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C-07

Determining Optimal Soil Moisture for Irrigated Rice in Indonesia with System of Rice Intensification

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In this study, an optimal combination of soil moisture for irrigated rice in Indonesia that maximizes both yield and water productivity of system of rice intensification (SRI) paddy field was determined by genetic algorithm (GA) model-based optimization. Before performing optimization, a formula to describe yield by soil moisture and meteorological parameters was identified using multiple non-linear regression analysis. The GA model was performed based on the identification process according to the empirical data during three cropping seasons. Here, we classified soil moisture level into three levels i.e. wet (W), medium (M) or dry (D) based on the soil water retention curve. As the results, the optimal soil moisture was a combination of wet, wet, medium, and dry levels for initial, crop development, mid-season and late season growth stages, respectively. We called this regime as W-W-M-D regime. The wet level in the initial and crop development growth stages should be achieved providing enough water for the plant to develop root, stem and tiller, and then the field can be drained into the medium level with the irrigation threshold of field capacity to avoid spikelet sterility in mid-season stage and finally, let the field in the dry level to save more water in the late season stage when plant water requirement is minimum. By this scenario, it was simulated that the yield can be increased up to 8.35% and water productivity up to 13.49% with saving water up to 12.28% compared to the empirical data.

Keywords: *system of rice intensification (SRI), non-flooded irrigation, water productivity, water saving, genetic algorithm*

1. 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). Rice is highly possible produced under water saving technology with system of rice intensification (SRI) in which continuous flooded irrigation is not essential anymore to gain high yield and biomass production (Lin et al., 2011; Sato et al., 2011; Zhao 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 (Dobermann, 2004; Sheehy et al., 2004; Sinclair and Cassman, 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-flooding 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 (Van der Hoek et al., 2001).

Many experiments have been conducted by comparing continuous flooding and non-flooding regimes under SRI (Barison and Uphoff, 2011; Chapagain and Yamaji, 2010; Choi et al., 2012; Hameed et al., 2011; Sato et al., 2011; Zhao et al., 2011). Water productivity can be raised and water can be saved 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, 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 management of SRI paddy field. Thus, the current study was undertaken to find optimal soil moisture level in each growth stage to maximize both yield and water productivity during cultivation period.

In the irrigation planning model, there are many factors to be considered, such as crop water requirement, production function, precipitation, soil water balance including irrigation water, plant growth stage, etc (Zhang et al., 2008). It is difficult problem to find the optimal or near optimal solution with traditional optimization methods because the limitations in integrating of multi-factors in the model. Thus, genetic algorithm (GA) proposes global optimization search with many remarkable characteristics by searching the entire population instead of moving from one point to the next as the traditional methods (Kuo et al., 2000).

GA has the 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). GA differs from the traditional optimization and other search methods in the following ways: (1) GA works with a coding of the parameter set, not the parameters themselves, (2) GA searches from population of points, not a single point, (3) GA uses objective function, not derivatives or other auxiliary knowledge, and (4) GA uses probabilistic transition rules, not deterministic rules (Goldberg, 1989). GA has been applied to several irrigation planning applications (Kuo et al., 2000; Raju and Kumar, 2004; Wardlaw and Bhaktikul, 2004; Zhang et al., 2008). However, optimizing water management in any SRI paddy fields have not yet been achieved by finding the optimal soil moisture in each growth stage.

Therefore, the main objectives of this study was to find the optimal water management by determining optimal combination of soil moisture levels using GA model in maximizing both yield and water productivity.

2. Materials and Methods

2.1 Field Experiments

The optimization process was carried out based on the field experiments in the experimental paddy field in the Nusantara 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).

Source: earth.google.com (2012)

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

There were four plots and each plot was planted with the variety of rice (Oryza sativa L), Sintanur using the following SRI elements: single planting of young seedlings spaced at 30 cm × 30 cm, applying an organic fertilizer at 1 kg/m2 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).

Table 1 Cultivation period of each cropping season

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

Each plot was irrigated under non-flooded condition with different soil moisture level in each growth stage. Here, during cultivation period, growth stage was divided into four stages, i.e., initial, crop development, mid-season and late season stages (Allen et al., 1998; Mohan and Arumugam, 1994; Tyagi et al., 2000; Vu et al., 2005). Also, soil moisture level was classified into three levels i.e. wet (W), medium (M) or dry (D) based on the soil water retention curve as presented in Fig. 2. The wet level was achieved when pF value was between 0 and 1.6 which was the air entry value for this soil. The medium level 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 level, the condition was regarded as the dry level.

