Trends in Life Sciences
An International Peer-reviewed Journal
www.sciencejournal.in

WATER PRODUCTIVITY OF RICE PRODUCTION IN NORTHERN IRAN UNDER WATER DEFICIT CONDITION: FIELD AND MODELING APPROACH

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ABSTRACT
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 2009 and 2010 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 variety as subplots and four different irrigation regimes 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 between varieties the highest amount of different water productivity $WP_{ET,}$ $WP_{T,}$ WP_{I} was measured in Hybrid and Dorfak was in second range. Also our result showed that Water productivity of Alikazemi with changes in irrigation management from I1 to I2 was decreased but in Hybrid and Dorfak change in water management had not significant Effect on water productivity because with decrease of water consumption the yield of these two varieties was decreased.

KEYWORDS: Irrigation, ORYZA2000, Rice, Water Productivity.

INTRODUCTION
Rice is the third highest grain produced after maize and wheat with approximately 158 million ha harvested, 88.9% in Asia (Food and Agriculture Organization, 2010). Optimization of irrigation water is an important issue in agricultural production for maximizing the return from the limited water availability. Water stress affects crop growth and productivity in many ways. Most of the responses have a negative effect on production, but crops have different and often complex mechanisms to react to shortages of water. While agricultural water supply is increasingly limited, many irrigation schemes are routinely operated according to maximum supply conditions, and lack appropriate procedures and mechanisms to adjust supply and cropping pattern to water availability. Because rice receives more irrigation water than other grain crops, water-saving irrigation technologies for rice are seen as a key component in any strategy to deal with water scarcity (Li and Barker 2004). In northern Iran, irrigated lowland rice usually experiences water deficit during the growing season. This area has 700 –1000 mm annual rainfall and 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 (Amiri *et al.,* 2011). Optimal irrigation scheduling under deficit conditions is highly complex since it depends on the interaction of physical constraints of the irrigation system, soil moisture availability at the time of irrigation, growth stage of the crop, effect of previous and subsequent irrigations on crop growth and yield, and nature of weather conditions.

Crop models are useful tools for integrating knowledge of the biophysical processes governing the plant–soil–atmosphere system and for extrapolating research results to other locations or sites. Crop growth simulation models are recognized as valuable tools in agricultural research. They can help to compare experimental research findings across sites, extrapolate experimental field data to wider environments, develop management recommendations and explore effects of climate change, and make yield predictions (Jones et al., 2003). Crop simulation models consider the complex interactions between weather, soil properties, and management factors (water and N) that influence crop performance. Mechanistic models are very helpful in deciding the best management options for optimizing crop growth and yield. If pests and diseases are controlled, yield of any crop in a given environment mainly depends upon irrigation and fertilizer nitrogen (N) management. Recent developments in crop growth simulation models have given the opportunities for simulating the field conditions. Adequately calibrated and validated agricultural system models provide a systems approach and a fast alternative method for developing and evaluating agronomic practices that can

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utilize technological advances in limited irrigation agriculture (Saseendran *et al.* 2008). 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 WPET values in rice found in previous studies showed a rather wide range (between 0.6 kg m^{-3} and 1.6kgm^{-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.

