WATER PRODUCTIVITY OF RICE UNDER VARYING CROP DENSITY AND IRRIGATION MANAGEMENT (FIELD AND MODELING APPROACH)

PRODUCTIVITE DE L'EAU DANS DIFFERENTES DENSITES AGRICOLES ET GESTION D'IRRIGATION (APPROCHE DU CHAMP ET DE LA MODELISATION)

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ABSTRACT

A field experiment was conducted during 2001 - 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 spacing as subplots (20 cm ×20 cm, 15 cm ×15 cm and 10 cm ×20 cm) and four different irrigation regimes (continuous submergence-control, 100%, 75% and 50% evaporation of Pan) as main plots. In order to simulate the various water productivity components, ORYZA2000 model was used. The comparison of model results with observed data was performed using adjusted coefficient of correlation, t-test of means, root mean square errors (RMSE), normalized root mean square errors and line 1:1. The RMSE ranged between 150-182 kg ha^{-1} and normalized RMSE was 6% - 7% for observed yields, which varyied between 1848 and 3193 kg ha^{-1}. Paired t-test showed no significant difference between the observed and simulated yields ($P > 0.05$). In the field experiment, water saving regimes reduced the yield by 11% when compared to the control; the average water input was 22% lower than the control for this situation. ET simulated by ORYZA2000 ranged from 312 mm to 462 mm for different combination of water and plant density. The mean of 2 years yield of irrigation and crop density conditions was 2611 $kg.ha^{-1}$ and the mean of WP_I, WP_{I+R}, WP_{ET}, and WP_T of water-crop density scheme were calculated as 0.84, 0.64, 0.67, and 1.04 ($kg.m^{-3}$). The average WPET expressed as Yg/ET ($kg.m^{-3}$), which was 0.63 for rice crop. The results showed that irrigation by 75% evaporation from pan evaporation and 20 cm × 20 cm crop plant and row spacing were the optimum combination of irrigation regime and crop density.

Key words: *Crop density, Irrigation, ORYZA2000, Rice, Water balance.*

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RESUME

Dans cette recherche présentée ici, une expérience a été menée durant les années 2001 et 2002 afin de déterminer les effets de la densité des plants et aussi les régimes d'irrigation sur la productivité de l'eau de riz. L'étude a été réalisée dans un plan confusion des parcelles divisibles avec trois espacements des plants comme sous-parcelles (20 cm × 20 cm, 15 cm × 15 cm et 10 cm × 20 cm) et quatre régimes d'irrigation (submersion continue comme le traitement contrôle, 100%, 75 % et 50% d'évaporation du bac classe A) comme les traitements principales. Les systèmes agricoles sont complexes, et la compréhension de cette complexité nécessite une recherche systématique, mais le financement pour la recherche agricole est limité. Les expériences sur le terrain ont une capacité limitée pour évaluer seulement un certain nombre de variables sous des conditions spécifiques du site. Les modèles de simulation des cultures considèrent des interactions complexes entre les conditions météorologiques, les propriétés du sol, et les facteurs de gestion, qui influent sur le rendement des cultures. Afin de modéliser les différentes composantes de la productivité de l'eau, le modèle ORYZA2000 a été utilisé. La comparaison des résultats du modèle avec les données mesurées a été réalisée en utilisant le coefficient de corrélation ajusté, le T-test, la racine carrée moyenne de l'erreur (RMSE), la racine carrée moyenne de l'erreur normalisée et la ligne 1:1. La RMSE était compris entre 150-182 kg ha^{-1} et le RMSE normalisé était de 6%-7% pour les rendements observés qui variaient entre 1848 et 3193 kg ha^{-1}. T-test apparié n'a montré aucune différence significative entre les valeurs de rendement observés et simulés (P> 0,05). En ce qui concerne les traitements d'irrigation, les régimes d'économie d'eau réduisent le rendement de 11% par rapport au traitement contrôle, sachons que l'apport d'eau moyen était de 22% moins que le contrôle. ET simulée par ORYZA2000 après la calibration et la validation du modèle variaient de 312 mm à 462 mm pour la combinaison de différentes conditions de densité des plants et des régimes d'irrigation. La moyenne de rendement des 2 années sous des conditions différentes de densité et de l'irrigation a été de 2611 kg.ha^{-1} et la moyenne de WP_I, WP_{I+R}, WP_{ET}, et WP_T ont été de 0,84; 0,64; 0,67; et 1,04 (kg.m^{-3}). La WP_{ET} moyenne exprimée en tant que Yg / ET (kg.m^{-3}) pour le riz était de 0,63. Dans cette recherche, les données météorologiques, les données du sol et de la culture, en combinaison avec des modèles éco-physiologiques comme par exemple ORYZA2000, devrait être utilisé pour produire des informations requises hydrologiques et biophysiques. Les résultats ont montré que l'irrigation selon 75% de l'évaporation du bac classe A et l'espacement de 20 cm × 20 cm sont le régime d'irrigation et la gestion de la densité des plants optimales. Le modèle ORYZA2000 a été suffisamment précis pour la simulation du rendement, l'économie d'eau et les conditions de densité des plants pour ce site d'étude.

