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Original article

Quantitative response of wheat to sowing dates and irrigation regimes using CERES-Wheat model

Eajaz Ahmad Dar [a,b,*], A.S. Brar [a], Showket A. Dar [c,*], Bandar S. Aljuaid [d], Ahmed M. El-Shehawi [d], Rizwan Rashid [e], Zahoor A. Shah [f], Abrar Yousuf [g], Mohammad Amin Bhat [g], Mushtaq Ahmed [h], Fayaz Ahmad Bahar [i], Hesham El Enshasy [j,k], Marian Brestic [l,*], Maria Barboricova [l], Marek Zivcak [l], Shahid Farooq [m], Mohammad Javed Ansari [n,*]

[a] *Department of Agronomy, Punjab Agricultural University, Ludhiana 141004, India*
[b] *Krishi Vigyan Kendra Ganderbal-190006, Sher-e-Kashmir University of Agricultural Sciences & Technology of Kashmir, Shalimar, Srinagar 190025, J&K, India*
[c] *Division of Entomology, KVK- Kargil-II (Zanskar), Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Jammu and Kashmir, India*
[d] *Department of Biotechnology, College of Science, Taif University, P.O. Box 11099, Taif 21944, Saudi Arabia*
[e] *Division of Vegetable Science, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Shalimar, Srinagar, Jammu and Kashmir, India*
[f] *Faculty of Agriculture, Wadura Sopore, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar 190025, Jammu and Kashmir, India*
[g] *Regional Research Station, Punjab Agricultural University, Ballowal Saunkhri SBS Nagar-144521, Ludhiana, India*
[h] *Mountain Research Centre for Field Crops (MRCFC) Khudwani, Sher-e-Kashmir University of Agriculture Sciences and Technology, Jammu and Kashmir, India*
[i] *Division of Agronomy, Faculty of Agriculture-Wadura Sopore, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India*
[j] *Institute of Bioproduct Development (IBD), Universiti Teknologi Malaysia (UTM), Skudai, Johor Bahru 81310, Malaysia*
[k] *City of Scientific Research and Technology Applications, New Burg Al-Arab, Alexandria 21934, Egypt*
[l] *Department of Plant Physiology, Slovak University of Agriculture, A. Hlinku 2, 94976 Nitra, Slovakia*
[m] *Department of Plant Protection, Faculty of Agriculture, Harran University, Sanliurfa, Turkey*
[n] *Department of Botany, Hindu College Moradabad (Mahatma Jyotiba Phule Rohilkhand University Bareilly) India*

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ABSTRACT

An experiment was conducted at Punjab Agricultural University, Ludhiana during 2014–15 and 2015–16, keeping four sowing dates {25th Oct (D_1), 10th Nov (D_2), 25th Nov (D_3) and 10th Dec (D_4)} in main plots and five irrigation schedules {irrigation at 15 (FC_{15}), 25 (FC_{25}), 35 (FC_{35}) and 45 (FC_{45}) % depletion of soil moisture from field capacity (FC) and a conventional practice} in sub plots. The objective of the study was to evaluate the performance of CERES-Wheat model for simulating yield and water use under varying planting and soil moisture regimes. The simulated and observed grain yield was higher in D_1, with irrigation applied at FC_{15} as compared to all other sowing date and irrigation regime combinations. Simulated grain yield decreased by 19% with delay in sowing from 25th October to 10th December because of 8% reduction in simulated crop evapotranspiration. Simulated evapotranspiration decreased by 16%, wheat grain yield by 23% and water productivity by 15% in drip irrigation at 45% depletion from field capacity as compared to drip irrigation at 15% of field capacity. It was further revealed that the model performed well in simulating the phenology, water use and yield of wheat.

1. Introduction

Punjab has 3.5 million ha under wheat cultivation with production and productivity of 18.5 million tonnes and 5.2-ton ha^{-1}, respectively. The state known as the food bowl of India, contributes 40% of wheat to the central pool (GOI, 2019). The crop is highly influenced by variations in environmental conditions for better emergence, growth and flowering (Dabre et al., 1993; Dar et al., 2018) and is more vulnerable to high temperature exposures during reproductive stages (Kalra et al., 2008). Yield reduction in crops is contributed by many factors like disease, insect pests (Dar et al.

