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Effects of Crop Density and Irrigation Management on Water Productivity of Rice Production in Northern Iran: Field and Modeling Approach

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Freshwater availability for irrigation decreases because of increasing demand from urban and industrial areas, degrading irrigation infrastructure, and water quality. The demanding for high production of rice with less water use is crucial for food supply. In this research, a field experiment was conducted during 2001 and 2002 to determine the effect of crop density on water productivity of rice crop. The study was carried out in a split-plot design with three plant spacings as subplots (20 cm × 20 cm, 15 cm × 15 cm, and 10 cm × 20 cm) and four different irrigation regimes (continuous submergence as the control and 100%, 75%, and 50% evaporation of pan) as main plots. To model the various water productivity components, the ORYZA2000 model was used. The comparison of model results with observed data was performed using different statistical methods. The results showed that the irrigation by 75% evaporation from pan evaporation and 20 cm × 20 cm crop size are the optimum irrigation method and crop density management.

Keywords Crop density, irrigation, ORYZA2000, rice, water balance

Introduction

Freshwater availability for irrigation is decreasing as a result of increasing demand from urban and industrial areas, degrading irrigation infrastructure, and water quality (Molden 2007). The demanding for high production of rice with less water use is crucial for food supply. Iran is a semi-arid country with 240 mm mean annual rainfall and 600,000 ha under cultivation of paddy field. Roughly, the whole area of lowland rice uses a continuously submerged irrigation regime by keeping 3–5 cm of water over the soil for the growing season. In northern Iran, irrigated lowland rice usually experiences water deficit during the growing season. Two northern provinces (Guilan and Mazandaran) close to the Caspian Sea have an annual rainfall of 700–1000 mm, covering 70–80% of paddy field cultivation area. However, the majority of rainfall does not occur within rice cultivation season. Irrigation dominates the water use in Iran, and surface water storage will be increased by construction

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of numerous multipurpose dams and reservoirs along rivers that comes from Zagros and Alborz mountains.

Agricultural systems are complex, and understanding this complexity requires systematic research, but resources for agricultural research are limited. The field experiments investigate a number of variables under a few site-specific conditions. Crop simulation models consider the complex interactions of weather, soil properties, and management factors, which influence crop performance. Mechanistic models are very helpful in deciding the best management options for optimizing crop growth and the yield. In the middle of 1990s, Rice Research Institute of Iran (IRRI), Wageningen University, and the Research Centre developed the ORYZA model series to simulate the growth and development of tropical lowland rice (Ten Berge and Kropff 1995). In 2001, a new version of the ORYZA model was released that improved and incorporated all previous versions into one model called ORYZA2000 (Bouman et al. 2001). The ORYZA2000 was evaluated under limited water and/or nitrogen conditions in the Philippines (Bouman and Van Laar 2006), India (Arora 2006), Indonesia (Boling et al. 2007), Iran (Amiri 2008), Japan (Bannayan et al. 2005), and China (Belder, Bouman, and Spiertz 2007; Jing et al. 2007; Bouman et al. 2007; Feng et al. 2007; Xue et al. 2008). Measurements of some of the hydrological variables (such as transpiration, evapotranspiration, and infiltration) in the field conditions were difficult and/or needed sophisticated instruments such as a lysimeter. Therefore, field experiments that yield site-specific information are expensive, laborious, and time-consuming, especially if they should be representative for a number of years. However, the ORYZA2000 model in combination with field experiments offers the opportunity to gain detailed insights into the system behavior in space and time.

Water productivity (WP) could be defined as total water input through rainfall and irrigation or as evapotranspiration (E). The WP expresses the input/output relationship or "crop per drop" (Kijne, Barker, and Molden 2003). Water productivity will be computed as the ratio of grain yield to total water input (WP_{I+R}) or by evapotranspiration (WP_{ET}). Decreasing the amount of water availability for agriculture threatens the productivity of the irrigated rice ecosystem, and various approaches should be sought to save water and increase the water productivity of rice (Guerra et al. 1998). Turner (1997) suggested two ways to increase the water productivity under water-stress conditions: (1) plant genetic improvement and (2) agronomic practices. Tuong (1999) discussed that improvement of water productivity would involve (1) increasing yield per unit of ET and (2) reducing the portion of water input to the field that is not available for crop ET. The WP_{ET} values in rice found in previous studies showed a rather wide range (between 0.6 kg m^{-3} and 1.6 kg m^{-3} (Zwart and Bastiaanssen 2004)), which is caused by environmental factors, crop management, and genotypic variation (Turner 1997; Belder et al. 2004 and 2005). Water productivity (WP_{I+R}) of rice ranges from 0.50 to 1.48 kg m^{-3}, and water productivity (WP_{ET}) ranges from 0.7 to 1.6 kg m^{-3}.

In this study, we evaluated the crop growth model ORYZA2000 by using 2 years of field data. Then we employed this model to determine the parameters of the water balance of the field experiments to estimate the optimum irrigation regime across different plant densities.

