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Evaluation of DSSAT- Ceres Model for Maize under Different Water and Nitrogen Levels

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ABSTRACT

Crop models can accurately estimate crop growth, biomass yield (BY) and grain yield (GY) with a priori information of the crop, soil properties and water management. Generation of new knowledge through traditional agricultural practices is not possible to meet the requirements for novel agro-technologies and they are generally season specific, expensive and time consuming. Hence, the CERES (Crop Environmental Resource Synthesis) model was calibrated using the data of 2009 and validated with the data of 2010 acquired from the field data of WTC, IARI, India. Irrigation applications comprised rainfed, i.e. no irrigation (I_1), irrigation at 50% of field capacity (FC) (I_2), at 75 % FC (I_3) and 100% FC or full irrigation (I_4). Nitrogen levels were: no nitrogen (N_1), 75 kg ha^{-1} (N_2) and 150 kg ha^{-1} (N_3). Model performance statistics of model efficiency (E), root mean square error (RMSE) and normalized root mean square error (NRMSE) were applied to evaluate the model performance. Model calibration for simulation of GY and BY provided prediction error statistics of $0.78<E<0.84$, $0.238<RMSE<0.70$ t ha^{-1} and $6<NRMSE<7$ %, respectively for all irrigation levels. Also, the model was validated for simulation of GY and BY for all treatment levels with the prediction error statistics of $0.86<E<0.88$, $0.36<RMSE<0.86$ t ha^{-1}, $0.95<R^2<0.98$ and $6<NRMSE<8$%. Nonetheless, it was observed that the CERES-maize model could be applied to estimate yield and biomass under the regional situations with reasonable accuracy.

Keywords: Calibration, maize, nitrogen, validation

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INTRODUCTION

Maize is the third most important grain crops after wheat and rice. According to advance prediction it is cultivated in 8.7 M ha, which covers 80% of cultivated area, in India. Maize grain production is more sensitive to lack or excess amounts of water and nitrogen fertilizer compared to the other cereals. Therefore, research on water and nitrogen management for enhancing maize productivity and use of appropriate crop model to simulate maize growth and yield assumes importance.

Crop modeling approaches a new possibility to educators, planners and policy makers to explore cultivar potential for new regions before conducting costly and time consuming field studies (Abedinpour et al., 2014). Today more than ever, raised crop production depends on judicious use of resources. In addition, issues such as climate change, soil carbon sequestration, long-term food security, and environmental sustainability have become important issues. Crop simulation models incorporating water, soil, plant and environment system can make a precious contribution to both furthering our understanding of the processes that determine crop responses and estimating crop performance, resource use, and environmental effects for different environments and management scenarios. The decision support system for agro-technology transfer (DSSAT) version 4.6 is a Windows-based computer program that comprises crop simulation models for over 42 crops. The model was established by database management programmers for soil, weather, and crop management and experimental data, and by utilities and application programs (Hoogenboom et al., 2010).

The CERES–maize model, which is a component of the Decision Support System for Agro- technological Transfer (DSSAT) is supported by data base management programs for soil, weather, and crop management and experimental data, and by utilities and application programs. The crop simulation models simulate growth, development and yield as a function of the soil-plant-atmosphere dynamics (Hoogenboom et al., 2017). The model has a capacity to simulate the daily crop growth, development and yield for variable soil and climatic conditions with various agronomic managements (Khaliq et al., 2007). The CERES-Maize response regarding yield simulation has been tested in Virginia (Hodges et al., 1987), and Australia (Hargreaves and McCown, 1988). CERES-Maize model simulates grain yield under water limiting conditions by calculating potential evaporation; and potential soil-water evaporation and potential plant-water transpiration are derived from potential evaporation and leaf area index. Simulations of deficit irrigation practices using models like the CSM-CERES-Maize can be used to look at numerous weather years and geographic locations. Amaral et al. (2015) indicated that, the CERES-maize model simulated maize growth, development and yield for both mineral fertilizer and poultry litter sources of nitrogen. Jianmei et al. (2014) evaluated the CERES model for wheat crop in Guanzhong Plain of Northwest China under different irrigation and nitrogen levels. The results showed that the deviations of simulated BY, GY, leaf area index (LAI), cumulative evapotranspiration (ET) and crop water productivity (WP) from the observed values were reasonable, with NRMSE less than 21 %.

