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CONTENTS

Optimizing Non-flooded Irrigation Regime under System of Rice Intensification Crop Management using Genetic Algorithms

Chusnul Arif, Budi Indra Setiawan, Masaru Mizoguchi and Ryoichi Doi

Abstract: In this study, an optimal non-flooded irrigation regime that maximizes both the yield and water productivity of System of Rice Intensification (SRI) crop management was simulated by genetic algorithms (GAs) model. Here, the field was classified into wet (W), medium (M) and dry (D) conditions in each growth stage, namely initial, crop development, mid-season and late season stages according to the soil moisture level. The simulation was performed based on the identification process according to the empirical data during three cropping seasons. As the results, the optimal combination was 0.622 (W), 0.563 (W), 0.522 (M), and 0.350 cm^3/cm^3 (D) for initial, crop development, mid-season and late season growth stages, respectively. The wet conditions in the initial and crop development growth stages should be achieved to provide enough water for the plant to develop root, stem and tiller in the vegetative stage, and then the field can be drained into medium condition with the irrigation threshold of field capacity to avoid spikelet fertility in mid-season stage and finally, let the field dry to save more water in the late season stage. By this scenario, it was simulated that the yield can be increased up to 6.33% and water productivity up to 25.09% with saving water up to 12.71% compared to the empirical data.

Keywords: system of rice intensification (SRI), non-flooded irrigation, crop productivity, water productivity, genetic algorithms.

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Introduction

Recently, the scarcities of water resources and competition for their use have made water saving the main challenge in maintaining the sustainability of rice farming. Therefore, water saving technology becomes one of the priorities in rice research (Barker et al. 2000). From the previous findings, rice is highly possible produced under water saving technology with System of Rice Intensification (SRI) crop management in which continuous flooded irrigation is not essential anymore to gain high yield and biomass production (Zhao et al. 2011; Sato et al. 2011; Lin et al. 2011).

SRI is well-known as a set crop management practices for raising the productivity of irrigated rice by changing the management of plants, soil, water and nutrients. Although some critics were dismissed to the SRI (Sinclair and Cassman 2004; Sheehy et al. 2004; Dobermann 2004), however, its benefits have been validated in 42 countries of Asia, Africa and Latin America (Uphoff et al. 2011). In the SRI paddy field, non-flooded irrigation is applied in which the field is allowed dry during particular time instead of keeping them continuously flooded, a practice called alternate wetting and drying irrigation (AWDI) (Van der Hoek et al. 2001).

Many experiments have been conducted by comparing continuous flooded and non-flooded irrigations under SRI crop management (Choi et al. 2012; Zhao et al. 2011; Sato et al. 2011; Hameed et al. 2011; Barison and Uphoff 2011; Chapagain and Yamaji 2010). Water productivity can be raised by saving water significantly, as reported in studies that provide data for different countries, e.g., 28% in Japan (Chapagain and Yamaji 2010), 40% in Eastern Indonesia (Sato et al. 2011), and 38.5% in Iraq (Hameed et al. 2011). Also by SRI crop management, the land productivity raised more than double in Madagascar (Barison and Uphoff 2011), 78% in Eastern Indonesia (Sato et al. 2011), 65% in Afghanistan (Thomas and Ramzi 2011), 42% in Iraq (Hameed et al. 2011), and 11.3% in China (Lin et al. 2011). However, the optimal wet and dry levels (represented by soil moisture) in each growth stage is still unclear because there is lack information study on optimizing water irrigation regime under SRI crop management. Thus, the current study was undertaken to find optimal soil moisture level in each growth stage to maximize both land and water productivity during cultivation period.

In the irrigation planning model, it has always been a difficult problem to find optimal or near optimal solutions with traditionally dynamic optimizations method because of multi-factors, uncertainty and non-linearity in the model (Zhang et al. 2008). Also, traditional optimizations have limitations in finding global optimization results for a complex irrigation planning problem because they search from point to point (Kuo et al. 2000). Thus, genetic algorithms (GAs) model proposes global optimization search with many remarkable characteristic by searching the entire population instead of moving from one point to the next as the traditional methods (Kuo et al. 2000).