Materials and Methods

Field Experiments

The experiments were performed at RRII, Guilan Province, located in northern Iran (37° 12′ N, 49°3 8′ E) under clay soil during the rice cropping season of 2001 and 2002. The experiments were laid out as a split-plot design with three replications consisting of four irrigation regimes as the main plot and three different crop spacings as subplots. Four irrigation treatment regimes in this study are included:

I_1, continuous submergence (about 5 cm height) as a control treatment;
I_2, irrigation based on 100% evaporation rate measured by an evaporation pan instrument (class A pan);
I_3, irrigation based on 75% evaporation rate;
and I_4, irrigation based on 50% evaporation rate.

Also, three crop spacing are included:

S_1, 20 cm × 20 cm;
S_2, 15 cm × 15 cm;
S_3, and 10 cm × 20 cm.

The main plot was 10.5 m × 3.5 m with three equal subplots separated by 0.5-m space between them to avoid lateral seepage. The entire main and subplot treatments were selected randomly. The daily evaporation and precipitation were monitored by using the evaporation pan and storage udometer. The total evaporation and precipitation rates over the preceding 5-day period were used to determine the amount of water for irrigation per each plot for each treatment. The amount of irrigation water used was monitored at each plot from transplanting until maturity by using flow meters installed in the irrigation pipes.

The seedlings at age of 35–45 days were transplanted at a rate of 3 seedlings per hill on 2 June 2001 and 4 June 2002; and the harvest dates were 30 August 2001 and 28 August 2002. The yield was measured with 5 m^2 harvests of each plot. In all experiment plots, 60 kg nitrogen (N) per hectare, 25 kg phosphorus pentoxide (P_2O_5) per hectare, and 75 kg potassium oxide (K_2O) per hectare were applied before transplanting.

Model ORYZA2000

A detailed description of the model is given by Bouman et al. (2001), and just summary of the model is described in this section. ORYZA2000 follows a daily calculation pattern for the rate of dry-matter production of the crop organs and the rate of phenological development. By integrating these rates over the time, dry-matter production and development stage were simulated through the growing season. The calculation processes for dry-matter production were well documented (Bouman et al. 2001). Total daily rate of canopy carbon dioxide (CO_2) assimilation was calculated from daily incoming radiation, temperature, and leaf area index (LAI). The daily dry-matter accumulation was calculated by subtraction of maintenance and growth respiration requirements from total assimilation amount. The dry-matter increment was partitioned among the various plant organs as a function of phenological development stage, which is tracked as a function of mean daily air temperature. Spikelet density at flowering was derived from total dry-matter accumulation over the period of panicle initiation to flowering stage.

The water dynamics in the ORYZA2000 model was accounted for using a soil–water balance module (PADDY; Wopereis et al. 1996; Bouman et al. 2001). In PADDY, a lowland rice soil was modeled as a layer of muddy topsoil overlying a 3- to 5-cm plow sole and nonpuddled subsoil. With pounded water on surface, vertical water movement will be a fixed infiltration rate. The water retention and conductivity characteristics were expressed by Van Genuchten parameters (Van Genuchten 1980).

ORYZA2000 Input Data

Model calibration is the adjustment of parameters so that simulated values compare well with observed ones; calibrations started with standard crop parameters for cultivar IR72 and following the procedures set by Bouman et al (2001). First, development rates were calculated using observed (2001 year) dates of emergence, transplanting, panicle initiation, flowering, and physiological maturity. Second, specific leaf area value was calculated from observed values of leaf area and leaf dry weight amounts. The partitioning of assimilates was derived from observed data, which use the leaf, stem, and panicle biomass portions. Daily climatological data, which included sunshine hours, maximum and minimum temperatures, vapor pressure, wind speed, and rainfall rate for crop season were obtained from the Rasht meteorological station. The summary of meteorological data during the experiment period is given in Table 1. The soil water content at specified depth was estimated by the pressure plate instrument (Table 2). The Van Genuchten parameters (Table 2) for different soil layers were derived by using pedotransfer functions (Van Genuchten, Leij, and Yates 1991). The Quick method instruments were used for determination of infiltration and seepage during the rice growing season (Amiri 2008). The saturated hydraulic conductivity (K_s) of different soil layers (including plow sole) was determined based on undisturbed soil cores in the laboratory.

