1)$$

where E is the flux of each gas (in mg/m^2/min), δC/δt is slope of four different concentration during sampling time (in ppm/min), V_{ch} is volume of chamber (in m^3), A_{ch} is area of chamber (in m^2), mW is mass of molecule (in g), mV is volume of molecule (in liter), and T is temperature inside chamber during measurement (in °C).

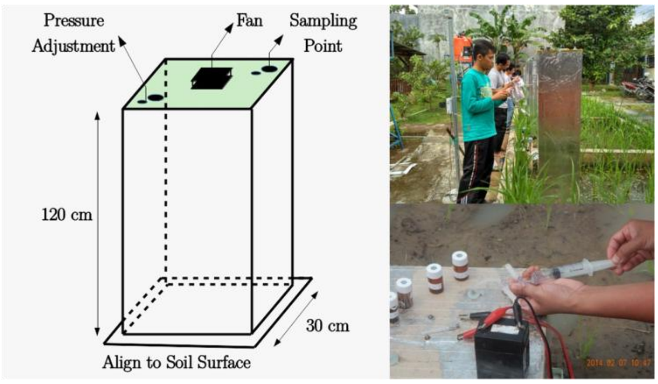

Figure 1. Chamber box schema for greenhouse gas measurement in the fields.

2.3 Optimization model development

Genetic algorithms (GA) model was developed with maximizing the following objective function:

$$F(Y, GWP) = aY - bGWP \quad (2)$$

where Y is yield (ton/ha) and GWP is global warming potential, a and b are coefficient of those two parameters given by 0.65 and 0.35, respectively. GWP was calculated based on CH_4 and N_2O emissions total in one season with the following equation:

$$GWP = 25 \times CH_4 + 298 \times N_2O \quad (3)$$

The constraints of the objective function were given as follow:

$$WL_{min} \le WL_1, WL_2, WL_3, WL_4 \le WL_{max} \quad (4)$$

$$SM_{min} \leq SM_1, SM_2, SM_3, SM_4 \leq SM_{max} \tag{5}$$

Where WL_{min} and WL_{max} are minimum and maximum water depth, SM_{min} and SM_{max} are minimum and maximum soil moisture based on empirical data in each growth stage, WL_1, WL_2, WL_3, WL_4 are optimum water depth in the initial, crop development, mid-season and late season growth stages, respectively and SM_1, SM_3, SM_3, SM_4 are for optimum soil moisture in those consecutively growth stages.

To search optimal parameters, chromosome structure of the GA model was represented by an individual that was coded as a set of six-bit binary strings with the fitness function was the same as the objective function (Equation 2). The operators of the model consisted of crossover and mutation in which the rates were 60% and 5% for crossover and mutation, respectively.

3. Results and Discussion

3.1 Effect of water regimes on plant growth performances

Figure 2 shows effects of water regimes on the plant growth performances in term of plant height, tillers and panicles numbers. All those parameters were comparable among the regimes and not significant different. FL and MD regimes have higher plant height than that DR regime. However, higher plant height in FL regime was not associated to more tillers and panicles numbers. Comparing to MD regime, tillers and panicles numbers in FL regime was lower. It was indicated that MD regime has the best growth performance among others. In the harvesting day, total numbers of tillers and panicles in this regime were 25 and 24, respectively. Meanwhile, total numbers of tillers for FL and DR regime were 22 and 23, respectively, while total numbers of panicles in both regimes were same numbers, 22. The best performance in MD regime showed that non-flooded water promoted more tiller development particularly in the vegetative stage.