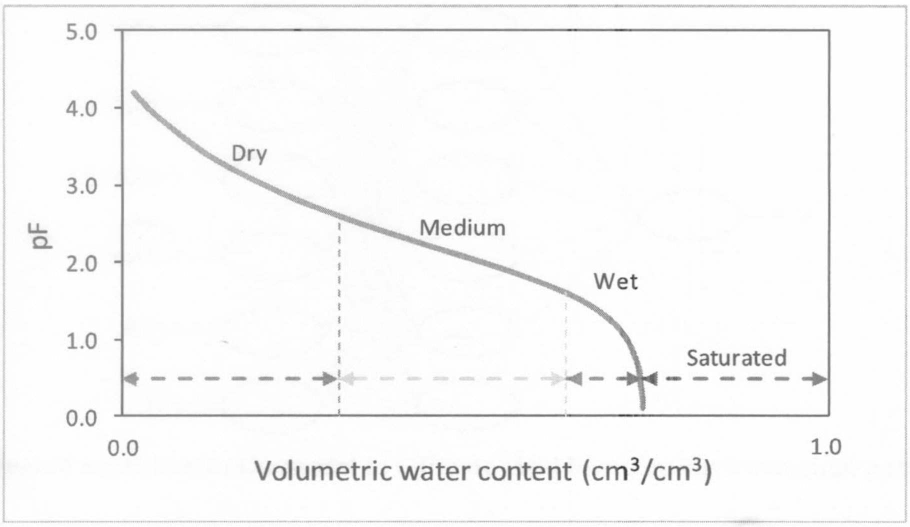

Fig. 2 Classification of soil moisture level during cultivation period.

Soil moisture was measured by 5TE sensor by Decagon Devices, Inc., USA. Meanwhile, precipitation, solar radiation and air temperature were measured by Davis Vantage Pro2 weather station. After harvesting, yield in each plot was obtained to determine water productivity with respect of total water input (Bouman et al., 2005) by the following equation:

$$WP = \frac{Y}{\sum(I+P)} \tag{1}$$

where Y is yield (ton/ha), I is total irrigation (mm), P is precipitation (mm) and WP is water productivity (g grain/kg water).

2.2 Modeling approach

2.2.1 Identification procedure

Since we focused on water management, all of inputs of production such as fertilizer and seeds were given at same levels except for water input. Therefore, identification process was carried out to correlate between soil moisture and weather parameters as the inputs with yield as the outputs before performing the GA model by the following equation:

$$Y = f(SM1, SM2, SM3, SM4, Rs, T) \tag{2}$$

where, Y is yield (ton/ha), Rs is total solar radiation (MJ/m^2/season), T is average air temperature (^oC), SM1, SM2, SM3, SM4 are the average soil moisture for initial, crop development, mid-season, and late season stages (cm3/cm3). Since there is no mathematical equation from previous research because of the complexity of this relationship, we implemented neural networks model to show its correlation because 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 as presented in Fig.3.

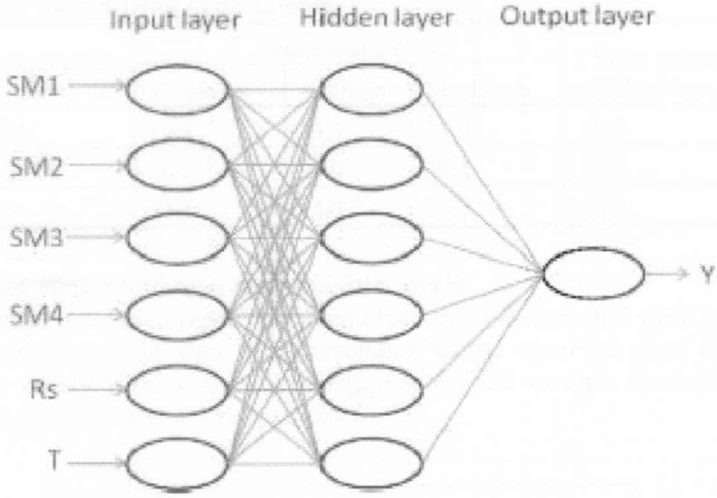

Fig. 3 Structure of neural networks model to estimate yield based on environmental parameters.

2.2.2 Optimization procedure

Optimization process was carried out by the GA model by the following objective function:

$$F = a_1 Y + b_2 WP \quad (3)$$

Maximize F, subject to:

$$SMmin \leq SM1, SM2, SM3, SM4 \leq SMmax \quad (4)$$

where, a_1 and b_1 are weights for yield and water productivity and their values are 0.5 and 0.5, respectively. SMmin and SMmax are the minimum and maximum soil moisture levels from the empirical data during three cropping seasons (cm^3/cm^3). Since both yield and water productivity have different units, their values were normalized using the maximum and minimum values based on empirical data.