Model Evaluation

For model evaluation, the root mean square error (RMSE) and normalized root mean square error ($RMSE_n$) were calculated as follows:

$$\mathrm{RMSE} = \left(\sum_{i=1}^{n} (P_i - O_i)^2/n\right)^{0.5} \tag{1}$$

$$\mathrm{RMSE_n} = 100\left(\sum_{i=1}^{n} (P_i - O_i)^2/n\right)^{0.5} /O_{\mathrm{mean}} \tag{2}$$

Table 1

Monthly total rainfall and average temperature and sunshine hours during 2001–2

Year	Month	Minimum temperature (°C)	Maximum temperature (°C)	Mean temperature (°C)	Rainfall (mm)	Sun (h)
2001	April	10.8	19.4	15.1	29.2	4
	May	15.0	24.3	19.7	111	5.4
	June	18.2	27.8	23.0	6.3	9.6
	July	20.7	29.9	25.2	29	6.3
	August	21.2	31.9	26.6	85.5	7.5
2002	April	10.4	16.1	13.2	121	4.2
	May	13.4	20.8	17.1	82.4	5.3
	June	18.8	27.6	23.2	1.5	9.5
	July	21.3	31.6	26.4	17.6	6.9
	August	22.1	30.8	26.5	119.5	7.6

Table 2

Physical properties and Van Genuchten parameters per soil layers of the experiment field

Depth (cm)	Sand (%)	Loam (%)	Clay (%)	Bulk density (g cm^{-1})	θ_{SAT}	K_{SAT} (cm/day)	θ_{FC}	θ_{PWP}	λ	n	α (cm^{-1})
0–10	14	39	47	1.10	0.65	57.54	0.40	0.27	050	1.23	0.03
10–20	17	39	44	1.20	0.62	30.80	0.40	0.30	050	1.20	0.03
20–30	9	44	47	1.32	0.62	0.40	0.41	0.30	050	2.99	0.06
30–40	11	42	47	1.31	0.60	11.40	0.42	0.30	050	1.17	0.26
40–60	9	42	49	1.33	0.60	10.4	0.42	0.32	050	1.16	0.03
60–80	5	34	61	1.29	0.60	21.4	0.39	0.29	050	1.19	0.03

Notes. Parameter abbreviations are as follows: α, Van Genuchten alpha parameter; λ, Van Genuchten lambda parameter; n, Van Genuchten n parameter; Ks, saturated hydraulic conductivity; θ_{SAT}, saturated volumetric water content; θ_{FC}, field capacity volumetric water content; and θ_{PWP}, permanent wilting point.

where P_i is the simulated value, O_i is the observed value, O_{mean} is the mean of observed data, and n is the number of observations. Paired t-test and linear regression analysis were also used to assess the goodness-of-fit relationship between the observed and simulated datasets.

Soil–Water Balance

The seasonal water balance of the root zone of field could be calculated as follows:

$$\mathrm{I} + \mathrm{R} = \mathrm{E} + \mathrm{T} + \mathrm{D} + \Delta\mathrm{W} \tag{3}$$

where I is the irrigation rate, R is rainfall rate, E is evaporation rate, T is transpiration rate, P is percolation rate beyond the root zone, and ΔW is change in the soil water storage. The rainfall amount was obtained from the meteorological data and all other components simulated by ORYZA2000. For the seasonal water balance, the daily components were added from transplanting until physiological maturity stage. The daily inflow rates were added from transplanting until maturity stage, where irrigation and rainfall events were directly observed. The evaporation, transpiration, percolation, and the difference in field water storage rates were calculated by ORYZA2000. The evaporation and transpiration rates were calculated using Priestley–Taylor equations (Van Kraalingen 1995).

Water Productivity

The water productivity should be defined in different ways referring to different type of crop productions, for instance, dry matter or grain yield, and amount of water used, such as transpiration, evapotranspiration, and irrigation (Molden et al. 2001). The $\mathrm{WP_T}$ was expressed as crop grain yield $\mathrm{Y_g}$ per unit amount of transpiration T, and set the lower limit of water used by the crop. The actual evapotranspiration ($\mathrm{ET_a}$) represents the actual amount of water that was used in crop production, which is no longer available for reuse in the agricultural production system. It should be used as $\mathrm{WP_{ET}}$ instead of $\mathrm{Y_g}$ per unit value of ET. The inevitable loss of water due to evaporation caused decreases in water productivity ($\mathrm{WP_T}$ to $\mathrm{WP_{ET}}$). Therefore, relatively low values of $\mathrm{WP_{ET}}$ when compared to $\mathrm{WP_T}$ suggested reducing the evaporation rate by agronomic measurements, such as soil mulching and conservation tillage. The irrigation and rainfall rates are the total water used in the field. In this situation, and the water productivity values $\mathrm{WP_I}$ and $\mathrm{WP_{I+R}}$ were expressed in terms of $\mathrm{Y_g}$ per unit water available in field through irrigation, I, and rainfall, R, as inputs.

Results and Discussion

Model Evaluation

The model was calibrated using the data for 2001, and the 2002 dataset was used for validation. The ORYZA2000 model was evaluated based on the simulation of grain yield across various saving regimes and plant densities.