MATERIAL AND METHODS

Description of experimental site

A 2-year field experiment was conducted at the experimental farm of the Iranian Rice Research Institute in Rasht (37′12°N; 49′38° S; 7 m below sea level) from 2009 to 2010. The soil was sandy loam. At the start of the experiment, soil physical (texture, bulk density, hydraulic conductivity, drained upper limit, drained lower limit, field capacity) and chemical [pH, cation exchange capacity (CEC), organic carbon (OC), total N, phosphorus (P), potassium (K)] properties of the field were determined up to a depth of 40 cm, at an interval of 10 cm, following standard procedures (Table 1). The site has a warm semi-Mediterranean climate with warm summers, mild winters, annual means of 1441 mm rainfall, and 16.8 ˚C temperature. Daily weather data of maximum and minimum temperatures, maximum and minimum relative humidity, rainfall, and sunshine hours were collected for the entire growing seasons from a meteorological station beside the Iranian Rice Research Institute. The experiment was established in a split-plot design with four irrigation regimes as the main plot and three variety of rice as the subplot and three replications. The plot size for the subplots was 15 m^2 (5 m × 3 m). The irrigation regimes were I_1: continuous submergence, I_2: irrigation at 5-day intervals, I_3: irrigation at 8-day interval and I_4: irrigation at 11-day interval. The three rice varieties were Alikazemi, Dorfak and Hybrid. Land preparation consisted of wet tillage followed by harrowing, a process referred to as "puddling." Puddling is practiced to create a semi-impermeable layer (hardpan) and to ease transplanting. The plots were separated by plastic sheets installed to 30 cm below the soil surface to restrict water and N flows between adjacent plots. Phosphorus (P) and potassium (K) were applied at transplanting in all plots at 25 kg phosphorus pentoxide (P_2O_5) as triple superphosphate and 75 kg potassium oxide (K_2O) of potash (KCL) ha^{-1}. Seedlings were transplanted on 10 May 2009, 15 May 2010. Weeds, insects, and diseases were effectively controlled to avoid yield loss. All treatments were harvested on 11–15 August. The amount of irrigation water applied to each plot at irrigation from transplanting until maturity was measured using a pipe system equipped with flow meters that were installed in the field. Dates of heading and physiological maturity were determined for each treatment. Heading and physiological maturity occurred when 50% or more of the selected plants (tagged after transplanting) reached the specified stage. All samples were then oven dried at 70 ◦ C for 48 h and weighed. In all 3 years of experiment, grain yield and aboveground biomass (after drying at 70 ◦ C for 48 h) were determined from a 5-m^2 area at maturity.

Model description

ORYZA2000 is a crop model that simulates growth and development of lowland rice for potential, water and N-limited production situations. ORYZA2000 simulates the growth, development, and soil water balance of rice in three production situations, potential, water limited, and nitrogen limited (Bouman et al. 2001). For all production situations, it is assumed that the crop is free from diseases, pests, and weeds and that no reductions in yield take place. The processes of crop growth and development follow the typical calculation schemes of the School of De Wit models (Bouman et al. 1996) and have been summarized by Bouman and Van Laar (2006), Belder et al. (2007), and Boling et al. (2007). The model computes the rate of phenological development of rice on a daily time scale based on the daily average temperature and photoperiod. The dry matter at plant organs is computed considering the daily heat units. The simulated total dry matter is partitioned by the model among various parts of the crop (roots, leaves, stems, and panicles) using partitioning factors, which are to be determined through calibration. The development stage is tracked as a function of daily mean temperature and photoperiod. On the basis of single leaf photosynthetic characteristics, instantaneous rates of CO_2 assimilation are calculated at three moments during the day and at three depths in the canopy. Integration over total leaf area and over the day, yields gross daily assimilation rates. Net daily growth rate is obtained by subtracting maintenance and growth respiration requirements, and then is partitioned into roots, leaves, stems and panicles, using experimentally derived factors. Leaf area grows exponentially as a function of temperature sum when the canopy is not yet closed. Then, leaf area grows linearly and is calculated from the increase in leaf weight times a specific leaf area. Spikelet number at flowering is obtained from the biomass accumulated between panicle initiation and flowering, taking into consideration spikelet sterility due to either too high or too low temperatures. The model requires inputs of management practices, soil properties and weather data in addition to crop parameters. The required management practices are crop variety, spacing or plant population, transplanting depth, nursery duration, and fertilizer and irrigation application. Soil properties required are volumetric soil water content at saturation, field capacity and wilting point and corresponding soil water potential, depth of puddled soil, and saturated hydraulic conductivity of the soil. The weather data include the rainfall and temperature during the growing season. The crop parameters include phonological development parameters and many other parameters related to the process of crop growth, and most of them can be obtained from literature. However, the cultivar specific parameters such as development rates, partitioning factors, relative leaf growth rate, specific leaf area, and leaf death rate are to be calibrated using experimental data (Bouman et al. 2001).