3. Results and Discussion

3.1 Meteorological conditions

Table 2 summarizes the climatic data during the experiments in three seasons. There are two seasons in Indonesia classified based on the pattern of precipitation. Here, precipitation among seasons was quite different in which the highest intensity occurred in the first season with total precipitation of 1332 mm in rainy season. Consequently, different pattern in precipitation corresponded to the different pattern of solar radiation. The lowest solar radiation occurred in the first season with total values of 1464 MJ/m^2/season. Meanwhile, temperatures among the seasons were quite same in which maximum temperature was 32.8°C and minimum temperature was 16.2°C in the second season.

Table 2 Meteorological data during experiments

Seasons	Precipitation (mm)	Temperature (°C)			Solar radiation (MJ/m^2/season)
		Minimum	Average	Maximum	
I (Rainy)	1332	19.5	23.5	31.9	1464
II (Dry-Rainy)	626	16.2	24.0	32.8	1827
III (Rainy-Dry)	551	17.4	24.3	32.3	1829

3.2 Correlation between yield and soil moistur levels

Fig. 4 shows model validation results between observed and estimated yield by neural networks model. The model estimated yield with high correlation to the observed yield (R^2 = 0.93) which indicated that yield is mainly affected by soil moisture levels and weather conditions when fertilizer and others inputs were given at same level in all plots.

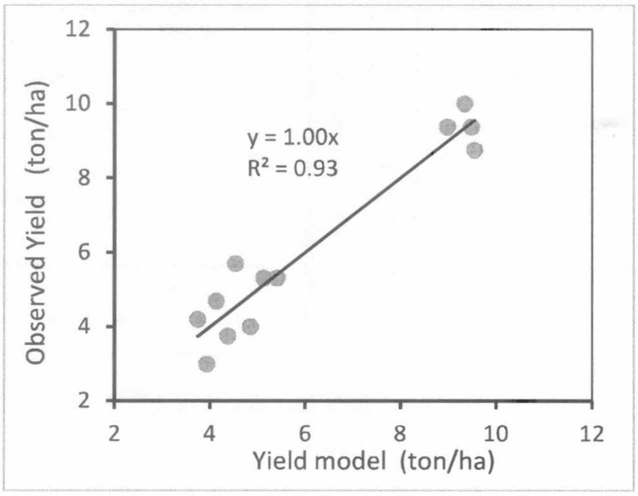

Fig. 4 Model validation of neural networks model to estimate yield

Fig. 5 shows linear correlation between the average soil moisture in each growth stage and the yield. The third season obtained the highest yield compared to other seasons. The average yield was 4.77, 4.23 and 9.38 ton/ha for the first, second and third seasons, respectively. Hence, soil moisture levels have correlation to the yield for all growth stages.

In the initial and crop development stages, soil moisture had positive correlation to yield with an R2 of higher than 0.6. This result revealed that at higher soil moisture levels, more yield was produced. In the initial stage, the maximum yield was produced when the soil moisture level was over the saturation border indicating shallow standing water was occurred in the field. Then, in the crop development stage, the maximum yield was achieved when the soil moisture level was close to the saturation border. The field condition in the crop development stage was drier than that in the initial stage, even though both conditions were classified as wet condition.

On the contrary, soil moisture had negative correlation to yield in the mid-season and late season stages. Based on the empirical data, the mid-season stage was probably the transition in which the water can be drained to produce more yields. Here, the maximum yield was obtained when the soil moisture level was higher than that the field capacity border. This revealed that the medium level was appropriate to produce more yields by draining water in the mid-season stage. Then, in the late season stage, the driest condition can be applied to save more water without a loss of significant yield.