The parameters obtained in model calibrations were used for validation and performance evaluation of ORYZA2000. The statistical output was used to evaluate the model performance, which is shown in Table 3. The RMSE was ranged between 150 and 182 kg ha^{-1} and normalized RMSE was 6–7% for observed yields, which varies between 1848 and 3193 kg ha^{-1}. Paired t-test results showed no significant difference between the observed

Table 3

Evaluation results of ORYZA2000 simulations of yield for the calibration and validation conditions

Year	Crop variable	N	X_{obs} (SD)	X_{sim} (SD)	α	β	R^2	P(t)	RMSE	$RMSE_n$ (%)	SE	CV
	Calibration											
2001	Yield (kg ha^{-1})	12	2135 (247)	2193 (264)	0.78	407	0.71	0.29*	150	7	167	6
	Validation											
2002	Yield (kg ha^{-1})	12	2924 (221)	3011 (277)	0.63	1009	0.63	0.20*	182	6		

Notes. N, number of observed/simulated data pairs; X_{obs}, mean of observed values in whole population; X_{sim}, mean of simulated values in whole population; SD, standard deviation of population; α, slope of linear relation between simulated and observed values; β, intercept of linear relation between simulated and observed values; R^2, adjusted linear correlation coefficient between simulated and observed values; RMSE, absolute root mean square error; $RMSE_n$ (%), normalized root mean square error. An asterisk (*) means simulated and observed values are the same at 95% confidence level; SE, standard error of observed variables; CV, coefficient of variation of observed variables.

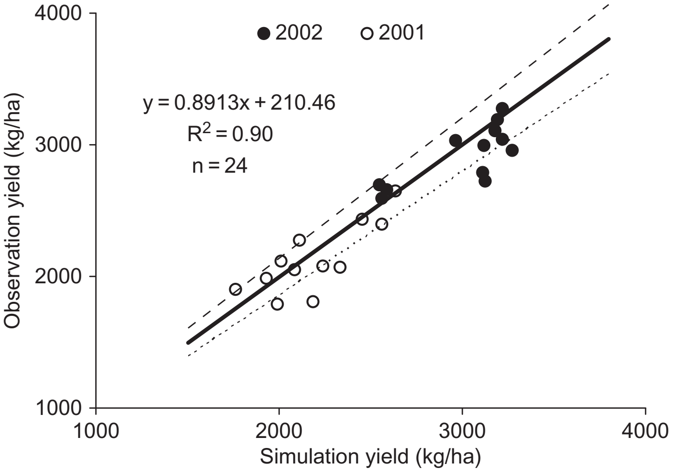

Figure 1. Simulated versus observed grain yields. The solid line is 1:1, and the dotted line is plus and minus standard error around the 1:1 line.

and simulated yield values ($P > 0.05$). The 1:1 line and the standard error (SE) of the observed variables were also shown. Figure 1 shows nearly 75% yield data points dropped in plus and minus SE lines of observed yield. The linear regression model was performed between simulated and observed values, and it shows the slope (α) close to 1 and relatively small intercept value (β). Correlation coefficient for this analysis is larger than 0.63 for yield, which indicated a fair simulation.

The capability of ORYZA2000 model to simulate rice yield in a water-saving regime and crop density is shown in Figure 2. The accuracy of ORYZA2000 simulated yields in

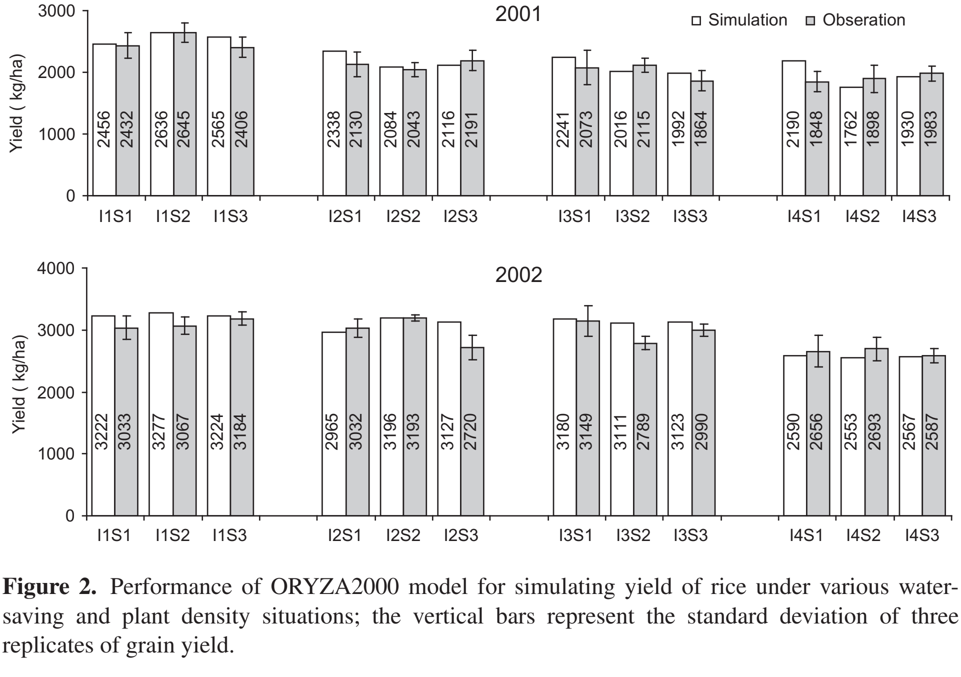

Figure 2. Performance of ORYZA2000 model for simulating yield of rice under various water-saving and plant density situations; the vertical bars represent the standard deviation of three replicates of grain yield.

our field experiment results were compared with other publications using the same crop model (see Table 4).