Model evaluation

We evaluated ORYZA2000 for the parameterization data set (2003) and for the validation data set (2009 and 2010) following the procedures presented by Bouman and Van Laar (2006). We graphically compared simulated against measured values of LAI, biomass of the whole crop and of crop organs, soil water tension, and grain yield. For the same variables, we calculated the slope (a), intercept (b), and coefficient of determination (R^2) of the linear regression between simulated (Y) and measured (X) values. We also calculated Student's t test of means assuming unequal variance [P(t*)], and the absolute ($RMSE_a$) and normalized ($RMSE_n$) root mean square errors between simulated and measured values:

$$\mathrm{RMSE_a} = \left[\frac{1}{n}\sum_{i=1}^{n}(Y_i - X_i)^2\right]^{1/2}$$

$$\mathrm{RMSE_n} = \frac{100\mathrm{RMSE_a}}{\sum_{i=1}^{n} X_i/n}$$

Where n is the number of observations. A model reproduces experimental data best when a is 1, b is 0, R^2 is 1, P(t*) is larger than 0.05, RMSEa is similar to SE of measured values, and RMSEn is in the same order of magnitude as the CV of measured values.

Soil–Water Balance

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

I + R = E + T + D + W

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 W 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 WP_T was expressed as crop grain yield Yg per unit amount of transpiration T, and set the lower limit of water used by the crop. The actual evapotranspiration (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 WP_{ET} instead of Yg per unit value of ET. The inevitable loss of water due to evaporation caused decreases in water productivity (WP_T to WP_{ET}). Therefore, relatively low values of WP_{ET} when compared to 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 WP_I and WP_{I+R} were expressed in terms of Yg per unit water available in field through irrigation, I, and rainfall, R, as inputs.

RESULT AND DISCUSSION

Model Evaluation

As mentioned earlier, 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. The results of calibration of the model in terms of simulated and measured crop yield are presented in Table 3. It can be observed from Table 3 that the calibrated model satisfactorily predicts the expected crop yield. This is evident from the fact that the deviation between measured and simulated crop yield is within ±5% during calibration.

The statistical output of first year (Calibration) in Table 3Showed that the RMSE was ranged between 361 and 423 kg ha^{-1} and normalized RMSE was 7–9% for observed yields, which varies between 3825 and 6229 kg ha^{-1}. These results indicated that ORYZA2000 model simulated grain yield of rice in calibration period. The parameters obtained in model calibrations were used for validation and performance evaluation of ORYZA2000. During the validation period, the model is able to predict the crop yield with reasonable accuracy. It is to be noted that the yield reduction due to water stress is higher in irrigation treatment I_4, I_3 and I_2 compared to I_1. Grain yield of three rice varieties was decreased as affected with water stress in I_4, I_3 and I_2 compared to I_1 irrigation treatments. Obtained results in table 4 showed that maximum amount of grain yield in Hybrid kg/ha was 9642 in I1 and water stress cause to decreased the yield such that minimum yield was recorded in I4 with mean of 7750 kg/ha. This scenario was observed in Dorfak and Alikazemi varieties. The maximum and minimum amount of grain yield in Dorfak were 7945 and 6268 respectively and in Alikazemi this values were 4267 and 3550 Kg/ha respectively.

Our results showed ORYZA2000 simulated effect of water stress on grain yield of rice varieties reasonable accuracy. In the validation set, simulated values matched measured values much better, grain yield. Recorded $RMSE_n$ and $RMSE_a$ for hybrid were 3% and 241 kg/ha that showed high accuracy of grain yield prediction for Hybrid in this part measured grain yield was 8574 and simulated grain yield was 8619. Results in table 4 showed model predicted yield of Dorfak and Alikazemi with high accuracy. The mean of obtained yield for Dorfak was 6939 and mean of simulated grain yield for this variety was 7261. The measured RMSEa and RMSEn for Dorfak grain yield was 7% and 486 kg/ha that showed reasonable accuracy of grain simulation of this variety of rice.