The aim of the research was to assess the performance of CERES model in simulating the impact of water and nitrogen fertilizer managements on growth and yield of maize in a semi-arid environment.

METHODS

Experimental Procedure

This study compares results from the CERES-maize model with observed data from a field experiment under rainfed, deficit and full irrigation in interaction with nitrogen levels at Water Technology Center (WTC) in Indian Agricultural Research Institute, (77° 8´ 45” to 77° 10´ 24” E longitude and 37° 22´ to 38° 39´ N latitude). The Meteorological Station is situated at 350m from the research field. The DSSAT model requires six weather parameters, including: daily minimum and maximum air temperature, daily relative humidity (%), rainfall, wind speed and, solar radiation. The collected weather parameters are presented in Figures 1and 2. The experiment was carried out using split-plot design based on randomized complete block design (RCBD) with three replications. Main factors were assigned with four irrigation levels *viz.* rainfed (I_1) and three irrigations at 50% (I_2), 75% (I_3) and 100% (I_4) of field capacity and three nitrogen levels [*viz.* non-fertilized (N_1), 75 (N_2) and 150 kg ha^{-1} (N_3)] as sub factors. Each plot consisted of 5 furrows spaced 0.75 m apart, with a furrow length of 4 m. Soil characteristics are given in Table 1. Maize cultivar BIO-9681 seed was sown at depth of 3 to 5 cm.

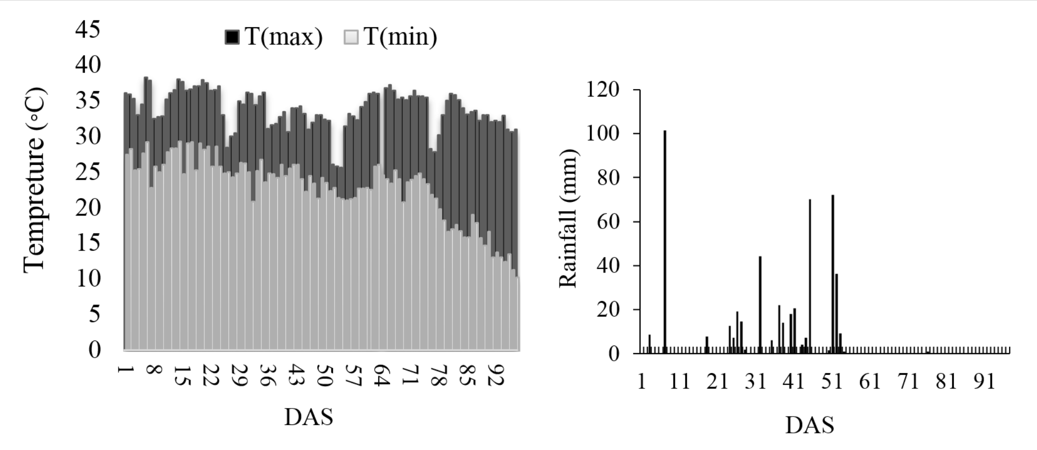

Figure 1. Daily maximum and minimum temperatures, and daily total rainfall during the crop growing season in 2009