Water Balance Components

The water balance components of the field experiments are presented in Table 5. The amounts of rainfall from transplanting to harvest stage were 119 mm for 2001 and 71 mm for 2002. The amount of irrigation water applied varied between 195 mm to 430 mm. The water-saving regimes used less irrigation water than continuous submergence regimes. In the field experiment, water-saving regimes reduced the yield by 11% when compared to the control. The average water input was 22% less than the control for this situation. The evaporation depends on the water regime and plant density; the seasonal evaporation varied from 88 to 183 mm and showed a significant reduction with a decrease in plant spacing and applied water amount. The continuous surface ponding caused high soil evaporation during the rice growing season.

The lower plant spacing caused greater leaf growth, more light interception, and less light transmission to the soil surface, which also reduced the evaporation rate (Belder et al. 2005). Our results showed that S1 evaporation rate was greater than S2 and S3 rates.

The transpiration (T) varied from 181 to 374 mm and also reflected canopy development and biomass growth that was strongly affected by water and plant density. The T value is directly related to the leaf area index (LAI), but evaporation (E) has an indirect relationship with LAI. Because paddy is a sensitive crop to water stress, even light stress will affect the LAI.

In addition, the evaporation loss will increase because most of the paddy fields were kept under saturated conditions during the growing season. This will result in a more or less equal potential and actual E. Decreasing the LAI amount reduces the transpiration; however, it increases the evaporation rate (Belder et al. 2005). In this research, ET simulated by the calibrated and validated ORYZA2000 ranged from 312 to 462 mm for different combination of water and plant density conditions. Additionally, Doorenbos and Kassam (1979) mentioned ET varied from 450 to 700 mm for rice crop.

The seasonal amount of infiltration was varied from 90 to 236 mm. The amount of infiltration is greater for the continuous submergence regime than for the water-saving regime (see Table 5). A decrease in infiltration caused a reduction in irrigation depth. Earlier studies (Arora 2006; Belder, Bouman, and Spiertz 2007) showed a reduction in ponded water depth caused a substantial decrease in infiltration rate.

Water Productivity Components

The water productivity for rice was analyzed using the ORYZA2000 simulation model. We calculated the water productivity rates using the simulated water balance components of T and ET by ORYZA2000 and the actual (observed) grain yield (see Table 6). Both water productivities WP_{I+R} and WP_I showed a maximum value at I_4 regimes (irrigation by 50% evaporation from evaporation pan).

The WP_I varied from 0.7 $kg.m^{-3}$ at continuous submergence treatment to 0.9 $kg.m^{-3}$ at I_4 regime due to a decrease in irrigation water requirements. It was reported by Tuong and Bouman (2003) that water productivity WP_{I+R} of irrigated rice ranged from 0.2 to 1.1 $kg.m^{-3}$.

In this study, the amount of WP_{ET} varied from 0.57 to 0.69 $kg.m^{-3}$ (see Table 6). Based on previous studies in the past 25 years, Zwart and Bastiaanssen (2004) established global

Table 4

Root mean square error (RMSE) and normalized root mean square error (RMSE_n) of yield simulated by ORYZA2000

Rice variety Evaluation type	XD90247 Calibrate[a]	Wuxiangjing9 Calibrate[b]	Wuxiangjing9 Validate[b]	2You725 Calibrate[c]	Apo Calibrate[c]	IR64 Calibrate[d]	IR72 Calibrate[e]	IR72 Validate[e]	HD297 Calibrate[a]	HD297 Calibrate[f]	HD297 Validate[f]
RMSE											
Yield (kg/ha)	660	1193	1193	894	646	0.65	852	838	560	3218	989
RMSE_n											
(%)Yield	11	13	13	13	13	16	13	11	19	124	19

[a] Feng et al. (2007).
[b] Jing et al. (2007).
[c] Belder et al. (2007).
[d] Boling et al. (2007).
[e] Bouman and Van Laar (2006).
[f] Xue et al. (2008).