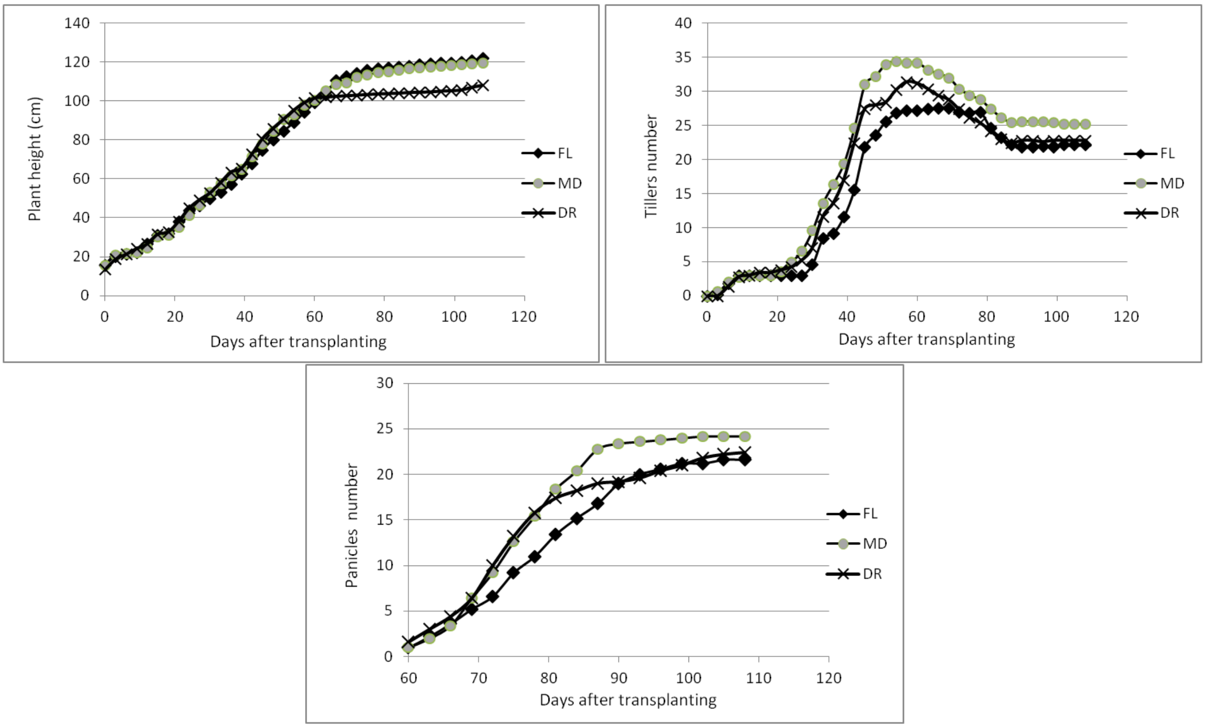

Figure 2. Plant growth performances under different water regimes.

3.2 Actual water depths and soil moisture condition

The weekly actual water depth of each regime is shown in Figure 3. The FL regime was intended to be flooded continuously, but the water depth was fluctuated and it has highest water depth in which water flooded was occurred during vegetative growth stage particularly from 2-10 weeks after transplanting. It is indicated that water loss through evapotranspiration and percolation higher than that its irrigation rate. On the other hand, the actual water depth in both MD and DR regimes were lower than soil surface during planting period. The highest water depths in both regimes were during vegetative growth stages in 1-4 weeks after transplanting. Although weekly average water depths were lower than soil surface, MD regime has the best growth performance as previously presented. It was probably caused by more oxygen availability under non-flooded, thus enhanced more tiller development. This reason is dealing with the previous finding that aerobic condition promoted more activities particularly root activity [17] and even for shoot activity under intermittent irrigation [18].

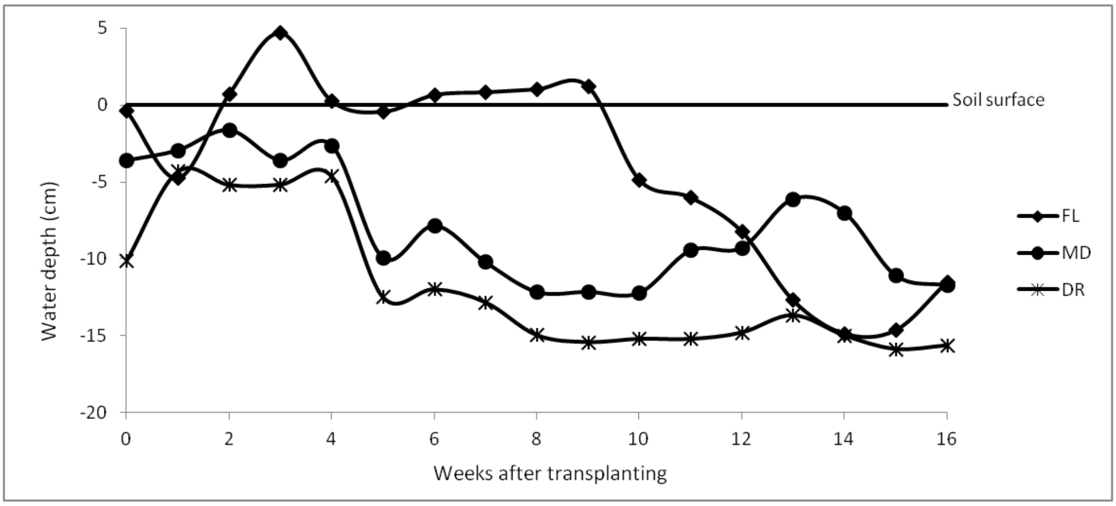

Figure 3. Actual water depth in each water regime.