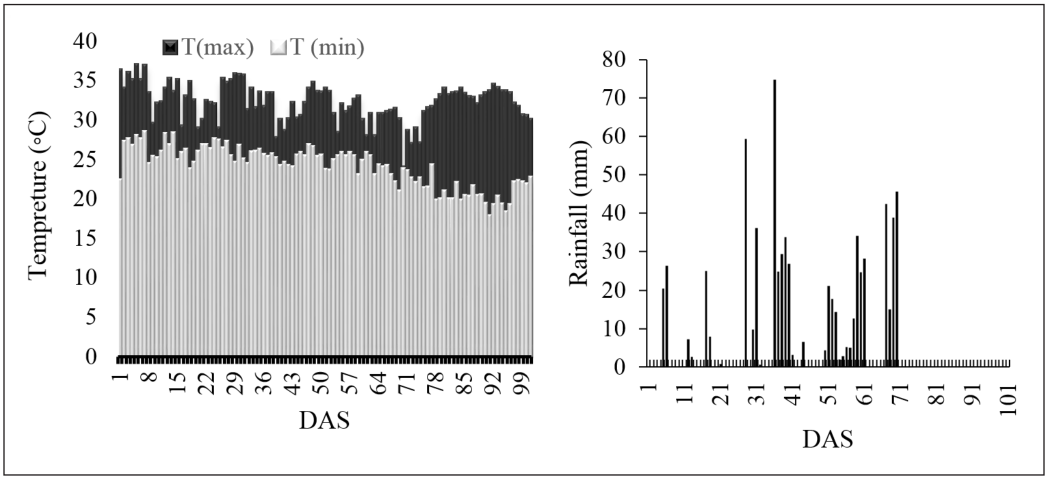

Figure 2. Daily maximum and minimum temperatures, and daily total rainfall during the crop growing season in 2010

Table 1
Physical and chemical properties of the soil of experimental field

Determination	Soil Depth (cm)				
	0-15	15-30	30-45	45-75	75-105
Sand (%)	52.4	53.7	44	39	38
Silt (%)	21	19	23	25	27
Clay (%)	26.6	27.3	33	36	35
Soil Texture	Sandy loam	Sandy loam	Loam	Loam	Clay loam
FC (w/w)	21.3	25.6	27.9	32.8	33.0
PWP(w/w)	9.5	10.2	13.7	14.7	15.0
K_S (cm day^{-1})	27.4	26.2	18.6	19.1	19.5
Bd (g cm^{-3})	1.41	1.43	1.39	1.37	1.36

Note: Bd: Bulk Density, Ks: Saturated Hydraulic Conductivity, FC: Field Capacity, PWP: Permanent Wilting Point

Assuming an effective root zone of 1.0 m, the total soil water content (SWC) in the top 1.0 m of soil was used in the analyses. One-third of total maize nitrogen requirement (N) was applied as basal dose. Additional N was applied with two split doses with one-third given at 21 days after sowing (DAS) and the remaining at 42 DAS of the crop. Measured quantity of irrigation water based on soil moisture content was directly applied to the furrows in experimental plots using High Density Poly Ethylene (HDPE) pipes. The conveyance loss was avoided by the use of HDPE pipes for supply of water from the source to all the experimental plots. In full irrigation treatment, water was applied up to field capacity level when soil moisture in the root zone approached 50% of total available water (TAW). In the deficit irrigation treatments (*i.e.* 50 and 75% of full irrigation), water was applied on the same day as the fully irrigated plot, but the irrigation depths were reduced to 50 and 75% of the full irrigation treatment. There was no irrigation in the rainfed plots of the experiment. Irrigation water depths indicated by soil moisture deficit (SMD) in each treatment was calculated using soil-moisture content before irrigation, root zone depth of the plants and bulk density using Eq. 1.

$$SMD = \left(\theta_{fc} - \theta_i\right) \times \rho_b \times D_{rz} \times f \qquad [1]$$

In Eq. (1),
SMD: Soil moisture deficit (mm), θ_{fc}: soil moisture at field capacity, θ_i: soil moisture before irrigation (weight basis in %), D_{rz}: depth of effective root zone (mm), ρ_b: bulk density of the given soil layer (g cm^{-3}) and f: coefficient of each irrigation treatment (i.e. 0, 0.5, 0.75 and 1).

Canopy development was measured in terms of growth stages, leaf area, root length, and above ground biomass on bi-weekly basis by removing two plants per plot. Date of emergence, maximum canopy cover (CC), duration of flowering, start of senescence, and maturity were also recorded. In each crop growth stages, green leaves were separated and leaf area of each plant measured by leaf area meter to obtain leaf area index (LAI). The LAI was converted to crop canopy cover (CC). Dry biomass of above ground plant at each crop growth stages were obtained by weighing it after keeping in an oven for 48 hours at 65^{o} C. Grain yield was measured as weight of harvested grain with 13% grain moisture. Total biomass yield was determined by taking the weight of above ground plant parts, including the grain.