Table 5
Water balance components and rice yield under different irrigation regimes and plant densities

				Water balance components (mm)					
Year	Irrigation regime	Plant density	Yield (kg/ha)	Evaporation (mm)	Transpiration (mm)	ET (mm)	Irrigation (mm)	Percolation (mm)	ΔW storage (mm)
2001	Continuous submergence	20 × 20 cm	2432	183	197	380	375	203	89
		15 × 15 cm	2645	145	278	423	375	164	93
		10 × 20 cm	2397	152	260	412	375	174	92
	Irrigation based on 100% evaporation	20 × 20 cm	2063	175	191	366	342	194	99
		15 × 15 cm	2043	134	264	398	342	170	107
		10 × 20 cm	2272	140	250	390	342	176	105
	Irrigation based on 75% evaporation	20 × 20 cm	2073	146	181	327	251	141	98
		15 × 15 cm	2115	120	238	358	251	116	104
		10 × 20 cm	1784	123	230	353	251	122	105
	Irrigation based on 50% evaporation	20 × 20 cm	1804	140	172	312	195	113	111
		15 × 15 cm	1898	115	224	339	195	93	118
		10 × 20 cm	1983	118	214	332	195	98	116
2002	Continuous submergence	20 × 20 cm	2950	156	242	398	430	236	133
		15 × 15 cm	2893	112	335	447	430	203	149
		10 × 20 cm	3193	118	319	437	430	211	147
	Irrigation based on 100% evaporation	20 × 20 cm	3032	171	236	407	417	168	87
		15 × 15 cm	3158	119	333	452	417	138	102
		10 × 20 cm	2641	126	317	443	417	146	101
	Irrigation based on 75% evaporation	20 × 20 cm	3149	102	339	441	367	110	113
		15 × 15 cm	2731	92	369	461	367	90	113
		10 × 20 cm	2965	88	374	462	367	91	115
	Irrigation based on 50% evaporation	20 × 20 cm	2715	141	258	399	318	137	147
		15 × 15 cm	2702	96	331	427	318	114	152
		10 × 20 cm	2681	107	318	425	318	115	151

Table 6

Water productivity of rice under irrigation regime and plant density conditions, 2001–2

		2001				2002			
Irrigation regime	Plant density	WP_I	WP_{I+R}	WP_{ET}	WP_T	WP_I	WP_{I+R}	WP_{ET}	WP_T
Continuous submergence	20 × 20 cm	0.65	0.49	0.64	1.23	0.69	0.59	0.74	1.22
	15 × 15 cm	0.71	0.54	0.63	0.95	0.67	0.58	0.65	0.86
	10 × 20 cm	0.64	0.49	0.58	0.92	0.74	0.64	0.73	1.00
Irrigation based on 100% evaporation	20 × 20 cm	0.60	0.45	0.56	1.08	0.73	0.62	0.75	1.28
	15 × 15 cm	0.60	0.44	0.51	0.77	0.76	0.65	0.70	0.95
	10 × 20 cm	0.66	0.49	0.58	0.91	0.63	0.54	0.60	0.83
Irrigation based on 75% evaporation	20 × 20 cm	0.83	0.56	0.63	1.15	0.86	0.72	0.71	0.93
	15 × 15 cm	0.84	0.57	0.59	0.89	0.74	0.62	0.59	0.74
	10 × 20 cm	0.71	0.48	0.51	0.78	0.81	0.68	0.64	0.79
Irrigation based on 50% evaporation	20 × 20 cm	0.93	0.57	0.58	1.05	0.85	0.70	0.68	1.05
	15 × 15 cm	0.97	0.60	0.56	0.85	0.85	0.69	0.63	0.82
	10 × 20 cm	1.02	0.63	0.60	0.93	0.84	0.69	0.63	0.84

benchmark numbers of WP_{ET}, expressed as Y_g/ET (kg m^{-3}), at 1.09 for rice crop. To improve the WP_{ET} for the crop, the fraction of soil evaporation section in the evapotranspiration process is the important issue. During the rice cultivation, high evaporative demands and continuous surface water ponding caused a high soil evaporation rate. Improving agronomic practices such as water-saving regimes could reduce this nonbeneficial loss of water through soil evaporation E, and subsequently will improve WP_{ET} (Turner 1997). In this study, the mean value of WP_{ET} was 0.63 kg m^{-3}, 35% less than WP_T. The differences in WP_T for different treatments were due to the differences in the chemical harvest index and evaporative demands during the respective seasons.

The results of this study showed that the I2, I3, and I4 irrigation regimes caused yields to decline by 7%, 10%, and 16%, respectively. Reducing water inputs from continuous submergence conditions to water-saving conditions will decrease rice yields, but it will substantially increase water productivity.

In Figure 3, the average water productivity components during many years were calculated for irrigation regimes and crop density. As Figure 3 shows, changing the irrigation method will improve water productivity components (such as WP_I and WP_{I+R}). However, increasing water productivity did not affect crop density (except WP_T parameter). Therefore, for agricultural managers the optimum irrigation and crop density would be

