Jurnal
Teknologi

Full Paper

SIMULATION OF RICE YIELD UNDER WATER AND SALINITY STRESS IN RASHT AREA USING AQUACROP MODEL

Article history
Received
15 July 2015
Received in revised form
2 August 2015
Accepted
26 August 2015

Amiri Ebrahim[a], Ahmadzadeh Araji Hamidreza[b*], Wayayok, Aimrun[b], Rezaei Mojtaba[c]

[a]Department of Agriculture, Lahijan Branch, Islamic Azad University, Lahijan, Iran
[b]Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra Malaysia, Malaysia
[c]Rice Research Institute of Iran

*Corresponding author
Hamid_araji@yahoo.com

Abstract

Guilan is a north province of Iran in which plays an important role in rice production. Since 78.8% of Giulan farmlands are under cultivation of rice, it is the second province ranking as rice producer in Iran. On the other hand, because of dam construction and neighborhood to the Caspian Sea, the volume of fresh water is declining, and is transformed to saline water. In this study, AquaCrop model version 4.0 with additional salinity module was used for calibration and validation in two successive years at Rasht rice Research Institute that is located nearby Rasht city. Five irrigation levels: full irrigation, alternate wetting and drying (AWD), irrigation at 100, 90 and 80% of field capacity (FC) and Four water salinity treatments: fresh water = S0 (EC = 1 dS m^{-1}) while S1, S2, and S3 are saline water with 2, 4, and 6 dS m^{-1}, respectively, were applied for evaluation of rice yield. Statistical analysis, including root mean square error normalized, coefficient of determination (R^2), and paired t-tests showed that simulated and observed values are the same at 95% confidence level. Moreover, the FAO AquaCrop model predicted rice yield with more accuracy in less salinity values (EC = 2 dS m^{-1} and less). Overall, AquaCrop model represented acceptability in simulation of rice yield under simultaneously water and salinity stress.

Keywords: AquaCrop model, yield; salinity, irrigation

1.0 INTRODUCTION

Guilan is a north province of Iran that plays a significant role in Iran's Agricultural sector by allocation of 78.8% of farmlands to rice cultivation. Rice water requirement in these regions is provided by existed water resources in dams, rivers, springs and wells. Increasing demands of using fresh water resources in agriculture, urban, and industry sectors together with climate change impacts on water resources are consequences of salinization and shortage of fresh water. On the other hand, reports represent that construction of dams above sefidroud dam in Guilan province will change water quality due to decreasing of inlet water and disposal of drainage water to the river. However, this trend will encounter problems for farmers and agricultural sectors in sustainability of rice production. Not only should water degradation impacts on water volume but also changes water quality and salinity [1, 2]. Since, rice is a sensitive crop to salinity [3, 4, 5] and EC threshold for yield loss is 1-2 dS m^{-1} for local varieties[6, 7] , the importance of using new approaches based on increasing water productivity and using saline water specifically in dry seasons are recommended in paddy fields.

When water stress is not a limiting factor, transferring nutrients to plants is usually unavoidable [8]. In other words, photosynthesis decreases as a result of both water and salt stress [9]. However, water stress decreases leaf area, tillering rate, dry matter, filled grains, and number of panicle, kernel weight and finally yields.

In fact, saline water led to lessening in leaf water potential, stomatal conductance, evapotranspiration, leaf area and finally yield [5, 10, 11, 12] . Overall, those mentioned circumstances would be accelerated during hot season conditions and increasing evaporation [13].

AquaCrop model has recently developed by FAO for simulation of yield response to water in which is practical for most generic field crops. Since AquaCrop model requires the minimum input parameters, this model is worthwhile particularly in case of water limiting conditions. However, in comparing with other Crop models, a better balance between simplicity, accuracy, and vigorousness is obvious [14, 15].

Based on available literature, the ability of AquaCrop model to simulate yields for various crops under different irrigation levels has been tested in different parts of the globe e.g., potato, sunflower [16, 17]; maize [16, 18, 19]; oats, vetch, and faba bean [17]; cotton [16, 20, 21]; Teff (Eragrostis tef) [22]; rice [19]; winter wheat [23, 24] and wheat [19, 25]. Since salinity stress has recently added to soil fertility module in version 4.0 of Aqua Crop model, the results of simulated yield and model calibration is still questionable and novel.