GAs model has ability to rapidly search a global optimal value of a complex objective function using a multi-point search procedure involving crossover and mutation processes (Goldberg 1989). GAs model differs from traditional optimization and other search procedures in the following ways: (1) GAs works with a coding of the parameter set, not the parameters themselves, (2) GAs searches from population of points, not single point, (3) GAs uses objective function information, not derivatives or other auxiliary knowledge, and (4) GAs uses probabilistic transition rules, not deterministic rules (Goldberg 1989). GAs model has been applied to several irrigation planning applications (Zhang et al. 2008; Wardlaw and Bhaktikul 2004; Raju and Kumar 2004; Kuo et al. 2000). However, optimizing non-flooded irrigation regime by finding optimal soil moisture in each growth stage has not yet been achieved particularly under SRI crop management.

Therefore, the objective of current study was to find optimal soil moisture level in each growth stage of paddy rice under SRI crop management using GAs model to maximize both land and water productivity.

Materials and Methods

Field Experiments

The optimization process was carried based the field experiment in the experimental paddy field in the Nagrak Organics SRI Center (NOSC), Sukabumi, West Java, Indonesia located at 06°50'43" S and 106°48'20" E, at an altitude of 536 m above mean sea level (Fig. 1) during three cropping seasons (Table 1).

Table 1. Cultivation period of each cropping season

Period	Planting date	Harvesting date	Season
First	14 October 2010	8 February 2011	Wet
Second	20 August 2011	15 December 2011	Dry - Wet
Third	22 March 2012	5 July 2012	Wet - Dry

There were four plots and each plot was planted with the variety of rice (*Oryza sativa* L), Sintanur using the following SRI crop management: single planting of young seedlings spaced at 30 cm × 30 cm, applying an organic fertilizer at 1 kg/m^2 in the land preparation, but no chemical fertilizer. The weeding was performed every 10 days in the period between 10 and 40 days after transplantation supplying local indigenous microorganism to enhance biological activity in the soils (Uphoff et al. 2011)

Source: earth.google.com (2012)

Fig. 1 Experimental field location in West Java, Indonesia.

Each plot was irrigated under different water irrigation regimes according to the growth stages, namely, initial, crop development, mid-season and late season stages (Vu et al. 2005; Tyagi et al. 2000; Allen et al. 1998; Mohan and Arumugam 1994). Non-flooded condition was applied in all regimes and in each growth stage the soil was classified into three conditions i.e. wet (W), medium (M) or dry (D) to realize the soil moisture described by changes in soil suction head (i.e. pF value) (Arif et al. 2011a) presented in Fig. 2. The wet condition was achieved when pF value was between 0 and 1.6 which was the air entry value for this soil. The medium condition was achieved when pF value was between 1.6 and 2.54 which was the field capacity value. When the soil was drier than the medium condition, the condition was regarded as the dry condition.

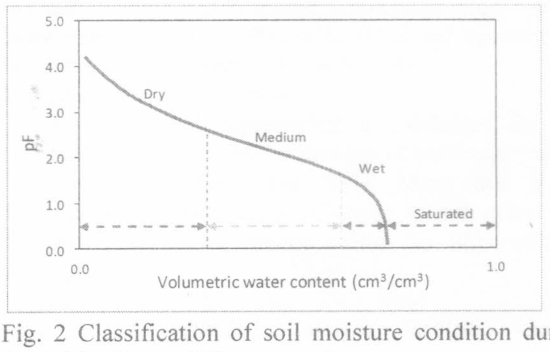

Fig. 2 Classification of soil moisture condition during the cultivation period.

Soil moisture and meteorological data consisting of air temperature, wind speed, relative humidity, solar radiation and precipitation were collected by a quasi real time monitoring system (Arif et al. 2011b). Here, meteorological data were used to calculate reference evapotranspiration (ET_o) based on the FAO Penman-Monteith model (Allen et al. 1998). Then, using monitoring data, total irrigation, crop evapotranspiration were estimated by Excel Solver (Arif et al. 2012a).