Model Description

The Decision Support System for Agrotechnology Transfer, DSSAT, Version is a software application program that comprises crop simulation models for over 42 crops (as of Version 4.6). For DSSAT to be functional, it is supported by data base management programs for soil, weather, and crop management and experimental data, and by utilities and application programs. The crop simulation models simulate growth, development and yield as a function of the soil-plant-atmosphere dynamics. Also, DSSAT and its crop simulation models have been applied for many applications, ranging from on-farm and precision management to regional assessments of the impact of climate variability and climate change. The crop models require daily weather data, soil surface and profile information, detailed crop management and crop genetic information, and cultivar or variety information as input data. Crop model evaluation is accomplished by inputting the user’s minimum data, running the model, and comparing outputs with observed data. By simulating probable outcomes of crop management strategies, DSSAT offers users information with which to rapidly appraise new crops, products, and practices for adoption.

Statistics for Model Evaluation

The prediction error (P_e), coefficient of determination (R^2), mean absolute error (MAE), root mean square error (RMSE) and model efficiency (E) were used as the error statistics to testing the calibration and validation outputs of the model. Model performance was tested using the following statistical parameters:

$$P_e = \frac{(S_i - O_i)}{O_i} \times 100 \qquad [2]$$

$$E = 1 - \frac{\sum_{i=1}^{n} (O_i - S_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2} \qquad [3]$$

where S_i and O_i are simulated and actual (observed) data, $\bar{O}$ is mean value of O_i and n is the number of observations.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{n}} \qquad [4]$$

$$MAE = \frac{1}{n} \sum_{i=1}^{n} \left| S_i - O_i \right| \qquad [5]$$

$$NRMSE = \frac{RMSE}{\overline{O}} \times 100 \qquad [6]$$

Model efficiency (E) and R^2 approaching one, and Pe, MAE, NRMSE and RMSE close to zero were indicators for better model performance. At last, the simulation is done significantly well with a NRMSE < 10%, good if 20 > NRMSE > 10, fair if 30 > NRMSE > 20, and poor if NRMSE >30% (Jamieson et al., 1991).

RESULTS

Grain yield, Biomass and Water Productivity

Grain yield, above ground biomass, and water productivity (WP) under non limiting fertilized (N_3), moderately fertilized (N_2) and poorly fertilized (N_1) conditions for 2009 and 2010 experiments are listed in Table 2. The lowest grain and biomass yields were observed to be 1430 and 6430 kg ha^{-1}, respectively in rainfed (I_1) and non-fertilized (N_1) treatment and the highest yields were 5930 and 18150 kg ha^{-1}, respectively, under full irrigation (I_4) and recommended dose of nitrogen (N_3). The water productivity ranged from a minimum of 5.7 kg ha^{-1} mm^{-1} to a maximum of 12.9 kg ha^{-1} mm^{-1} in 2009. Water productivity for full irrigation (I_4) under N_3 treatment was the highest, whereas that for rainfed (I_1) treatment under non fertilized (N_1) condition was the lowest. During 2010, the highest (i.e. 12.4 kg ha^{-1} mm^{-1}) and lowest (6.9 kg ha^{-1}mm^{-1}) water productivity were obtained for I_1N_3 and both for I_4N_1 and I_3N_1 treatment combinations, respectively.

Table 2
Crop water use, irrigation water depths, grain yield, above ground biomass, water productivity (WP) and irrigation water use efficiency (IWUE) under varying N-fertilizer levels during 2009 and 2010