However, studies regarding the simultaneous investigation of salinity and water stress on rice yield by using crop model framework are still limited. Hence, in this research, the impacts of salinity and water stress were conducted by using statistical methods and last version of Aqua Crop model.

2.0 MATERIALS AND METHODS

This experiment was carried out as a pot trial based on Randomized Complete Block Design (RCBD) with three replications in Rasht station of rice Research Institute of Iran that is located nearby Rasht city. Field data were collected in Rasht station for local rice cultivar (Hashemi) in two successive years 2010 and 2011. In order to prevent of rainfall impacts on the experiment, the pots were covered by shelter with five meters height in which the ceiling was set up with a bright plastic. Furthermore, for better air flow the shelter sites were totally opened, and it was located in the center of research study area. The treatments consisted of five levels of irrigation including: full irrigation, alternate wetting and drying (AWD), irrigation at 100, 90 and 80% of field capacity (FC). The field capacity was determined by field experiments and field trials that have already done in the study area. Moreover, four different water salinity treatments were applied simultaneously including: fresh water = S0 (EC = 1 dS m^{-1}) S1, S2, and S3: saline water with 2, 4, and 6 dS m^{-1}. Each plastic pot was filled with 9 kg of soil of paddy field. After flooding the soil; transplantation started with three 25-days old seedlings. For a period of ten days, pots irrigation conducted by fresh water, then treatments were applied. Moreover, during preparing paddy field for performance, all phosphorus and potassium and half of nitrogen fertilizers from triple super phosphate, potassium and urea were mixed with soil.

The remaining nitrogen was applied and mixed with soil during maximum tillering which is one of the phenological development stages of rice. In order to simulate applied saline water to canal water, NaCl and CaSO4 with ratio of (2:1) was prepared as saline irrigation water, and was applied in each irrigation operation step.

As far as salt accumulation in pots is concerned, leaching and washing with fresh water in several stages was employed. Furthermore, as high as 5 cm of the soil surface, Irrigation was set at the appointed time. On the other hand, all agricultural practices and management were performed based on recommended methodologies of rice Research Institute of Iran. The total number of pots was sixty in both years of 2010 and 2011.

Eventually, In order to compare the measured and simulated data of grain yield at the end of growing period, the average of three replications for each treatment was taken into consideration.

2.1 Aquacrop Model

AquaCrop is a water-driven model that simulates crop yield and biomass under water stress and salinity stress conditions. The attributes of AquaCrop model including conceptual framework, underlying principles, and distinctive components are detailed by Steduto *et al*. [15], while the structural details and algorithms are described by Raes *et al.* [14].

The basis of AquaCrop model stems in conceptual equation which described by Doorenbos and Kassam, in 1979 [26]. The applied equation, describes the relation between crop evapotranspiration and crop yield as mentioned below:

$$\left(\frac{Y_x - Y_y}{Y_x}\right) = k_y\left(\frac{ET_{x-} ET_a}{ET_a}\right) \tag{1}$$

Where Yx and Yy are the maximum and actual yield, ETx and ETa are the maximum and actual evapotranspiration, and ky is the proportionality factor between relative yield loss and relative reduction in evapotranspiration.

AquaCrop developed by (i) separating ET into soil evaporation (E) and crop transpiration (Tr), (ii) developing a simple canopy growth and senescence model as the basis for the estimate of Tr and its separation from E, (iii) considering the final yield (Y) as a function of final biomass (B), and harvest index (HI), and (iv) separating impacts of water stress into four components: canopy growth and senescence, Tr, and HI [15].

The advantage of ET separation is avoidance of the confounding effect of the non-productive consumptive use of water (E) that is important especially during undeveloped ground cover. This led to following conceptual equation at the core of the AquaCrop growth engine [15].

$$B = WP \times \Sigma Tr \tag{2}$$

Where Tr is the crop transpiration (in mm) and WP is the water productivity parameter in units of kg (biomass) m^{-2} (land area) mm^{-1} (water transpired). Moreover, WP (biomass per unit of cumulative transpiration) tends to be constant for a given climatic condition. In fact WP has a conservative behavior when normalized for climatic conditions [27]. Therefore, stepping from Eq. (1) to Eq. (2) has a fundamental implication for the robustness and generality of the model [15].