Modeling Approach

Identification procedure

To determine optimal soil moisture level in each growth stage to maximize yield and water productivity, the relationship between their values and the yield as well as water productivity should be identified firstly based on empirical data. Since there was no mathematical model between them, identification process was carried out gradually and its procedure as follow:

1. Yield as function of plant height and tiller numbers/hill

The yield has positive correlation to plant growth represented by plant height and tiller numbers/hill. Therefore, we used multiple linear regressions to show the correlation between the yield and plant height as well as tiller numbers/hill. The basic formula was given as follow:

$$Y = aPH + bTH + c \qquad (1)$$

Where Y is yield (ton/ha), PH is plant height (cm), TH is tiller numbers/hill, a, b, c are coefficients of plant height, tiller numbers/hill and the intercept, respectively. Plant height and tiller numbers/hill were measured manually every 5 days and we used their average values in the end of mid-season stage when maturity time was started to show their correlation to the yield (Allen et al. 1998). Here, all coefficients in equation 1 were determined empirically according field experiments by multiple linear regressions.

2. Plant height and tiller numbers/hill as function of soil moisture

Plant height and tiller numbers/hill are affected by soil condition represented by the soil moisture level in each growth stage. In fact, it is difficult to identify the relationship between soil moisture and plant growth by mathematical model because it is characterized by non-linearity. Thus, we implemented neural networks model to show its correlation since neural networks model deals with complex system such as in agricultural system (Hashimoto 1997). The model consisted three layers, i.e. input, hidden and output layers. Soil moisture in the initial (SM1), crop development (SM2), mid-season (SM3) and late season (SM4) were used as in the inputs, while plant height (PH) and tiller numbers/hill (TH) as the outputs (Fig.3).

3. Water productivity with respect total water input

Since we focused to find the minimum water input as much as possible, thus we defined water productivity with respect total water input (Bouman et al. 2005) with the following equation:

$$WP = \frac{Y}{\sum(I+P)} \qquad (2)$$

Where I is total irrigation (mm) that affected by the soil moisture level in each growth stage, P is precipitation (mm) and WP is water productivity (g grain/kg water).

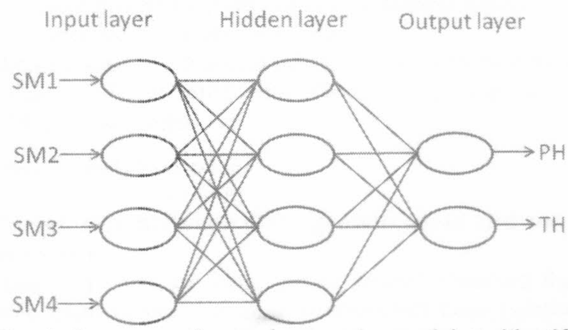

Fig. 3 Structure of neural networks model to identify plant height and tiller numbers/hill as affected by soil moisture.

Optimization procedure

The objective function can be described as:

$$F(SM1, SM2, SM2, SM4) = dY + eWP \qquad (3)$$

Maximize F(SM1,SM2,SM3,SM4)

Subject to:

$$0.586 \le SM1 \le 0.622\,(cm^3/cm^3) \qquad (4)$$

$$0.563 \le SM2 \le 0.593\,(cm^3/cm^3) \qquad (5)$$

$$0.455 \le SM3 \le 0.522\,(cm^3/cm^3) \qquad (6)$$

$$0.350 \le SM4 \le 0.505\,(cm^3/cm^3) \qquad (7)$$

Where d and e are weights for the yield (Y) and water productivity (WP) and their values were 0.6 and 0.4, respectively. Since both Y and WP have different unit, thus their values were normalized using their maximum and minimum values based on empirical data. Here, GAs model searched optimal combination of SM1, SM2, SM3, and SM4 with their interval (minimum and maximum soil moisture in each growth stage) according experiment data to maximize the objective function by multi-point searching procedure.

In order to employ GAs model, some parameters such as individual, population, fitness function and operators of GAs should be defined firstly as follows:

1. Definition of individual

   An individual represented a candidate for the optimal solution that consisting of particular values SM1, SM2, SM3 and SM4. Meanwhile a set individual was called population. An individual was coded as six-bit binary strings as illustrated as follow:

   Individual = SM1, SM2, SM3, SM4
   = 000101, 001000, 001100, 100001 (binary string)

= 0.598, 0.567, 0.468, 0.431 (decimal values in cm^3/cm^3)

2. Fitness function
   Fitness function is an indicator to show the quality of an individual. All individuals in a population were evaluated based on their performances in which the higher fitness function, the better ability to survive. In this problem, fitness function was given same as an objective function (equation 3).
3. Operators of GAs model
   The main operators were crossover and mutation. Crossover combined features from two individuals based on crossover rate (Pc). It is operated by swapping corresponding component in the binary strings represented an individual. Mutation inverted one or more bit binary string (also called gene) in each individual from 0 to 1 or 1 to 0 based on mutation rate (Pm). Here, Pc and Pm were 60% and 5%, respectively.