Year	Treatment	IWA (mm)	CWU (mm)	GY (kg ha^{-1})	WP (kg ha^{-1} mm^{-1})	IWUE (kg ha^{-1} mm^{-1})	Biomass (kg ha^{-1})
Non-limiting fertilizer level (N_3)							
2009	I_1	0	250	2360	9.4	NA	10240
	I_2	105	355	3625	10.2	12.56	14010
	I_3	158	408	4250	10.4	10.25	14670
	I_4	210	460	5930	12.9	15.7	18140
2010	I_1	0	423	5250	12.4	NA	16430
	I_2	24	447	5422	12.1	7.16	16370
	I_3	39	462	5525	11.9	7.05	17370
	I_4	58	481	5775	12.0	9.05	17600
Moderate-limiting fertilizer level (N_2)							
2009	**I_1**	**0**	**250**	**1950**	**7.8**	**NA**	**7950**
	I_2	**105**	**355**	**3190**	**9.0**	**11.81**	**10540**
	I_3	**158**	**408**	**4450**	**10.2**	**13.92**	**12390**
	I_4	**210**	**460**	**5120**	**11.1**	**15.1**	**14900**
2010	I_1	0	423	4535	10.7	NA	14100
	I_2	24	447	4685	10.5	6.25	14230
	I_3	39	462	4815	10.4	7.17	14620
	I_4	58	481	4785	9.9	4.31	14650
Poor fertilizer level (N_1)							
2009	**I_1**	**0**	**250**	**1430**	**5.7**	**NA**	**6400**
	I_2	**105**	**355**	**2535**	**7.1**	**10.52**	**8950**
	I_3	**158**	**408**	**3015**	**7.39**	**10.03**	**9360**
	I_4	**210**	**460**	**3395**	**7.38**	**9.35**	**10420**
2010	I_1	0	423	3160	7.5	NA	10170
	I_2	24	447	3245	7.3	3.54	10100
	I_3	39	462	3180	6.9	5.1	10200
	I_4	58	481	3315	6.9	2.67	10390

Note: CWU: Crop water used; IWA: Irrigation water applied; GY: Grain yield

Calibration of CERES-maize Model

Ceres model was calibrated using experimental data of 2009 to predict grain and biomass yields under different water and fertilizer application levels in the experiment. It was observed that, the maximum and minimum errors in grain yield prediction were in I_1N_1 and I_4N_3 treatments accounting 17% and 3%, respectively. The prediction errors in biomass for I_1N_1 and I_4N_3 treatments were 10% and 3%, respectively (Tables 3, 4 and 5). The model was calibrated for simulation of yield and biomass for all treatment levels with the prediction error statistics $0.78<E<0.84$, $0.238<RMSE<0.701$ t ha^{-1} and $6<NRMSE<7\%$ in simulating the yield and biomass for all irrigation levels. The result of model evaluation is presented in Table 6. The CERES model was able to predict the grain yield with good accuracy. The predicted biomass yield is illustrated in Figure 4**.**

Table 3

Calibrated values of above ground biomass, and grain yield of maize under different irrigation water regimes and non-limiting fertilizer doses (N_3)

	Yield (t ha^{-1})		Error	Biomass (t ha^{-1})		Error
Treatment	**Measured**	**Simulated**	**(±%)**	**Measured**	**Simulated**	**(±%)**
Rain fed	2.36	2	-10	10.24	9.35	-9
I_2	3.62	3.38	-7	14.01	13.21	-6
I_3	4.25	4.48	5	14.67	13.95	-5
I_4	5.93	5.75	-3	18.14	17.53	-3

Table 4

Calibrated values of above ground biomass, and grain yield of maize under different irrigation water regimes and moderate-limiting fertilizer doses (N_2)

Treatment	Yield (t ha^{-1})		Error	Biomass (t ha^{-1})		Error
	Measured	**Simulated**	**(±%)**	**Measured**	**Simulated**	**(±%)**
Rain fed	1.95	1.80	-7	7.95	7.34	-8
I_2	3.19	2.84	-11	10.54	9.93	-6
I_3	3.34	3.05	-9	12.39	11.37	-8
I_4	5.12	4.71	-8	14.9	13.50	-9

Table 5

Calibrated values of above ground biomass, and grain yield of maize under different irrigation water regimes and full-limiting fertilizer doses (N_1)

Treatment	Yield (t ha^{-1})		Error	Biomass (t ha^{-1})		Error
	Measured	**Simulated**	**(±%)**	**Measured**	**Simulated**	**(±%)**
Rain fed	1.43	1.18	-17	6.4	5.74	-10
I_2	2.54	2.24	-12	8.95	8.26	-8
I_3	3.01	2.67	-11	9.36	8.65	-8
I_4	3.65	3.39	-7	10.42	9.77	-6