Mots clés : *Densité agricole, irrigation, ORYZA2000, riz, bilan d'eau.*

(Traduction française telle que fournie par les auteurs)

1. INTRODUCTION

Agricultural systems are complex, and understanding this complexity requires systematic research. Field experiments provide opportunity to investigate a number of variables under a few site-specific conditions. Crop simulation models consider the complex interactions between weather, soil properties, and management factors, which influence crop performance.

Mechanistic models are helpful in deciding the best management options for optimizing crop growth and the yield. In the middle of 1990s, IRRI, the Wageningen University, and Research Centre developed the ORYZA model series to simulate the growth and development of tropical low-land rice (Ten Berge and Kropff, 1995). In 2001, a new version of the ORYZA was released that improved 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 et al., 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 either difficult, and/or needed sophisticated instruments such as lysimeter. Therefore, field experiments yield site-specific information, but are expensive, laborious, and time consuming. However, ORYZA2000 model in combination with field experiments offer the opportunity to gain detailed insights into the system behavior in space and time.

Water Productivity (WP) expresses the input/output relationship (Kijne et al., 2003). WP is computed as the ratio of grain yield to total water input (WP_{I+R}) or by evapotranspiration (WP_{ET}). Reduced water availability for agriculture, threatens the productivity of the irrigated rice ecosystem, and various approaches should be sought to save water and increase the WP of rice (Guerra et al., 1998). Turner (1997) suggested two ways to increase WP under water-stress conditions: (1) plant genetic improvement and (2) agronomic practices. Tuong (1999) discussed that the improving of WP would involve (1) increasing yield per unit of ET and (2) reducing the portion of water input to the field, which is not available for crop ET. WP_{ET} values in rice showed a long range: 0.6 to 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 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 two years 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.

2. MATERIALS AND METHODS

The experiments were conducted in clay soil during dry rice cropping season of 2001 and 2002 at the Rice Research Institute of Iran (RRII), Guilan province, located in the north of Iran (37°12′ N, 49°38′ E). The experiments were laid out in split-plot design consisting of 4 irrigation regimes in main plots and 3 crop spacing in sub-plots, with 3 replications. The irrigation treatments comprised: I_1 = Continuous submergence (about 5 cm height: control), I_2, I_3 and I_4, respectively, based on 100%, 75% and 50% evaporation rate; evaporation measured using Class A pan. The 3 crop spacing were: S_1 = 20 cm × 20 cm, S_2 = 15 cm × 15 cm and S_3 = 10 cm × 20 cm.