The other difference between Eq. (1) and Eq. (2) is time scale in which for Eq. (1) the relationship is used seasonally or for different phases of the crop lasting weeks or months, while for Eq. (2) the relationship is used for daily time steps, a period that is closer to the time scale of crop responses to water deficits [28].

2.2 Input Data in Aquacrop Model

Input data defines the environment in which the crop has developed. Input data are divided to four parts: weather data, crop, soil and field management data.
Although there are some input as default parameters in AquaCrop, the model is used to calculate crop water use, based upon inputs which are either measured in the experiments or determined from literature.

2.3 Weather Data Collection and Analysis

The weather data were obtained from Rasht synoptic meteorological station. Since the pots were covered by shelter during rainfall, the precipitation values were zero. Other weather data including temperature, relative humidity, sunshine hours and wind speed were collected for experimental site. The daily reference evapotranspiration (ETo), during the growing season 2010 and 2011 were calculated by FAO Penman-Monteith method, based on the paper 56 [29] via ETo calculator software [30].

2.4 Crop Data and Soil Data of the Experimental Sites

Input data of crop parameters used in AquaCrop model is shown in Table 1.

The chemical and physical soil characteristics for Rasht site is represented in Table 2 and Table 3 respectively. The measured physical soil characteristics are being used as data input for the AquaCrop model.

Table1 Input data of crop parameters used in AquaCrop model

Description	Value	Units
Base temperature	8.0	(°C)
Upper temperature (cut-off temperature)	30.0	(°C)
Canopy growth coefficient (CGC)	0.14013	% day^{-1}
Maximum canopy cover (CCx)	87	%
Canopy decline coefficient (CDC)	0.09246	% day^{-1}
Water Productivity normalized WP	19.0	gram m^{-2}
Soil water depletion factor for canopy expansion – Upper threshold	0.0	-
Soil water depletion factor for canopy expansion – Lower threshold	0.4	-
Soil water depletion factor for canopy senescence – Upper threshold	0.6	-
Soil water depletion fraction for stomatal control – Upper threshold	0.50	-
Soil water depletion factor for canopy senescence – Upper threshold	0.60	-
Stomata stress coefficient curve shape	3.0	-
Senescence stress coefficient curve shape	3.0	-
Electrical Conductivity of soil saturation extract at which crop starts to be affected by soil salinity	2.0	dS m^{-1}
Electrical Conductivity of soil saturation extract at which crop can no longer grow	13.0	dS m^{-1}
Maximum effective rooting depth	0.30	m
Reference Harvest Index (HIo)	47	%
Days from transplanting to maximum rooting depth	32	days
Days from transplanting to start senescence	70	days
Days from transplanting to maturity	85	days
Days from transplanting to flowering	51	days
Length of the flowering stage	20	days
Maximum effective rooting depth	0.30	m
Reference Harvest Index (HIo)	47	%

Table2 Soil chemical analysis in experimental field

Potassium ppm	Phosphorus ppm	Total Nitrogen %	pH
290	17	0/155	7/4

Table3 Soil physical characteristics in experimental field

Soil texture	%80 FC	%90 FC	FC*	saturation	
Silty-Clay	40	45	50	65	Water content (volumetric,%)

2.5 Model Prediction Accuracy

Evaluation of model performance plays an important role to finding the agreement between the observed and simulated results. These statistical indices including absolute root mean square error (RMSE) and root mean square error normalized (RMSEn) were used for comparing simulated and measured final yield. In agricultural modeling research, Root mean square error (RMSE) is one of the most widely used statistical indicators [31]. The RMSE indicates the amplitude of the differences between average of observed and simulated values. However, the ranges are between 0 to positive infinity in which the 0 values shows that model performance is good. On the other hand, mean square error normalized (RMSEn) is an index for displaying relative differences between simulations and observations and indicates as a percentage. Based on RMSEn values, model simulation is categorized in Excellent for smaller than 10%, good if between 10 and 20%, fair if between 20 and 30% and poor if larger than 30% [32]. The root mean square error (RMSE) and root mean square error normalized (RMSEn) are shown as Eq. [3], and root Eq. [4] respectively.

$$RMSE = \left[\frac{\sum_{i=1}^{n} (Pi - Oi)^2}{n} \right]^{1/2} \quad (3)$$

$$RMSEN = 100 \frac{RMSE}{O_{mean}} \quad (4)$$

Where, Pi and Oi are simulated and observed value respectively, and n is the number of measurements. Paired t-tests and Coefficient of determination (R^2) analysis was also used to assessing the goodness-of-fit between the observed and simulated results [33]. The coefficient of determination (R^2), ranges from 0 to 1, and is defined as the squared value of the Pearson correlation coefficient [32]. The R^2 values close to 1 indicating less error variance, and typically values greater than 0.5 are considered acceptable in watershed scales [34]. If the P-value from the paired t-test is greater than 0.05, it will be concluded that no significant differences existed between the observed and simulated values [33].