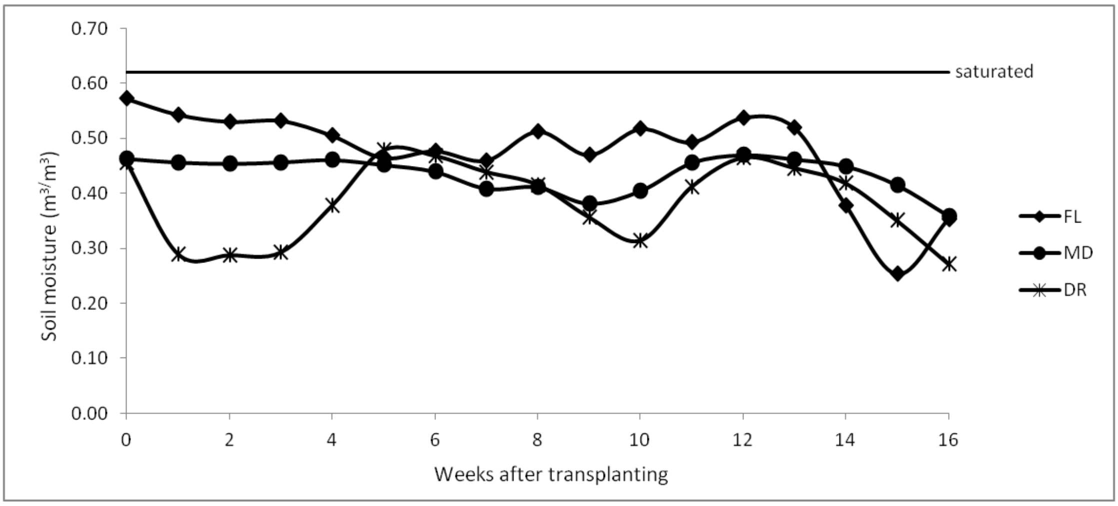

Figure 4. Actual soil moisture in each water regime.

The higher water depth in the FL regime was corresponded to higher soil moisture as shown in Figure 4. The soil moisture of FL regime was higher than that two others regimes almost in planting period except in three weeks before harvesting. It was represented that the FL regime was supplied more irrigation than that two other regimes. The average soil moisture in vegetative (initial and crop development) growth stage was 0.51 m^3/m^3, 0.44 m^3/m^3, 0.38 m^3/m^3 for the FL, MD and DR regimes, respectively. Meanwhile, in the generative (mid-season and late season) growth stages, the average soil moisture was respectively 0.41 m^3/m^3, 0.43 m^3/m^3, 0.39 m^3/m^3 for the FL, MD and DR regimes.

3.3 Effect water regimes on greenhouse gas emissions

Figure 5 shows seasonal CH_4 flux during planting period under different regimes. The peak of CH_4 emissions occurred during 3 – 9 weeks after transplanting particularly in the FL and MD regimes. On the other hand, CH_4 emission in the DR regime was lower than those the FL and MD regimes almost during planting season except in 2 weeks after transplanting. The FL regime released highest CH_4 emission in total as represented by more CH_4 emission during 3 – 9 weeks after transplanting. The average of CH_4 emission during that time was 353, 316 and -0.73 $mg/m^2/d$ for the FL, MD and DR regimes, respectively. More CH_4 released in the FL regime during that time when water depth and soil moisture higher than those others regimes (Figures 3- 4). It was indicated that more water in the field enabled methanogens activities and promoted CH_4 gas development during decomposing process. Also, CH_4 emission is released more when the oxygen limited in the field [19] This finding dealing with many previous recent studies related with water management and CH_4 emission [20, 21].