Main plot with size of 10.5 m × 3.5 m with three equal sub-plots was separated by 0.5 m space between them as buffer to avoid lateral seepage interference. All the treatments were imposed randomly. 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 June 2, 2001 and June 4, 2002; and the harvest date was August 30, 2001 and August 28, 2002. The yield was measured with 5 m^2 harvesting of each plot. In all experimental plots, 60 Kg Nitrogen, 25 kg P_2O_5 and 75 kg K_2O per hectare were applied before transplanting.

A detailed description of the model is given by Bouman et al. (2001) and summary of the model has described in this section. ORYZA2000 follows a daily calculation pattern for the rate of dry matter production of the crop 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. Total daily rate of canopy 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 by using a soil water balance module (PADDY; Wopereis et al., 1996; Bouman et al., 2001). In PADDY, a low-land rice soil was modeled as a layer of muddy top soil overlying a 3–5 cm plough sole and non-puddled sub-soil. With ponded 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 was parameterized for the rice crop; starting with standard crop parameters for cultivar IR72 and following the procedures set by Bouman et al (2001). First, development rates were calculated using observed (year 2001) 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. The partitioning of assimilates was derived from observed data, using the leaf, stem, and panicles biomass portions. Daily climatological data, which included sunshine hours, maximum and minimum temperature, vapor pressure, wind speed, and rainfall rate for crop season were obtained from Rasht meteorological station.

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

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

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

where, P_i: the simulated value, O_i: 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 dataset.

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

$$I + R = E + T + D + \Delta W \qquad (3)$$

where, I: irrigation rate, R: rainfall rate, E: evaporation rate, T: transpiration rate, P: percolation rate beyond the root zone, and ΔW is change in the soil water storage. The rainfall was obtained from the meteorological data and all other components were 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).

The water productivity is 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). WPT was expressed as crop grain yield Y_g per unit amount of transpiration T, and set the lower limit of water amount, which was used by crop. The actual evapotranspiration (ET_a) represents the actual amount of water used in crop production, which is no longer available for re-use in the agricultural production system. It should be used as WP_{ET} instead of Y_g per unit value of ET. The inevitable loss of water due to evaporation caused reduction in water productivity (WP_T to WP_{ET}). Therefore, relatively low values of WP_{ET} when compared to WP_T, suggested reducing in evaporation rate by agronomic measurements, such as soil mulching and conservation tillage. The irrigation and rainfall rates are the total water, which is used in field. In this situation, the water productivity WP_I and WP_{I+R} were expressed in terms of Y_g per unit water available in field through irrigation I and rainfall R as inputs.

3. RESULTS AND DISCUSSION

The model was calibrated using the data for the year of 2001, and the 2002 dataset was used for validation purpose. The ORYZA2000 model was evaluated based on the simulation of grain yield across various saving regime and plant densities. The statistical output was used to evaluate the model performance, which is shown in Table 1. The RMSE ranged between 150-182 kg ha^{-1} and normalized RMSE was 6% - 7% for observed yields which varied between 1848 and 3193 kg ha^{-1}. Paired t-test showed no significant difference between the observed and the simulated yield values ($P > 0.05$). The 1:1 line and the standard error (SE) of the observed variables were also shown. As Figure 1 shows, nearly 75% yield data points fell withine in plus and minus SE lines of observed yield. The linear regression was performed between simulated and observed values, and the regression slope (α) was close to 1 and intercept (β) was small. Correlation coefficient for this analysis is greater than 0.63 for yield, which indicated a fair simulation.