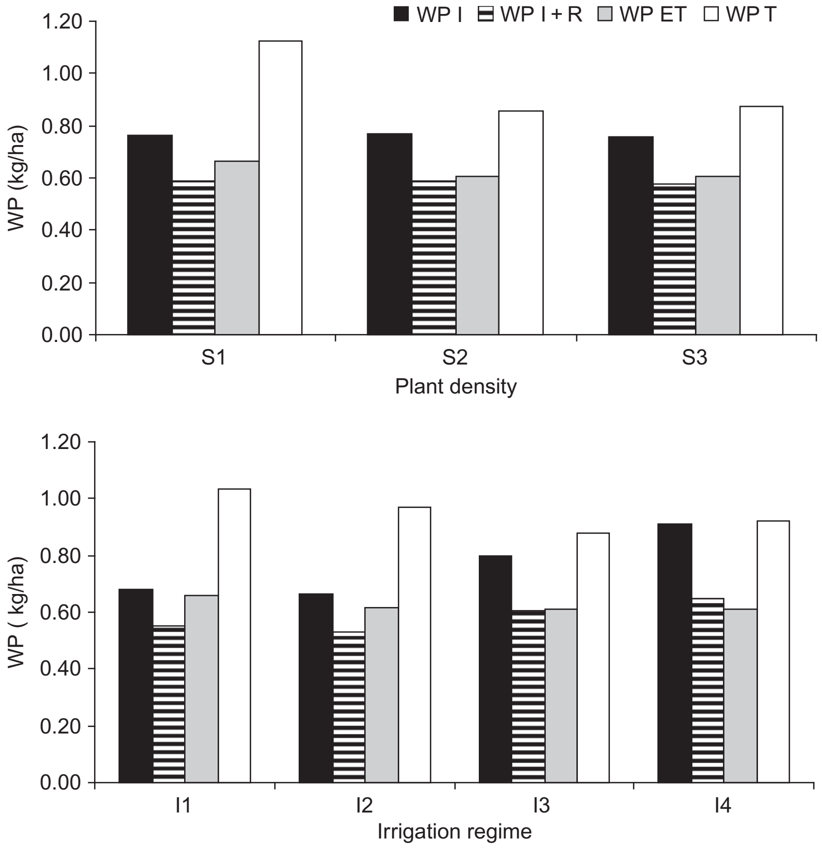

Figure 3. Water productivity of rice under irrigation regime and crop density conditions.

the greatest water productivity that was obtained. The results of this study showed that between two factors of irrigation regime and crop density, in terms of water productivity component and yield, the irrigation rate of 75% evaporation from pan and 20 cm × 20 cm crop spacing would be optimal. The mean yield of 2 years of irrigation and crop density conditions was 2611 kg.ha^{-1} and the means of $\mathrm{WP_I}$, $\mathrm{WP_{I+R}}$, $\mathrm{WP_{ET}}$, and $\mathrm{WP_T}$ of water–crop density scheme were calculated as 0.84, 0.64, 0.67, and 1.04 (kg m^{-3}).

Conclusions

The ORYZA2000 model was sufficiently accurate in the simulation of yield under water-saving and crop density conditions for our study site. The ecophysiological model ORYZA2000 in combination with field experiments was used to quantify hydrological variables such as transpiration, evapotranspiration, infiltration, and biophysical variables such as grain yields, which required water productivity analysis of rice crop. The large amount of evaporation (27–44%) in the evapotranspiration process presents a major non-beneficial loss of water. The average $\mathrm{WP_{ET}}$ expressed as Yg/ET (kg m^{-3}) was 0.63 for rice crop. Meteorological dataset, soil, and crop, in combination with ecophysiological models such as ORYZA2000, should be used to produce the required hydrological and biophysical information. The results were showed that irrigation by 75% evaporation rate from evaporation pan and also 20 cm × 20 cm crop spacing should be considered as optimum irrigation and crop density.

References

Amiri, E. 2008. Evaluation of the rice growth model ORYZA2000 under water management. *Asian Journal of Plant Sciences* 7 (3): 291–297.

Arora, V. K. 2006. Application of a rice growth and water balance model in an irrigated semi-arid subtropical environment. *Agricultural Water Management* 83:51–57.

Bannayan, M., K. Kobayashi, H. Kim, M. Lieffering, M. Okada, and S. Miura. 2005. Modeling the interactive effects of atmospheric CO_2 and N on rice growth and yield. *Field Crops Research* 93:237–251.

Belder, P., B. A. M. Bouman, R. Cabangon, G. Lu, E. J. P. Quilang, Y. H. Li, J. H. Spiertz, and T. P. Tuong. 2004. Effect of water-saving irrigation on rice yield and water use in typical lowland conditions in Asia. *Agricultural Water Management* 65 (3): 193–210.

Belder, P., B. A. M. Bouman, and J. H. J. Spiertz. 2007. Exploring option for water savings in lowland rice using a modeling approach. *Agricultural Systems* 92:91–114.

Belder, P., J. H. J. Spiertz, B. A. M. Bouman, G. Lu, and T. P. Tuong. 2005. Nitrogen economy and water productivity of lowland rice under water-saving irrigation. *Field Crop Research* 93: 169–185.

Boling, A. A., B. A. M. Bouman, T. P. Tuong, M. V. R. Murty, and S. Y. Jatmiko. 2007. Modelling the effect of groundwater depth on yield increasing interventions in rainfed lowland rice in Central Java Indonesia. *Agricultural Systems* 92:115–139.