3.0 RESULTS AND DISCUSSION

3.1 Model Prediction Accuracy

The data of the year 2010 and 2011 were used for model calibration, and model validation respectively. The AquaCrop model version 4.0 was evaluated considering simulation of grain yield under different irrigation levels and salinity treatments. The statistical outputs used for model evaluation are reported in Table 4 to 6, and shown in Figure 1 to 2. However, since the experiment was conducted in shelter sites rainfall rates have not significant effect on soil water balance.

3.2 Model Calibration Results

Calibration results of rice grain yields under different irrigation levels and Salinity treatments in 2010 is described in Table 4. It was observed that the maximum and minimum prediction error between observed and simulated grain yield was in I1S0 treatment (0%) and I2S2 treatment (46%) respectively. In other words, the best calibration result for grain yield was for full irrigation level with fresh water (EC = 1 dSm^{-1}), whereas the maximum prediction error was for alternate wetting and drying irrigation level with saline water (EC = 4 dSm^{-1}).

The results of statistical analysis for calibrated and observed grain yield for all treatments combinations including salinity and irrigation are shown in Table 6. The model prediction accuracy pertaining to grain yield was evaluated by root mean square error normalized (RMSEn) value 14%, paired t-test value 0.36, and R^2 value of 0.94 (Figure 1). The Paired t-test showed no significant differences between the measured and simulated values of yield.

Table 4 Calibration results of grain yield of rice, under different irrigation levels and Salinity treatments in 2010

Treatments	Irrigation level (mm)	Yield ($kg\ ha^{-1}$) Obs	Sim	Pe (±%)
S0 (EC = 1 $dS\ m^{-1}$)				
Full irrigation	695	4654	4667	0
Alternate wetting and drying (AWD)	565	4730	4501	-5
irrigation (100% FC)	445	4175	3955	-5
irrigation (90% FC)	425	3882	3779	-3
irrigation (80% FC)	325	2446	2521	-2
S1(EC = 2 $dS\ m^{-1}$)				
Full irrigation	695	3739	3990	7
Alternate wetting and drying (AWD)	565	3623	3701	2
irrigation (100% FC)	445	3589	3115	-13
irrigation (90% FC)	425	2566	2970	16
irrigation (80% FC)	325	1854	1974	6
S2 (EC = 4 $dS\ m^{-1}$)				
Full irrigation	695	2167	2844	31
Alternate wetting and drying (AWD)	565	1722	2517	46
irrigation (100% FC)	445	1623	1952	20
irrigation (90% FC)	425	1503	1824	21
irrigation (80% FC)	325	1405	1359	-3
S3 (EC = 6 $dS\ m^{-1}$)				
Full irrigation	695	1294	1817	40
Alternate wetting and drying (AWD)	565	1166	1500	29
irrigation (100% FC)	445	1070	1232	15
irrigation (90% FC)	425	931	1166	25
irrigation (80% FC)	325	802	530	-34

Obs., observed; Sim., simulated; Pe, prediction error.

3.3 Model Validation Results

Validation results of rice grain yield under different irrigation levels and Salinity treatments in 2011 is described in Table 5. It was observed that the maximum and minimum prediction error between observed and simulated grain yield was in I4S0 treatment (-2%) and I5S3 treatment (197%) respectively. In other words, the best validation result for grain yield was for irrigation at 90% of field capacity treatment with fresh water (EC = 1 dSm^{-1}), whereas the maximum prediction error was for irrigation at 80% of field capacity treatment with saline water (EC = 6 dSm^{-1}).

The results of statistical analysis for validated and observed grain yield for all treatments combinations including salinity and irrigation are shown in Table 6. The model prediction accuracy pertaining to grain yield was evaluated by root mean square error normalized (RMSEn) value 17%, paired t-test value 0.35, and R^2 value of 0.92 (Figure 2). As a result of the Paired t-test there are not any significant differences between the measured and simulated values of yield.