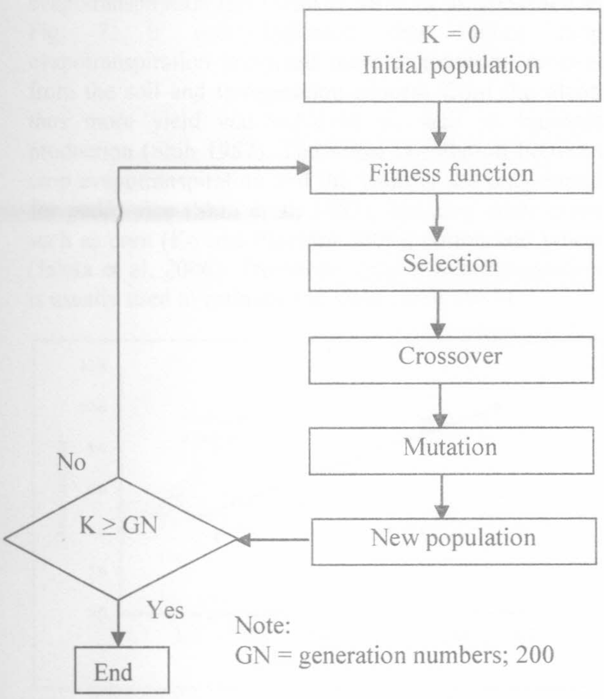

Fig. 4 Searching procedure of GAs model in the current study.

We adopted the searching procedure as developed previously (Suhardiyanto et al. 2009) and could be further explained as follow:

1. An initial population consisting of ten individuals were generated randomly as the first generation
2. Fitness function was calculated to show the performance of each individual
3. The performance of each individual was evaluated by sorting maximum to minimum fitness value. Here, 60% of all individuals with the highest performance were selected to next step, another fitness values were eliminated
4. Crossover and mutation operations were applied to the selected individual based on Pc and Pm rates
5. Then, new population was created. Here, 60% of selected individuals previous generation were compared to the new population. We implemented the elitist strategy to find global optimum by sorting the fitness value and then selected ten individuals with highest performance as the next generation.
6. Steps 2 to 5 were repeated until the required generation numbers achieved. The optimal values were given as an individual with highest fitness when the result was convergent

We developed both neural networks and GAs models in Microsoft Excel 2007 with Visual Basic Application with our own codes.

Results and Discussions

Correlation between plant growth, yield and soil moisture

Based on empirical data, it was cleared observed that both plant height and tiller numbers/hill have positive correlation to the yield with R2 of 0.86 and 0.89, respectively (Fig.5). These results were consistent with previous findings that higher plant height with more tiller numbers/hill promoted more yield and vice versa (Kumar et al. 2012; Zeng et al. 2003). Therefore, the correlation between the yield and both plant height and tiller numbers/hill can be presented well by multiple linear regressions with R2 of 0.94 (Fig.6). Commonly the yield of rice is highly dependent upon the number of fertile tiller numbers/hill, thus more tiller numbers/hill have high probability to produce more fertile tiller (Zeng et al. 2003).

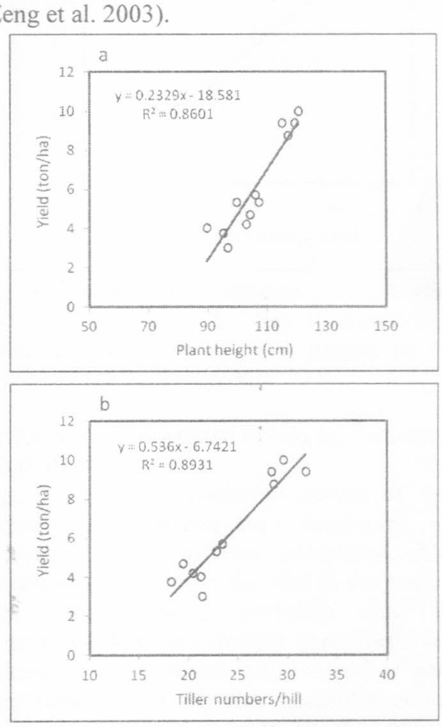

Fig. 5 Correlation between plant height, tiller numbers/hill and yield: a) plant height vs yield, b) tiller numbers/hill vs yield