Table 1. 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		

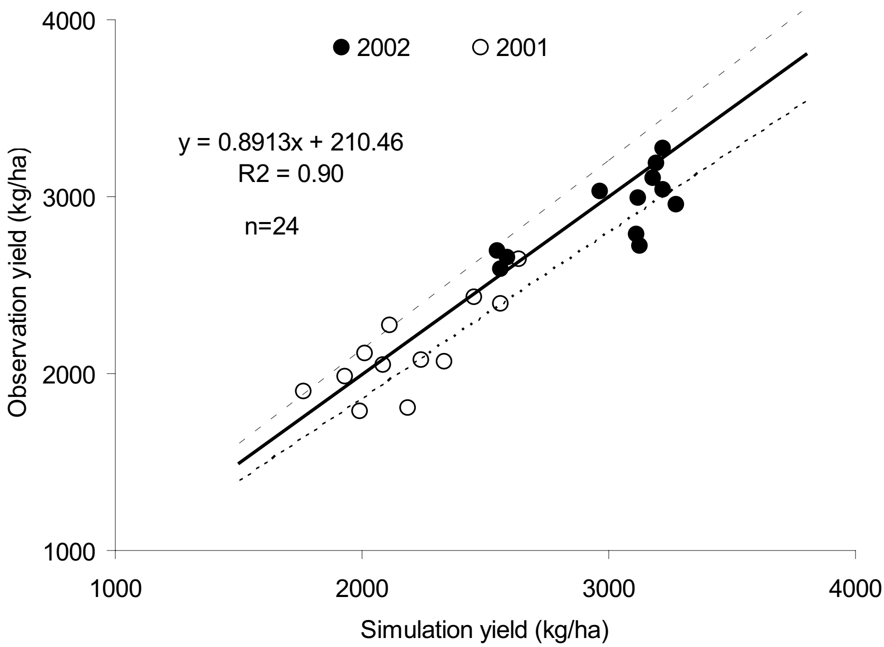

Fig. 1. The simulated versus observed grain yield. The solid line is 1:1; dot line is plus and minus standard error around the 1:1 line.

The rice WP rates were calculated using the simulated water balance components of T and ET by ORYZA2000 and the actual (observed) grain yield (Table 2). Both water productivities WP_{I+R} and WP_I showed a maximum value at I_4 regimes (Irrigation at 50% evaporation from evaporation pan).

The WP_I varied from 0.7 kg.m^{-3} at continuous sub-mergence treatment to 0.9 kg.m^{-3} at I_4 regime; due to reduction in irrigation water. It was reported by Tuong and Bouman (2003) that water productivity WP_{I+R} of irrigated rice ranged from 0.2 to1.1 kg.m^{-3}.

Table 2. Water productivity of rice under Irrigation regime and plant density conditions, 2001-02

Irrigation regime	plant density	2001				2002			
		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
	20 × 20 cm	0.60	0.45	0.56	1.08	0.73	0.62	0.75	1.28
Irrigation based on 100% evaporation	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
	20 × 20 cm	0.83	0.56	0.63	1.15	0.86	0.72	0.71	0.93
Irrigation based on 75% evaporation	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
	20 × 20 cm	0.93	0.57	0.58	1.05	0.85	0.70	0.68	1.05
Irrigation based on 50% evaporation	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

In this study, the amount of WP_{ET} was varied from 0.57 to 0.69 kg.m^{-3} (Table 2). Based on previous studies in the last 25 years, Zwart and Bastiaanssen (2003) established global 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 crop, the fraction of soil evaporation in the evapotranspiration process is important. During the rice cultivation, high evaporative demands and continuously surface water ponding caused high soil evaporation rate. Improving agronomic practices such as water saving regime could reduce this non-beneficial loss of water through the 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}, which was 35% lower 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.

When water resources are limited, the best irrigation scheme would be optimized water productivity than grain yield (Bouman and Tuong, 2001). The result of this study has shown that I_2, I_3, and I_4 irrigation regimes caused decline in yield by 7%, 10%, and 16%, respectively. Reducing water inputs from continuous submerge to water saving conditions will slightly depress rice yields, but it will substantially increase water productivity.