Obtained results from simulated values indicated that between three varieties ORYZA2000 model predicted grain yield of Alikazemi with low accuracy in compare to Hybrid and Dorfak. Our results showed mean of measured grain yield for Alikazemi was 3806 kg/ha and mean of simulated grain yield was 3831. Recorded $RMSE_n$ and $RMSE_a$ for Alikazemi grain Yield were 9% and 327 kg/ha (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 132 mm for 2009 and 116 mm for 2010. The amount of irrigation in 2009 water applied varied between 286 mm to 592 mm. The water-saving regimes (I_2, I_3 and I_4) used less irrigation water than continuous submergence regimes. The average water input was 52% less than the control for this situation.

The evaporation depends on the water regime and rice variety; the seasonal evaporation varied from 134 to 287 mm and showed a significant reduction with a decrease in applied water amount from I1 to I4. The continuous surface ponding caused high soil evaporation during the rice growing season in all Varieties. Hybrid has greater leaf growth, more light interception, and less light transmission to the soil surface, which also reduced the evaporation rate. Our results showed that Hybrid evaporation rate was greater than Dorfak and ALikazemi rates.

The transpiration (T) varied from 275 to 380 mm and also reflected canopy development and biomass growth that was strongly affected by plant variety. 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 414 to 667 mm for different combination of water and crop varieties. In another research Doorenbos and Kassam (1979) mentioned ET varied from 450 to 700 mm for rice crop. The seasonal amount of infiltration was varied from 112 to 170 mm among all treatments. The amount of infiltration is greater for the continuous submergence regime than for the water-saving regime (Table 5). A decrease in infiltration caused a reduction in irrigation depth. Earlier studies (Arora 2006) 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). Water productivities WP_I of Alikazemi with decreasing of used water from I1 to I4 increased and showed a maximum value at I4 regimes with mean of 1/24 but in both Dorfak and Hybrid highest amount of WP_I with mean of 1/32 and 1/31 respectively was measured in I_1 because decreasing of water consumption in water regimes cause to decreasing the yield of two varieties.

The WP_I varied from 0.98 $kg.m^{-3}$ at continuous submergence treatment in Alikazemi to 1/32 $kg.m^{-3}$ at Ii regime of Dorfak. It was reported by Tuong and Bouman (2003) that water productivity WP_I of irrigated rice ranged from 0.2 to 1.1 $kg.m^{-3}$.

In this study, the amount of WP_{ET} varied from 0/83 to 1/16 $kg.m^{-3}$ (Table 6). Based on previous studies in the past 25 years, Zwart and Bastiaanssen (2004) established global benchmark numbers of WP_{ET}, expressed as Yg/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).

CONCLUSIONS

The ORYZA2000 model was sufficiently accurate in the simulation of yield under water-saving three varieties 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 in the evapotranspiration process presents a major no beneficial loss of water. The average WP_{ET} expressed as Yg/ET (kg m^{-3}) was 0/91 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.

Table 1. Soil physical and chemical characteristics of the experimental site before sowing the rice crop

Soil characteristics	Depth (cm)			
	0–10	10-20	20-30	30-40
Texture				
Sand (%)	4	17	9	11
Silt (%)	39	39	44	42
Clay (%)	47	44	47	47
Bulk density (g cm^{-3})	1.1	1.2	1.32	1.31
Water content at saturation	0.65	0.62	0.62	0.60
Water content at FC (0.01 MPa)	0.40	0.40	0.41	0.42
Water content at PWP (1.5 MPa)	0.27	0.30	0.30	0.30
KSAT (cm day^{-1})	57.54	30.8	0.40	11.8
pH	7.15	7.23	7.26	7.08
CEC (meq $100g^{-1}$)	33	32	31	31
Organic carbon (%)	1.72	1.54	1.25	1.76
Total N (%)	0.16	0.14	0.074	0.047
Extractable P (ppm)	10.1	7.3	5.2	3.2
Extractable K (ppm)	195	176	185	161