4.0 CONCLUSION

Based on statistical analysis, the satisfactory results of calibration, and validation in version 4.0 of AquaCrop model under different irrigation levels and Salinity treatments using the experiment data of Rasht station represented the robustness and general applicability of the model. According to the values of root mean square error normalized, coefficient of determination (R^2), and paired t-tests simulated and observed values are the same at 95% confidence level, but the prediction error statistics shows that by increasing salinity levels the model performance for prediction of yield will be declined. It is undoubtedly clear that model prediction will be more reliable with saline water (EC = 2 dSm^{-1} and less). Nonetheless, from the results of this article, it is assumed that version 4.0 of FAO AquaCrop model could be used to predict grain yield of rice in salinity stress conditions with more accuracy in less salinity levels.

Table 5 Validation results of grain yield of rice under different irrigation levels and Salinity treatments in 2011

Treatments	**Irrigation level (mm)**	**Yield ($kg\ ha^{-1}$)**		**Pe (±%)**
		Obs	Sim	
S0 (EC = 1 $dS\ m^{-1}$)				
Full irrigation	660	4871	4704	-3
Alternate wetting and drying (AWD)	525	4417	4549	3
irrigation (100% FC)	480	3858	4448	15
irrigation (90% FC)	345	3507	3441	-2
irrigation (80% FC)	300	2500	2700	8
S1(EC = 2 $dS\ m^{-1}$)				
Full irrigation	660	4314	4156	-4
Alternate wetting and drying (AWD)	525	4284	3909	-9
irrigation (100% FC)	480	3643	3743	3
irrigation (90% FC)	345	3185	2770	-13
irrigation (80% FC)	300	1500	2192	46
S2 (EC = 4 $dS\ m^{-1}$)				
Full irrigation	660	3464	3096	-11
Alternate wetting and drying (AWD)	525	3036	2790	-8
irrigation (100% FC)	480	2039	2660	30
irrigation (90% FC)	345	1390	1858	34
irrigation (80% FC)	300	862	1429	66
S3 (EC = 6 $dS\ m^{-1}$)				
Full irrigation	660	2590	2124	-18
Alternate wetting and drying (AWD)	525	1219	1850	52
irrigation (100% FC)	480	931	1758	89
irrigation (90% FC)	345	872	1115	28
irrigation (80% FC)	300	250	742	197

Obs., observed; Sim., simulated; Pe, prediction error.

Table 6 Evaluation results of grain yield of rice under different irrigation levels and Salinity treatments in the calibration year 2010 and validation year 2011. Mean, standard deviation of population (SD), minimum, and maximum observed (OBS) and simulated (SIM) values are represented. Statistical analysis results are also shown: number of observations (N), correlation coefficient between simulated and observed values (r), P-value from the paired t-test [P (t)], absolute root mean square error (RMSE), normalized root mean square error (RMSEn), (*) means that simulated and observed values are the same at 95% confidence level

	Yield 2010 ($kg\ ha^{-1}$)		**Yield 2011 ($kg\ ha^{-1}$)**	
	Obs	**Sim**	**Obs**	**Sim**
Mean	2447	2596	2637	2802
SD	1284	1177	1382	1152
Min	802	530	250	742
Max	4730	4667	4871	4704
N	20		20	
R	0.97		0.96	
P(t)	0.36*		0.35*	
RMSE	349		446	
RMSEn(%)	14		17	