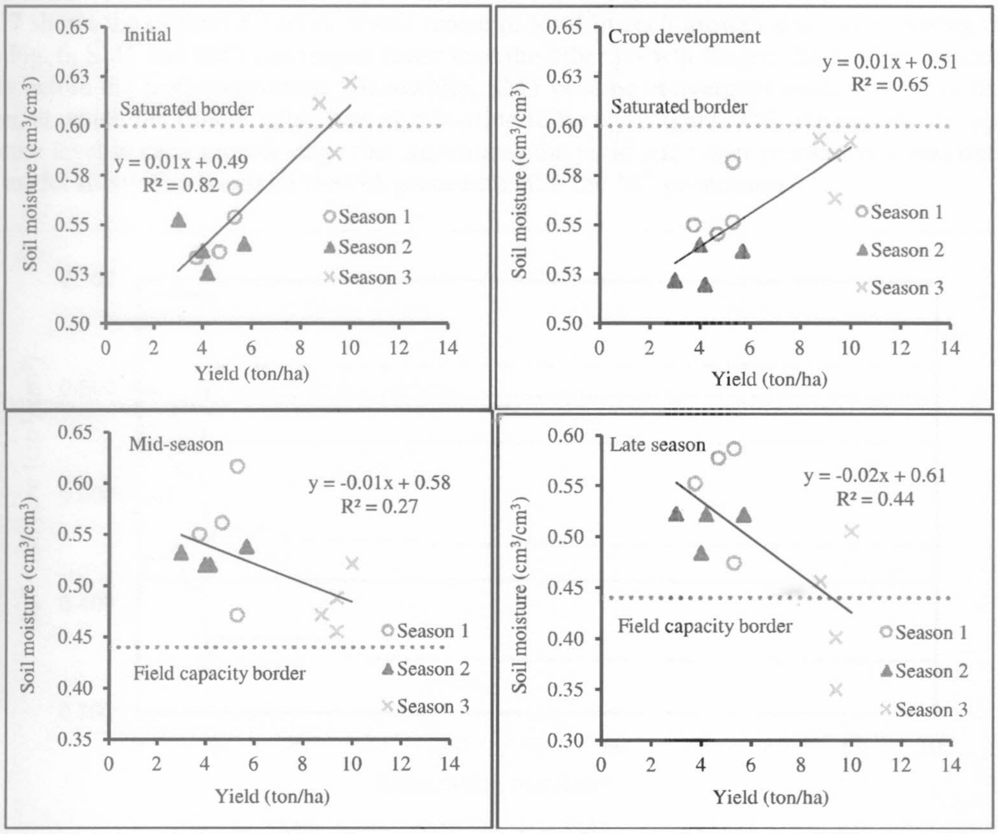

Fig. 5 Linear correlation between the average soil moisture and the yield in each growth stage

3.3 Optimal soil moisture by the GA model

As previously mentioned, during three cropping seasons the highest yield was obtained in the third season. So, we used meteorological data in this season as the inputs, and then the GA model searched the optimal soil moisture in each growth stage

Fig. 6 shows the evolution curves of fitness values between their maximum, average and minimum values in each generation. All values increased sharply from the first to the tenth generation, and then increased gradually until the 38th generation. After the 38th generation, the all fitness values were convergent until the end of generation and their values were 0.28. This means that the global maximum value was obtained because all of their maximum, average and minimum values were the same.

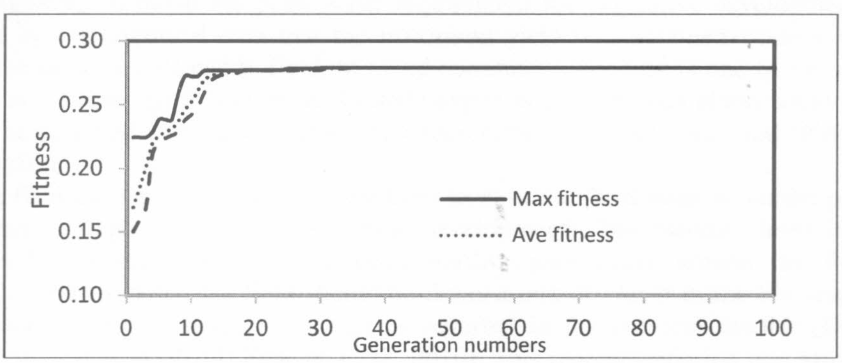

Fig. 6 Evolution curves in searching for a maximal value of fitness function

Fig. 7 shows the evolution curves of soil moisture level in each growth stage in obtaining fitness values in Fig. 6. SM1 and SM2 converged faster than the other growth stages; their values reached the asymptote before the tenth generation. Meanwhile, SM3 became convergent most slowly; in the 38th generation, at which the fitness value was also starting to be convergent. 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 GA procedure after the 38th generation.