On the other hand, after 10 weeks after transplanting less CH_4 emitted in all regimes or even their values were negative. It was occurred when the water was started drained particularly in the FL regime as indicated lower water depth and soil moisture (Figures 3-4). During this time CH_4 emission can be significantly decreased in which the average CH_4 emission was 16, 7 and -7 $mg/m^2/d$ respectively for the FL, MD and DR regimes. It was indicated that under minimum water availability in the field, oxidative process restrained methanogen bacteria and enhanced metanotrof bacteria that can significantly reduce CH_4 gas development.

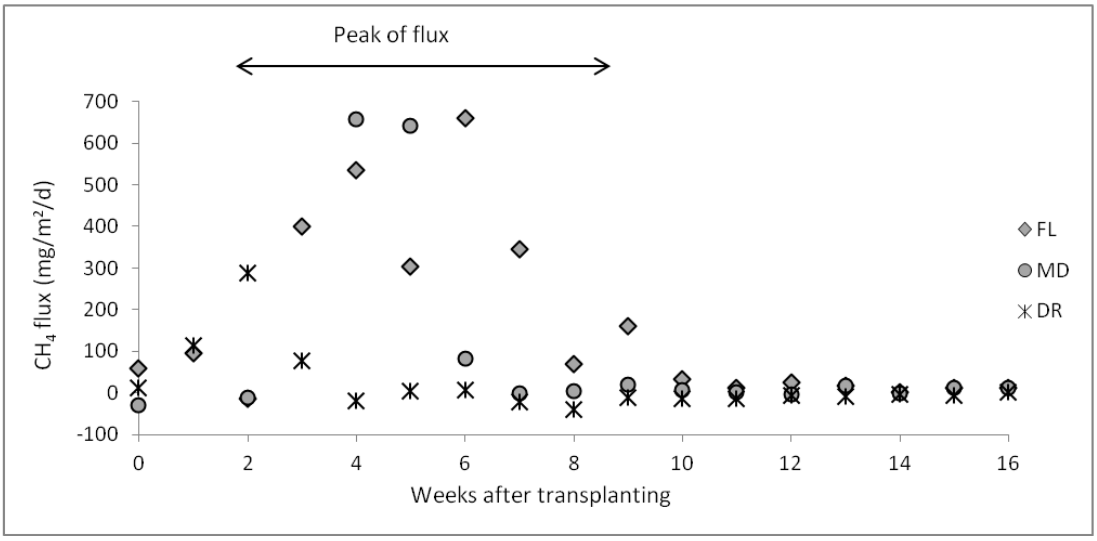

Figure 5. Weekly CH_4 flux in each water regime.

Trade off trend was shown in N_2O flux as figured out in Figure 6. The DR regime released more N_2O emission since this regime was driest among the regimes. The peak of N_2O emission occurred 5-7 weeks after transplanting in this regime with the average was 28 $mg/m^2/d$. This happened with the average water depth was -12 cm. For MD regime, the peak of N_2O emission was in 5 weeks after transplanting when water depth was dropped from -2.63 cm to be – 9.93 cm. Meanwhile, in the FL regime, N_2O emission was limited. The emission only occurred in the end of generative stage when water in the field was limited. N_2O is commonly developed in aerobic soil condition when water is limited and oxygen concentration is so high. This condition triggered nitrification process that convert NO became N_2O at higher pH [22].