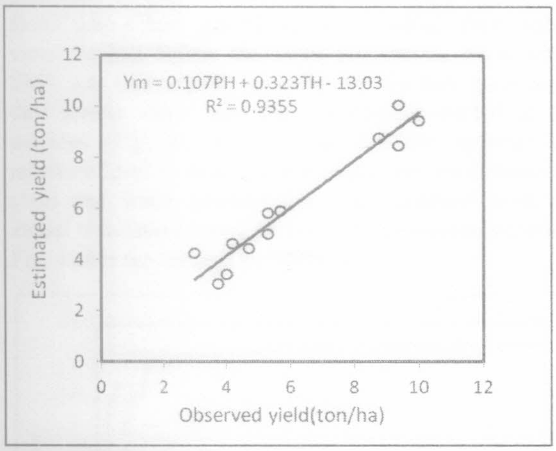

Fig. 6 Multiple linear regression plant height and tiller numbers/hill on the yield.

The yield also has positive correlation to the crop evapotranspiration (ET) with R^2 of 0.94 as presented in Fig. 7. It was indicated that higher crop evapotranspiration promoted more evaporation process from the soil and transpiration process from the plant, thus more yield was achieved as well as biomass production (Shih 1987). The linear correlation between crop evapotranspiration and the yield is not only found for paddy rice (Shih et al. 1983), but also other crops such as corn (Ko and Piccinni 2009), cotton and wheat (Jalota et al. 2006). Therefore, crop evapotranspiration is usually used to estimate the yield (Shih 1987).

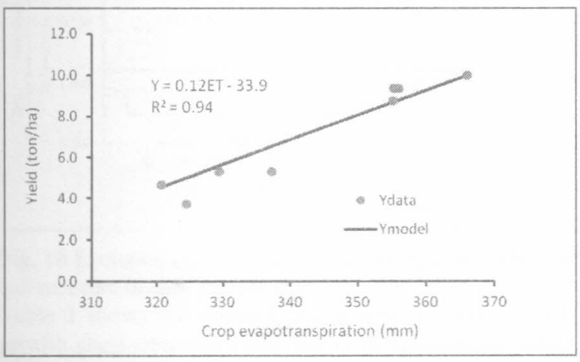

Fig. 7 Correlation between yield and crop evapotranspiration.

Crop evapotranspiration is vital for irrigation scheduling and water resource allocation, management and planning (Jensen et al. 1990). Also, it is a main component of water consumption in paddy fields, thus its rate is depend on water availability in the field represented by soil moisture. In other words, plant growth and the yield were clearly affected by soil moisture level in each growth stage (Arif et al. 2012b; Anbumozhi et al. 1998). However, there is no mathematical model was found showed the relation between soil moisture level in each growth stage and plant growth as well as the yield.

Here, we used neural networks model to estimate plant growth represented by plant height and tiller numbers/hill as affected by soil moisture level in each growth stage. Fig. 8 shows the comparisons between observed and estimated values of both plant height and tiller numbers/hill by neural networks model. It can be seen that the estimated values were closely related to the observed values with R^2 of 0.82 and 0.92 for estimation of plant height and tiller numbers/hill, respectively. This means that more than 80% of observed values can be explained linearly by neural networks model. Therefore, the results suggest that a reliable simulation model by neural networks could be obtained to estimate plant height and tiller numbers/hill.