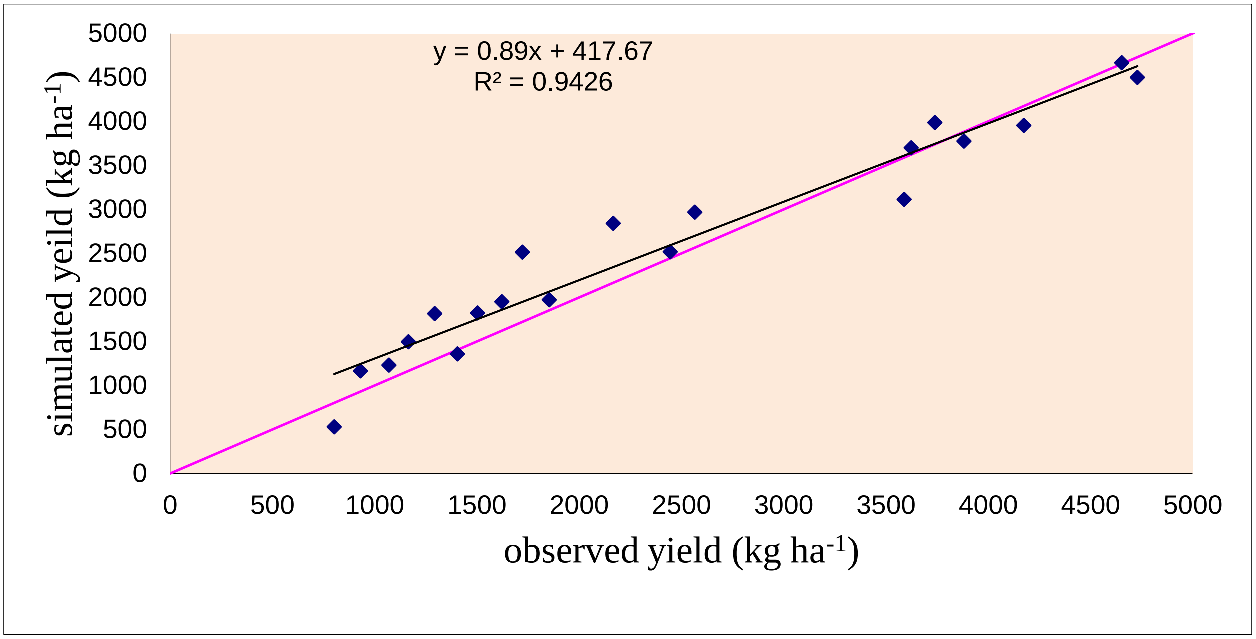

Figure 1 Model calibration results for grain yield under all different irrigation levels and Salinity treatments

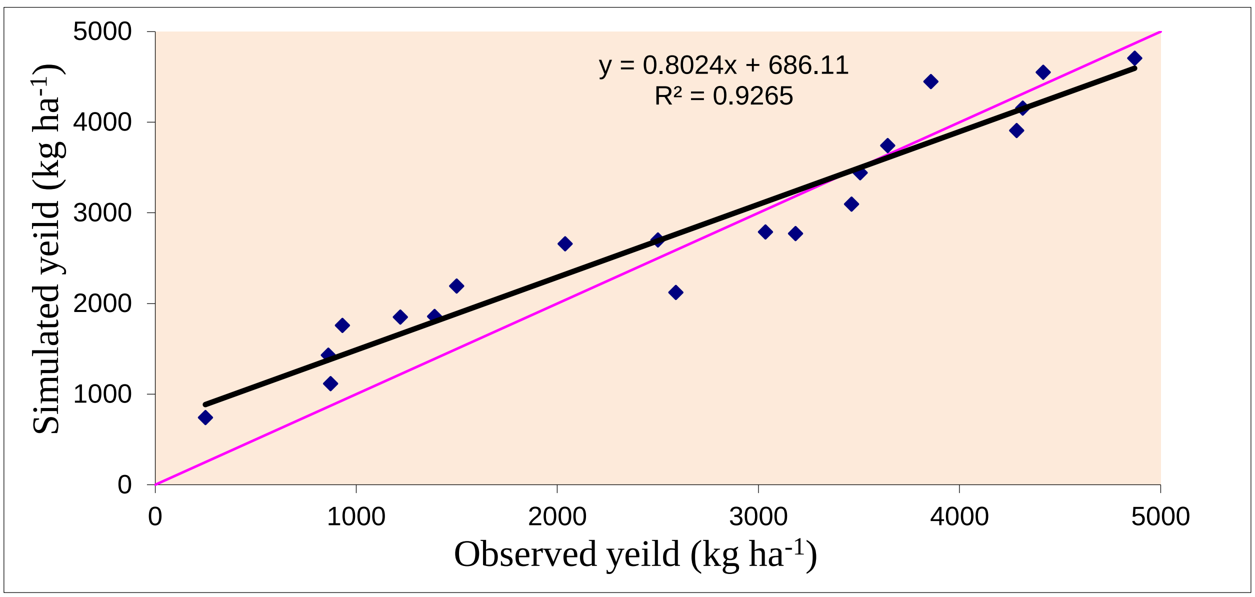

Figure 2 Model validation results for grain yield under all different irrigation levels and Salinity treatments

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