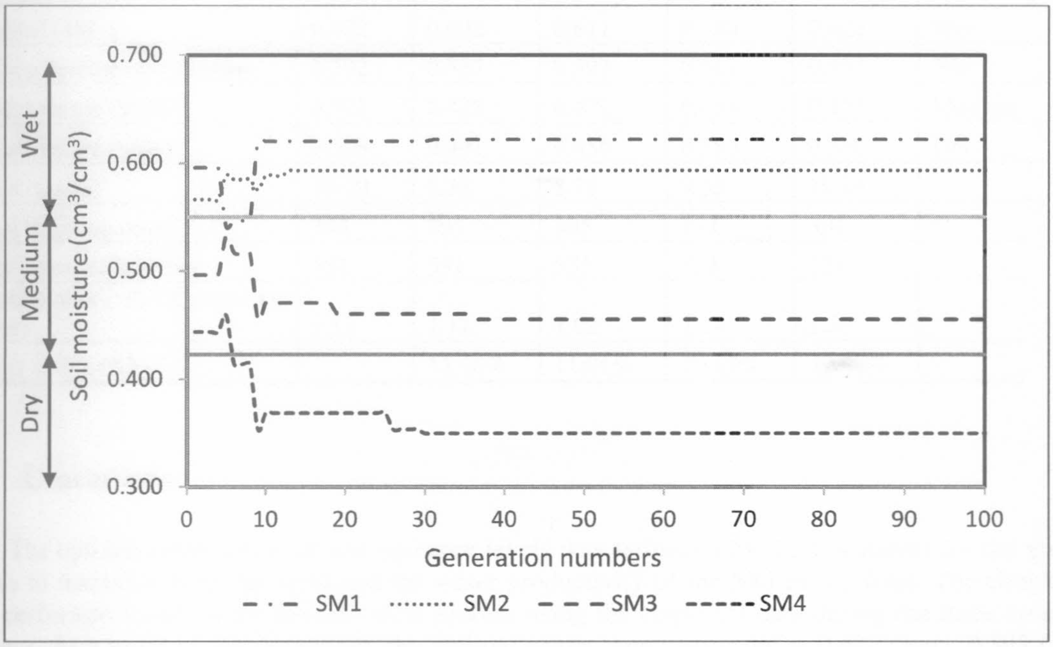

Fig. 7 Evolution curves in searching the optimal values of soil moisture in each growth stage

Table 3 shows the optimal soil moisture level in each growth stage obtained by the GA model. Four irrigation regimes with the combinations of soil moisture levels from the field measurements in the third season are also represented in the table as the comparison. The optimal combination of soil moisture levels in the growth stages obtained in this chapter was 0.622 (wet), 0.593 (wet), 0.455 (medium), and 0.350 cm^3/cm^3 (dry) for SM1, SM2, SM3 and SM4, respectively. We called this regime as W-W-M-D. By this scenario, it was simulated that the yield can be increased up to 8.35% and water productivity up to 13.49% with water saving up to 12.28%.

From this simulation, it was shown that during the first and second stages keeping the field in the wet level is important to fulfill the plant water requirement for vegetative development. This result was supported by the empirical data that the maximum yield was obtained when a wet level was developed in the field. In SRI paddy field, to avoid continuous flooding is one of the main elements because rice plants cannot grow best under limited oxygen in the soil, 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 the medium level in the third stage when the plants focusing on the reproductive stage (flowering and panicle development). The medium level is important in developing aerobic condition to avoid spikelet sterility particularly around the flowering time (Bouman et al., 2005). Finally, the field should be drained into dry level in the last stage when plant water requirement is minimum to save water as reported in the previous studies (Doorenbos and Kassam, 1979; Uphoff et al., 2011; Zawawi et al., 2010). This recommendation was also supported by the empirical data that medium and dry levels in the mid-season and late season stages resulted in the maximum yield.

Table 3 Optimal soil moisture level in each growth stage and its comparison to the irrigation regimes in the third season

Components	Irrigation regimes				GA model	
	Plot 1	Plot 2	Plot 3	Plot 4	Optimal Regime	Level
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	0.593	Wet
Mid-season (SM3)	0.522	0.488	0.472	0.455	0.455	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	10.84	
Total irrigation (mm)	343	295	305	272	301	
Total precipitation (mm)	551	551	551	551	551	
Water productivity (g grain/ kg water)	1.12	1.11	1.02	1.14	1.27	
Water saving (%)	-	13.86%	11.01%	20.65%	12.28%	

4. Conclusions

The optimal combination of soil moisture levels was estimated by the GA model for the growth stages to maximize both the yield and the water productivity of the SRI paddy field. The simulation was performed based on the identification process using the empirical data during the three cropping seasons. As a result of the simulation, the optimal values were estimated at 0.622 (wet), 0.593 (wet), 0.455 (medium), and 0.350 cm^3/cm^3 (dry) for the initial, crop development, mid-season, and late season growth stages, respectively. We called this regime as W-W-M-D regime. The wet level 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 sterility in the mid-season stage and finally, to complete the production, it is important to let the field dry to save more water in the late season stage. By this scenario, it was estimated that the yield can be increased up to 8.35% and water productivity up to 13.49% with water saving up to 12.28%.

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