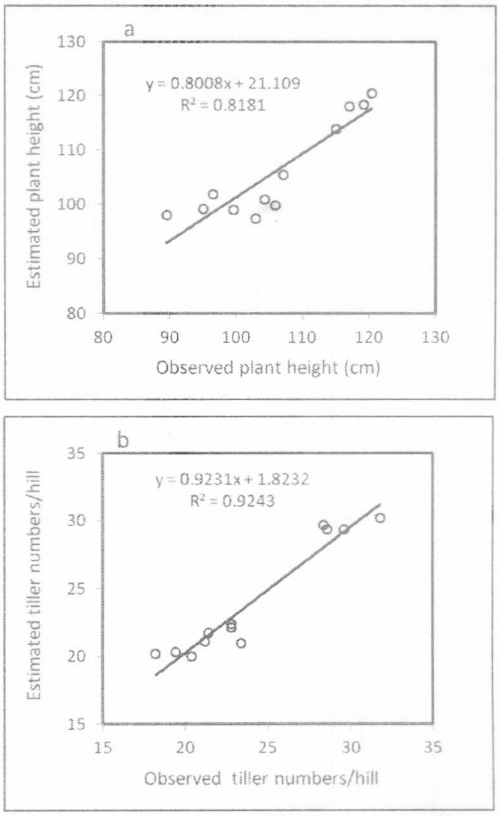

Fig. 8 Observed and estimated plant growth as affected soil moisture level by neural networks model: a) Observed vs estimated plant height, b) Observed vs estimated tiller numbers/hill.

Optimal soil moisture levels by Genetic Algorithms

Fig. 9 shows the evolution curves of fitness values (equation 3) between their maximum, average and minimum values in each generation. All of values increased sharply from the first to the tenth generation, and then increased gradually until the fortieth generation. After the fortieth generation, the all fitness values were convergent until the end of generation and their values were 0.68. This means that global maximum value was obtained because all of maximum, average and minimum values were same.

Fig. 10 shows the evolution curves of soil moisture level in each growth stage in obtaining fitness values presented in Fig. 9. SM1 and SM2 were convergent faster than others growth stages in which their values were reached before the tenth generation. Meanwhile, SM3 was convergent latest in the fortieth generation, thus fitness value was also convergent started at this moment (Fig. 9). This means that the optimal soil moisture level in each growth stage that maximizes the yield and water productivity was obtained from the model simulation based on the GAs procedure shown in Fig. 4 after the fortieth generation.

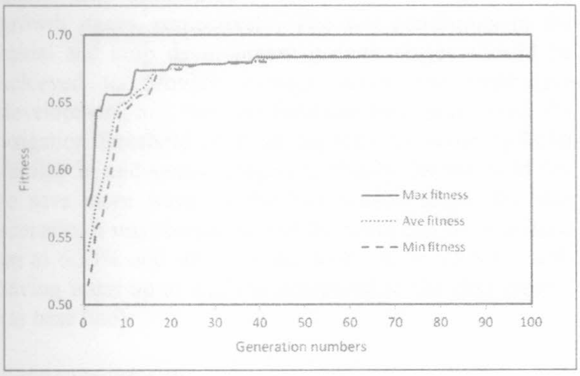

Fig. 9 Evolution curves in searching for a maximal value of fitness function.

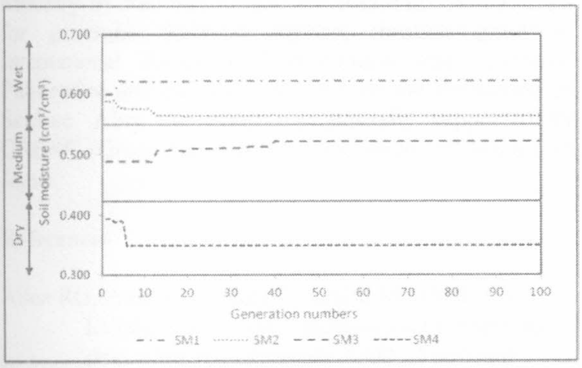

Fig. 10 Evolution curves in searching the optimal values of soil moisture in each growth stage.

Table 2 shows the optimal soil moisture level in each growth stage obtained from the GAs simulation, while Fig. 11 shows the optimal output simulated by GAs model. Four irrigation regimes with some combinations of soil moisture level from the field measurements are also represented in the table with the same precipitation during cropping season as the comparison. The optimal combination of soil moisture level in each growth stage obtained in this study was 0.622 (wet), 0.563 (wet), 0.522 (medium), and 0.350 cm^3/cm^3 (dry) for initial, crop development, mid-season and late season growth stages, respectively. By this scenario, it was simulated that the yield can be increased up to 6.33% and water productivity up to 25.09% with saving water up to 12.71% compared to the first regime (as base line).