Table 2. Soil physical and chemical characteristics of the experimental site before sowing the rice crop

Agronomic and management	
Transplanting date	10 May 2009, 15 May 2010
Row spacing	20
Number of plants per hill	6
Number of plants at emergence	44 m^2
Transplanting age	30 days
Based Temperature to estimate phonological phases	9˚C
Flowed water depth	15 cm
Planting depth	6 cm
Planting method	Transplanted
Fertilizer application fifteen day after transplanting	Application amount: 25 kg ha^{-1}
Twenty five day after transplanting	Application amount: 30 kg ha^{-1}
Fifty days after transplanting	Application amount: 25 kg ha^{-1}

Table 3. Evaluation results for ORYZA2000 simulations of rice yield, for the calibration

RMSEn (%)	RMSE (Kg/ha)	P (t)	X_{obs} (kg/ha)	X_{sim} (kg/ha)	
					Alikazemi
9	361	0.36	3961	3825	
					Dorfak
8	407	0.40	5097	5263	
					Hybrid GRH1
7	423	0.39	55917	6229	

Table 4. Evaluation results for ORYZA2000 simulations of rice yield for the Validation

Hybrid GRH1			Dorfak			Alikazemi			
Relative Error (%)	Simulated (Kg\ha)	Observed (Kg\ha)	Relative Error (%)	Simulated (Kg\ha)	Observed (Kg\ha)	Relative Error (%)	Simulated (Kg\ha)	Observed (Kg\ha)	
0	7738	7754	2	6309	6209	-4	4119	4289	**I** 1
10	6941	6282	11	5563	5001	4	4294	4123	**I** 2
10	5836	5312	9	5200	4789	3	4003	3878	**I** 3
0	4401	4318	-9	3981	4389	-19	2885	3555	**I** 4

Table 5: Components of water balance (mm)

Irrigation	Percolation	Precipitation	ET	Transpiration	Evaporation	Yield Kg/ha	Irrigation	Variety
408	146	116	526	332	194	4267	*I1*	*Alikazemi*
355	137	116	472	302	170	3550	*I2*	
346	128	116	464	287	177	3707	*I3*	
331	133	116	449	282	167	3801	*I4*	
513	164	132	614	362	252	7538	*I1*	*Dorfak*
437	139	132	535	341	194	7266	*I2*	
427	138	132	523	316	207	6800	*I3*	
401	137	132	529	350	179	7258	*I4*	
523	178	132	657	385	272	9642	*I1*	*Hybrid*
427	144	132	585	373	212	8826	*I2*	
407	144	132	556	353	203	8077	*I3*	
411	142	132	575	341	234	7750	*I4*	

Table 6: Water Productivity components

2010				2009					
WP_{ETO}	WP_T	WP_{ET}	WP_{IRRI}	WP_{ETO}	WP_T	WP_{ET}	WP_{IRRI}	Irrigation	Variety
0/63	1/29	0/81	1/05	0/64	1/29	0/83	0/98	I1	Alikazemi
0/58	1/18	0/75	1	0/70	1/28	0/88	1/143	I2	
0/61	1/26	0/78	1/04	0/68	1/22	0/86	1/17	I3	
0/65	1/35	0/85	1/15	0/68	1/29	0/86	1/24	I4	
0/97	2/08	1/23	1/47	0/83	1/78	1/05	1/32	I1	Dorfak
1/08	2/13	1/36	1/66	0/70	1/55	0/89	1/19	I2	
1/03	2/15	1/30	1/59	0/67	1/51	0/86	1/19	I3	
1/09	2/07	1/37	1/81	0/70	1/64	0/89	1/25	I4	
1/15	2/50	1/47	1/84	0/93	2/04	1/16	1/31	I1	Hybrid
1/21	2/37	1/51	2/07	0/83	1/76	1/04	1/27	I2	
1/15	2/29	1/45	1/98	0/70	1/61	0/88	1/19	I3	
1/08	2/27	1/35	1/89	0/60	1/49	0/76	1/09	I4	

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