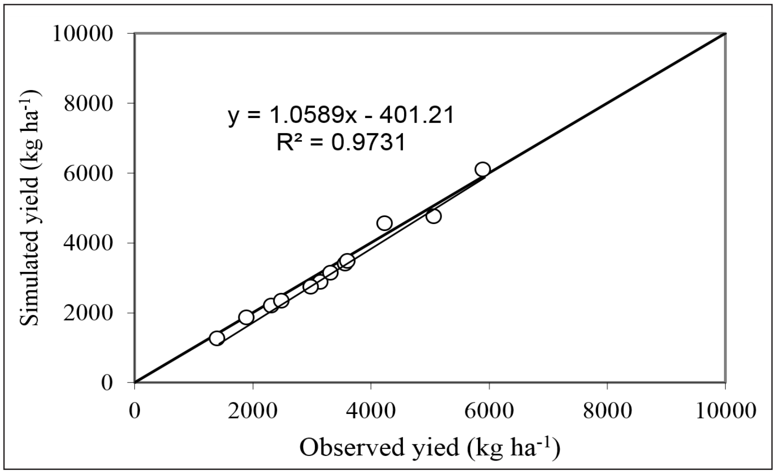

Figure 3. Simulated versus observed grain yield under all treatments

Table 6
Model calibration statistics for grain and biomass yields of maize

Crop parameters (t ha^{-1})	X_{obs}	X_{sim}	R^2	E	P(t)	RMSE	NRMSE (%)
Grain	3.36	3.16	0.97	0.84	0.47	0.238	7
Biomass	11.5	10.80	0.98	0.78	0.14	0.701	6

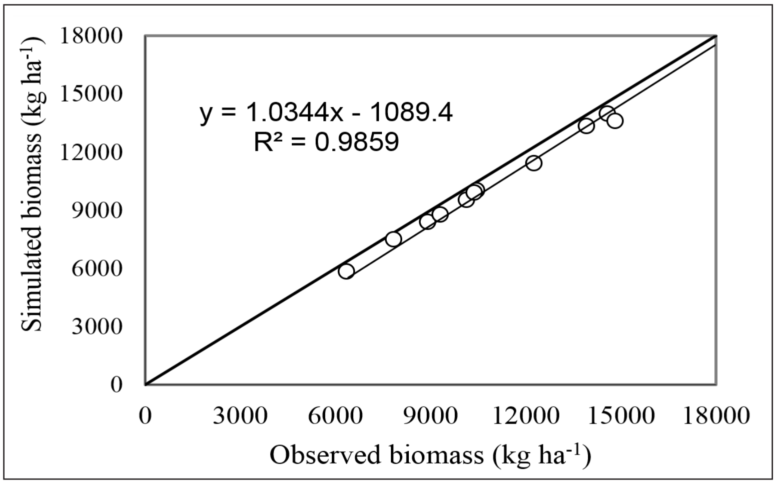

Figure 4. Simulated versus observed biomass yield for all treatments

Validation of Ceres model

Ceres model was validated using experimental data of 2010 to predict grain yield and biomass under different water and fertilizer application levels. It was observed that the maximum and minimum errors of grain yield prediction was obtained in I_1N_1 and I_4N_3

treatments at the rate of 15% and 3%, respectively. Similar this prediction was observed for biomass in I_1N_1 and I_4N_3 treatments by 11% and 2.9%, respectively (Tables 7,8 and 9). The model was validated for simulation of yield and biomass for all treatment levels with The prediction error statistics were $0.86<E<0.88$, $0.36<RMSE<0.86$ t ha^{-1}, $0.95<R^2<0.98$ and $6<NRMSE<8$ % in simulating the yield and biomass for all irrigation levels. The simulated versus observed values are illustrated in Figure 5 for grain yield and in figure 6 for biomass.