From this simulation, it can be concluded that during the first to the second stages keeping the field in the wet condition is important to fulfill plant water requirement. In the SRI, avoid continuous flooding is one of the their elements because rice plants cannot grow best under hypoxic soil conditions, thus plants should be given just enough water at saturated condition to meet their requirement for root, stem and tiller development (Uphoff et al. 2011). Then, the field can be drained into medium condition in the third stage when plants focusing on reproductive stage (flowering and panicle development). The medium condition with the threshold of irrigation was reduced to the field capacity (pF 2.54) is important in developing aerobic condition to avoid spikelet sterility particularly around flowering time (Bouman et al. 2005). Finally, the field should be drained into dry condition in the last stage to save the water input as reported previous studies (Uphoff et al. 2011; Doorenbos and Kassam 1979; Zawawi et al. 2010).

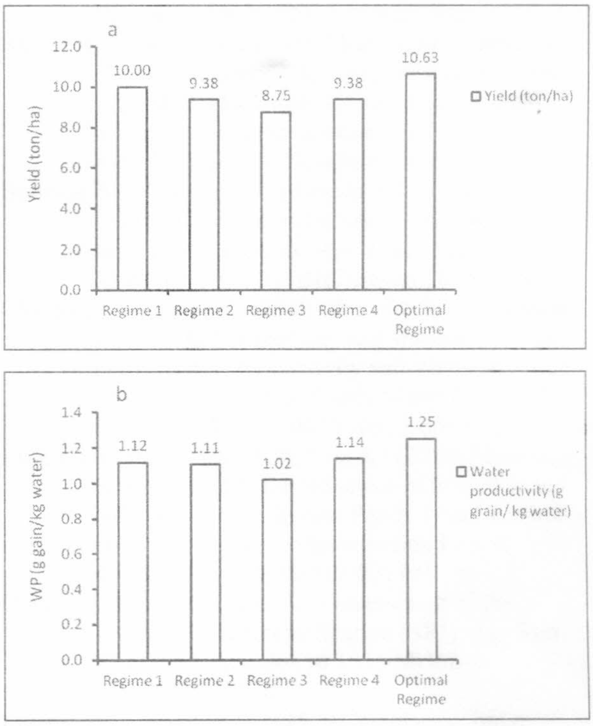

Fig. 11 Optimal the yield and water productivity simulated by GAs model and their comparison to the empirical data.

Table 2. Optimal soil moisture level in each growth stage and its comparison to the empirical data

	Field Experiments				GAs optimizer	
Components	Regime 1	Regime 2	Regime 3	Regime 4	Optimal Regime	Condition
Soil moisture (cm^3/cm^3)						
Initial (SM1)	0.622	0.602	0.611	0.586	0.622	Wet
Crop development (SM2)	0.592	0.585	0.593	0.563	0.563	Wet
Mid-season (SM3)	0.522	0.488	0.472	0.455	0.522	Medium
Late season (SM4)	0.505	0.401	0.456	0.350	0.350	Dry
Yield (ton/ha)	10.00	9.38	8.75	9.38	10.63	
Total irrigation (mm)	343	295	305	272	299	
Total precipitation (mm)	551	551	551	551	551	
Water productivity (g grain kg^{-1} water)	1.12	1.11	1.02	1.14	1.25	
Water saving (%)	Base line	13.86%	11.01%	20.65%	12.71%	

Conclusions

In this study, optimal combination of soil moisture level in each growth stage that maximizes both the yield and water productivity of SRI crop management was simulated by GAs model. The simulation was performed based on the identification process according to the empirical data during three cropping seasons. As the results, the optimal combination was 0.622 (wet), 0.563 (wet), 0.522 (medium), and 0.350 cm^3/cm^3 (dry) for initial, crop development, mid-season and late season growth stages, respectively. The wet conditions in the initial and crop development growth stages should be achieved to provide enough water for vegetative development, and then the field can be drained with the irrigation threshold of field capacity to avoid spikelet fertility in mid-season stage and finally, let the field dry to save more water in the late season stage. By this scenario, it was simulated that the yield can be increased up to 6.33% and water productivity up to 25.09% with saving water up to 12.71% compared to the first regime (as base line).

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