In Figure 2 the average of water productivity components during many years was calculated for irrigation regimes and crop density. As Figure 2 shows, changing of irrigation method will improve water productivity components (such as WP_I and WP_{I+R}). However, increasing of water productivity could not be seen in crop density (except WP_T parameter). Therefore, for agricultural managers the optimum irrigation and crop density would be the highest water productivity that was obtained. The results of this study show that between two factors of irrigation regime and crop density, in terms of water productivity component and yield, the

Irrigation at 75% evaporation from pan and 20 cm × 20 cm crop spacing would be optimum. The mean of 2 years yield of irrigation and crop density conditions was 2611 kg.ha^{-1} and the mean of WP_I, WP_{I+R}, WP_{ET}, and WP_T of water-crop density scheme were calculated as 0.84, 0.64, 0.67, and 1.04 (kg.m^{-3}).

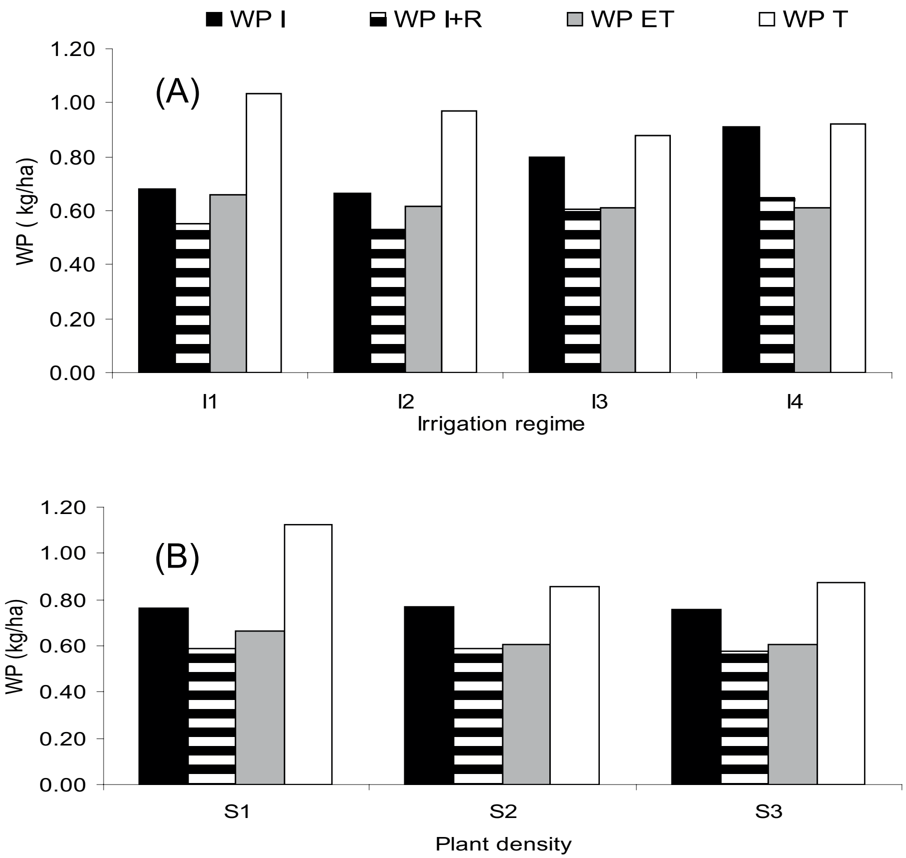

Fig. 2. The water productivity of rice under Irrigation regime (A) and crop density conditions (B).

The model ORYZA2000 was sufficiently accurate in the simulation of yield under water saving and crop density conditions for our study site. The eco-physiological 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 for water productivity analysis of rice crop. The large amount of evaporation (27–44%) in evapotranspiration process, presents a major non-beneficial loss of water. The average WP_{ET} expressed as Y_g/ET (kg.m^{-3}), which was 0.63 for rice crop. In this study, meteorological dataset, soil, and crop, in combination with eco-physiological models such as ORYZA2000, should be used to produce the required hydrological and biophysical information. The results showed that irrigation at 75% evaporation rate and 20 cm × 20 cm crop spacing as optimum irrigation and crop density management.

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