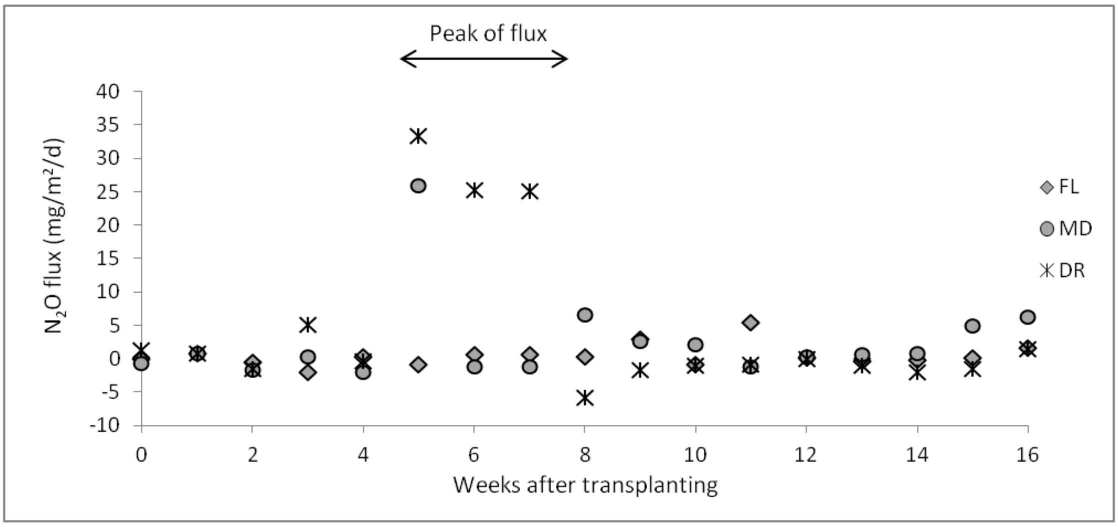

Figure 6. Weekly N_2O flux in each water regime.

3.4 Optimum water regimes

Table 2 shows the comparison between the soil moisture in each regime and optimum values generated by the GA model. The FL regime with highest soil moisture in three first growth stages produced highest CH_4 emission and lowest N_2O emission in total. On the other hand, the DR regime as water stress option released lowest CH_4 and highest N_2O emissions. As moderated option, the MD regime was proposed and it released CH_4 and N_2O at moderate level. Interestingly, the MD regime produced highest yield of 6.85 ton/ha. It was 5.26% and 10.89% higher than that the FL and DR regimes, respectively. However, this regime release more GHG emissions than that DR regime in which its GWP value was 87.85% higher than that DR regime. Among three empirical regimes, MD regime was the best in the point of view highest yield with moderate GWP.

Table 2. Scenario of optimum soil moisture by the GA model

Parameters	Water Regimes			
	FL	MD	DR	Optimum
Soil Moisture in Initial stage (m^3/m^3)	0.544	0.457	0.332	0.541
Soil Moisture in Crop development (m^3/m^3)	0.483	0.422	0.411	0.331
Soil Moisture in Mid-season (m^3/m^3)	0.518	0.456	0.427	0.402
Soil Moisture in Late season (m^3/m^3)	0.331	0.429	0.429	0.429
Yield (ton/ha)	6.51	6.85	6.18	6.9
N_2O (kg/ha)	0.55	2.88	5.56	4.55
CH_4 (kg/ha)	191.31	143.86	24.44	99.26
GWP (CO_2 eq kg/ha)	4564	4166	2218	3838

Considering the empirical results, the GA model was running out and optimum soil moisture was generated properly. The main objective this model was to find better regime than that MD regime with the main subject is yield and GWP. The optimum soil moisture in the initial, crop development, mid-season and late season stages were 0.541, 0.331, 0.402, 0.429 m^3/m^3, respectively. This scenario can increased 0.73% productivity of the MD regime and also reduced 7.87% GWP of the MD regime. Although increasing productivity insignificantly, however, the optimum soil moisture reduced GWP significantly.

Table 3. Scenario of optimum water depth by the GA model

	Water Regimes			
Parameters	FL	MD	DR	Optimum
Water depth in Initial stage (cm) *	0.375	-2.729	-5.027	-5.027
Water depth in Crop development (cm)*	-0.802	-10.842	-13.922	-13.922
Water depth in Mid-season (cm)*	-10.408	-7.447	-14.498	-10.916
Water depth in Late season (cm)*	-13.359	-11.127	-15.746	-11.127
Yield (ton/ha)	6.51	6.85	6.18	6.94
N_2O (kg/ha)	0.55	2.88	5.56	4.86
CH_4 (kg/ha)	191.31	143.86	24.44	94.36
GWP (CO_2 eq kg/ha)	4564	4166	2218	3807

*minus values indicated below soil surface water depth

For the second scenario, the GA model was used to optimize water depth in the each growth stage with the results presented in Table 3. Based on the scenario, optimal water depth was -5.03, -3.9, -10.9 and -11.12 cm for initial, crop development, mid-season, late season growth stages, respectively. This scenario can increase the yield by 1.31% and reduce GWP by 8.36% compare to MD regime.

4. Conclusion

The developed genetic algorithms (GA) model was obtained the optimal soil moisture and water depth in each growth stage. Based on the GA model scenarios, the productivity can be increased up to 1.31% and reduced global warming potential (GWP) by up to 8.36% compare to the medium (MD) regime as the best empirical regimes. For its application in the fields, it is recommended to integrate with soil moisture and water depth control systems. However, since the model was running out based on one cropping season, thus more field experiments are needed to validate the model under various climate conditions.

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