Table 7
Validation results of above ground biomass, and grain yield of maize under different irrigation water regimes and non-limiting fertilizer doses (N3)

Treatment	**Yield (t ha^{-1})**		**Error (±%)**	**Biomass (t ha^{-1})**		**Error (±%)**
	Measured	**Simulated**		**Measured**	**Simulated**	
Rain fed	5.12	4.75	-7	16.43	15.24	-7
I_2	5.62	5.30	-6	16.37	15.48	-5
I_3	5.52	5.78	5	17.37	17.81	3
I_4	5.77	5.58	-3	18.61	18.07	2.9

Table 8
Validation results of above ground biomass, and grain yield of maize under different irrigation water regimes and moderate-limiting fertilizer doses (N_2)

Treatment	**Yield (t ha^{-1})**		**Error (±%)**	**Biomass (t ha^{-1})**		**Error (±%)**
	Measured	**Simulated**		**Measured**	**Simulated**	
Rain fed	4.53	4.05	-8	14.10	13.00	-8
I_2	4.68	4.12	-14	14.23	13.17	-7
I_3	4.80	4.21	-12	14.62	13.34	-9
I_4	4.87	4.35	-11	14.65	13.48	-8

Table 9
Validation results of above ground biomass, and grain yield of maize under different irrigation water regimes and full-limiting fertilizer doses (N_1)

Treatment	**Yield (t ha^{-1})**		**Error (±%)**	**Biomass (t ha^{-1})**		**Error (±%)**
	Measured	**Simulated**		**Measured**	**Simulated**	
Rain fed	3.16	2.70	-15	10.17	9.02	-11
I_2	3.24	2.85	-12	10.20	9.19	-10
I_3	3.18	2.80	-12	10.25	9.34	-9
I_4	3.31	2.98	-10	10.39	9.57	-8

Figure 5 shows the performance of the model in terms of observed versus simulated grain yield. The regression line was more or less near to 1:1 line, indicating that the model was performing well under the test of different water and nitrogen levels. Similarly, goodness of fit (R^2) as well as regression coefficients between observed and simulated data was significant. The coefficient of prediction was to the extent of 95% in case of trend run between the observed and simulated values.

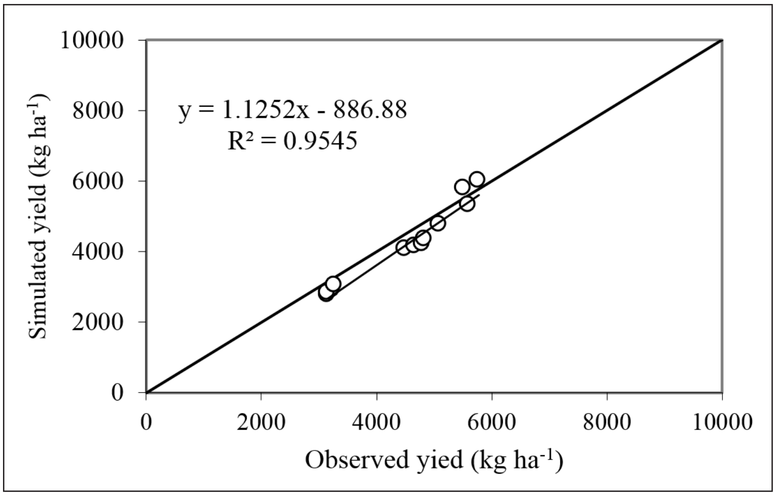

Figure 5. Simulated versus observed grain yield under all treatments

Table 10

Model validation statistics for grain and biomass yields of maize

Crop parameters (t ha^{-1})	X_{obs}	X_{sim}	R^2	E	P(t)	RMSE	NRMSE (%)
Grain	4.48	4.158	0.95	0.86	0.24	0.36	8
Biomass	13.86	13.06	0.98	0.88	0.027	0.86	6