Bouman, B. A. M., L. Feng, T. P. Tuong, G. Lu, H. Wang, and Y. Feng. 2007. Exploring options to grow rice under water-short conditions in northern China using a modelling approach, II: Quantifying yield, water balance components, and water productivity. *Agricultural Water Management* 88:23–33.

Bouman, B. A. M., M. J. Kropff, T. P. Tuong, M. C. S. Wopereis, H. F. M. Ten Berge, and H. H. Van Laar. 2001. *ORYZA2000: Modeling lowland rice*. Phillipines: International Rice Research Institute.

Bouman, B. A. M., and T. P. Tuong. 2001. Field water management to save water and increase its productivity in irrigated lowland rice. *Agricultural Water Management* 49:11–30.

Bouman, B. A. M., and H. H. Van Laar. 2006. Description and evaluation of the rice growth model ORYZA2000 under nitrogen-limited conditions. *Agricultural Systems* 87:249–273.

Doorenbos, J., and A. H. Kassam. 1979. *Yield response to water* (FAO Irrigation and Drainage Paper 33). Rome, Italy: FAO.

Feng, L. P., B. A. M. Bouman, T. P. Tuong, R. J. Cabangon, Y. L. Li, G. A. Lu, and Y. H. Feng. 2007. Exploring options to grow rice under water short conditions in northern China using a modeling approach, I: Field experiments and model evaluation. *Agricultural Water Management* 88:1–13.

Guerra, L. C., S. I. Bhuiyan, T. P. Tuong, and R. Barker. 1998. *Producing more rice with less water from irrigated systems* (SWIM Paper 5). Colombo, Sri Lanka: IWMI/IRRI.

Jing, Q., B. A. M. Bouman, H. Hengsdijk, H. Van Keulen, and W. Cao. 2007. Exploring options to combine high yields with high nitrogen use efficiencies in irrigated rice in China. *European Journal of Agronomy* 26:166–177.

Kijne, J., R. Barker, and D. Molden (Eds.). 2003. *Water productivity in agriculture: Limits and opportunities for improvement* (Comprehensive Assessment of Water Management in Agriculture, Series No. 1). Wallingford, UK: CABI Press.

Molden, D. 2007. *Water for food, water for life: A comprehensive assessment of water management in agriculture*. London: International Water Management Institute.

Molden, D., H. Murray-Rust, R. Sakthivadivel, and I. Makin. 2001. A water productivity framework for understanding and action. Workshop on Water productivity. Wadduwe, Sri Lanka, 12 and 13 November 2001.

Ten Berge, H. F. M., and M. J. Kropff. 1995. Founding a systems research network for rice. In *Eco-regional approaches for sustainable land use and food production*, ed. J. Bouma, A. Kuyvenhoven, B. A. M. Bouman, J. C. Luyten, and H. G. Zandstra, 263–282. Dordrecht, the Netherlands: Kluwer Academic Publishers.

Tuong, T. P. 1999. Productive water use in rice production: Opportunities and limitations. In *Water use in crop production*, ed. M. B. Kirkham, 241–264. Haworth Press.

Tuong, T. P., and B. A. M. Bouman. 2003. Rice production in water-scarce environments. In *Water productivity in agriculture:Llimits and opportunities for improvement* (Comprehensive Assessment of Water Management in Agriculture Series No. 1), ed. J. Kijne, R. Barker, and D. Molden, 53–67. Wallingford, UK: CABI Press.

Turner, N. C. 1997. Further progress in crop water relations. *Advances in Agronomy* 58:293–338.

Van Genuchten, M. T. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* 44:892–898.

Van Genuchten, M. T., F. J. Leij, and S. R. Yates. 1991. *The RETC code for quantifying the hydraulic functions for unsaturated soils*. Riverside, Calif.: U.S. Salinity Laboratory.

Van Kraalingen, D. W. G. 1995. *The FSE system for crop simulation: Version 2.1* (Quantitative Approaches in Systems Analysis Report 1). Wageningen, the Netherlands: C.T. de Wit Graduate School for Production Ecology and AB-DLO.

Wopereis, M. C. S., B. A. M. Bouman, T. P. Tuong, H. F. M. ten Berge, and M. J. Kropff. 1996. ORYZA_W: Rice growth model for irrigated and rainfed environments. *SARP Research Proceedings*. Wageningen, the Netherlands: IRRI/AB-DLO.

Xue, C., X. Yang, B. A. M. Bouman, W. Deng, Q. Zhang, W. Yan, T. Zhang, A. Rouzi, and H. Wang. 2008. Optimizing yield, water requirements, and water productivity of aerobic rice for the North China Plain. *Irrigation Science* 26 (6): 459–474.

Zwart, S. J., and W. G. M. Bastiaanssen. 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agricultural Water Management* 69 (2): 115–133.