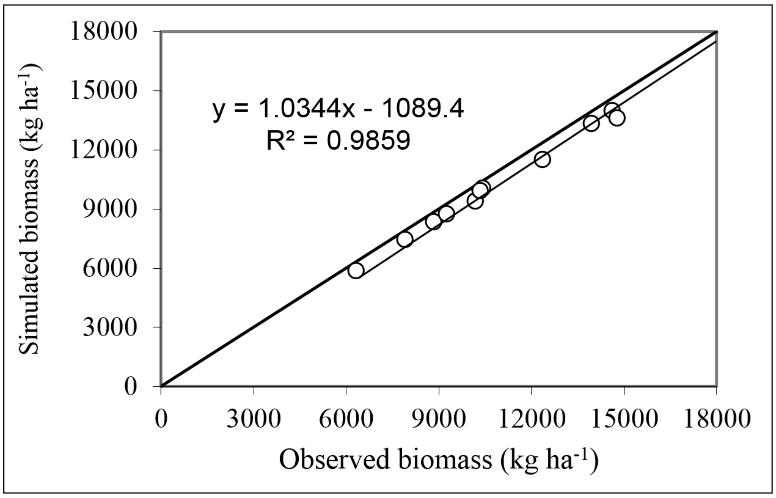

Figure 6. Simulated versus observed biomass yield under all treatments

Also, figure 6 shows the performance of the model in terms of observed versus simulated biomass yield. Goodness of fit (R^2) as well as regression coefficients between observed and simulated data was significant. The coefficient of prediction was to the extent of 98% in case of trend run between the observed and simulated values. Similarly, the regression line was near to 1:1 line, indicating that the model was performing well for maize crop under the test of different water and nitrogen levels.

DISCUSSION

Although in general, the grain and biomass yields were simulated by CERES-maize model correctly. However, in some case studies, the model had a slight trend of underestimating low observed yields. The result of this study is in agreement with findings by Panda et al. (2004) and Ló Pez-Cedrón et al. (2008). Also, a report showed that simulated mean grain yield was within 5% of measured grain yields for nine locations in the United States. But, Dogan et al. (2006) reported the opposite trend; however, this study had very poor correlation between simulated and observed yield values (R^2= 0.16). The close agreement between observed and simulated variables for both calibration and evaluation experiments means that the model can be used to predict performance of maize across different water and nitrogen levels. The outcomes of simulations resulted across all treatments indicating that the efficiency and robustness of the model are quite adequate and the model can be used in the environments under study. The results of many studies revealed the calibration and parameterization of CERES-maize model to test irrigation management for future use in different parts of the world (Hoogenboom et al., 2004; Nouna et al., 2000; Panda et al., 2004). A comparison of the performance evaluation of the EPIC and CSM-CERES-maize models was done using maize variety trial data. The results indicated that variations between the simulations of CSM-CERES-maize and measurements were less than 3% for calibration and equal to 8% for validation (Bao et al., 2017).

By contrast, similar study in Turkey found that WUE was under-estimated by 1.5% under non water stress treatments while it was over predicted by 1.4 and 1.7% for 75% and 50% of crop water requirement, respectively (Gercek & Okant, 2010). Numerous studies have shown previously that simulation of soil water content and maize yield is accurate enough for irrigated conditions, while recent studies using CSM-CERES-Maize as part of DSSAT package have raised more concerns about the accuracy of the model in its simulation mode under deficit-irrigation conditions in semi-aired environments (DeJonge et al., 2011; Dokoohaki et al., 2017; Mubeen et al., 2013). Also, CERES-Maize calibration and validation for maize for Delhi production environment open the way for use of the model for inputs and resource management, yield forecasting and climate change impact analysis. The performance of the model after its validation was satisfactory and the results were within significant limits and were similar to the results of Esmaeilian et al. (2014) and Ma et al. (2006). Overall, the results of this study revealed that model was able to simulate the maize grain and biomass yield accurately for full and deficit-irrigation treatments under a semi-arid condition.

CONCLUSION

This manuscript evaluated the CERES-maize model in a split plot experiment including four factors of irrigation levels and nitrogen fertilizer application. For each of the 12 combination of irrigation and fertilizer treatments, the CERES-maize model was evaluated for grain yield and biomass. The CERES-maize model was calibrated, evaluated and it estimated yield and biomass under the three N application rates with reasonable accuracy. It was observed that the CERES-maize model was more accurate in predicting the maize yield under full and 75% of FC irrigation as compared to the rainfed and 50% of FC irrigation. Finally, from the results of field data and modeling, it can be recommended that CERES-maize model can be applied to estimate the maize yield with acceptable accuracy under dynamic water and nitrogen regimes in the semi-arid environment.

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