* Corresponding authors at: Krishi Vigyan Kendra Ganderbal-190006, Sher-e-Kashmir University of Agricultural Sciences & Technology of Kashmir, Shalimar, Srinagar 190025, J&K, India (E.A. Dar).

E-mail addresses: eajazagron@skuastkashmir.ac.in, darajaz9@gmail.com (E. Ahmad Dar), showketdar43@gmail.com (S.A. Dar), marian.brestic@uniag.sk (M. Brestic), mjavedansari@gmail.com (M.J. Ansari).

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2015, Dar and Mir 2016, Dar et al. 2017) and other abiotic factors and among them: salt stress, the irrigation management, and proper sowing dates have a significant effect on total yield obtained (Ilyas et al., 2020a, Ilyas et al., 2020b). The selection of sowing date is an important agronomic practice to optimize the grain yield of wheat. Number of studies (Bassu et al., 2009; Bannayan et al., 2013; Dar et al., 2019a) have reported yield enhancement with advancement in sowing and yield reduction with postponement of sowing after the optimum time (Haq and Khan 2002; Qasim et al., 2008). Delay in sowing beyond normal sowing window reduces the yield and consumptive use vis-à-vis water productivity (Gao et al., 2014; Shivani et al., 2001).

In wheat season, rainfall is scanty as well as poorly distributed relative to the crop need, resulting in heavy dependence on irrigation for optimal grain yield. Effective irrigation management strategies aid in improving crop water productivity (WP) through regulated timing and application of irrigation water (Dar et al., 2019b); having the potential to deliver only the required amount of water for crop use. For similar reasons, interest in drip irrigation is increasing in the water scarcity regions of the world. Water saving of 12 to 84% over the conventional method of irrigation in vegetable crops, 45 to 81% in fruit crops and over 65% in sugarcane, and improved yields by 20 to 90% for different crops (INCID 1994), better crop quality and higher water use efficiency are the major advantages of drip irrigation (Hutmacher et al., 1996; Ayars et al., 1999; Kumari et al., 2014).

Knowledge of the influence of irrigation management on water balance, crop water use and requirements are the practical considerations to improve yield, crop water productivity and irrigation water productivity of wheat (Timsina et al., 2008). Several studies in Punjab have investigated the irrigation water requirements based on ET (Gajri et al., 1997), irrigation water/pan evaporation (Prihar et al., 1976), but very less are based on soil water deficit (SWD) (Prihar et al., 1978; Timsina et al., 2008). Prihar et al., (1978) observed no yield decline when crop was irrigated after depletion of 50–110 mm available soil water from the 180 cm profile. But grain yield declined largely when irrigated at a depletion of 140–170 mm. Panda et al., (2003) reported similar grain yield at a depletion of 15–45% of available soil water (ASW) and reduced yields for 60–75% depletion of ASW. However all of these studies were under flood irrigated conditions and very less literature is available for drip irrigation conditions.

Determining optimum sowing dates and irrigation schedules through field experimentation is costly and time consuming and has less extrapolatability to other soil and climate conditions due to spatio-temporal variability in experimental results. Analogous to this, researchers have used different simulation techniques for maximizing grain yield under limited resource availability. Different models (CERES, Cropsyst, Infocrop) developed in this regard have tried to correlate wheat grain yield to irrigation water (Stewart and Hagan 1973; Benli et al., 2007; Timsina et al., 2008; Arora et al., 2007; Arora and Gajri, 1998; Jalota et al., 2002). The CERES-Wheat model has been widely evaluated to optimize irrigation water in different parts of the world (Ritchie, 1998; Ritchie and Otter 1985; Benli et al., 2007; Timsina et al., 2008; Arora et al., 2007; Andarzian et al., 2015). In Punjab, an older version of CERES-Wheat has been used to forecast the long term variability in potential yield (Pathak et al., 2003), effect of sowing date and climate change on yield (Hundal and Kaur 1997), irrigation and fertilizer management (Arora et al., 2007) and sowing date and irrigation management (Timsina et al., 2008).

However, the studies regarding evaluation and application of the CERES-Wheat model for determining optimum sowing date and irrigation schedule of wheat under drip irrigation conditions are limited. So, this study was conducted with the objectives of evaluating the performance of DSSAT-CSM-CERES-Wheat (V4.6) for simulating the yield and water use of drip irrigated wheat grown in Punjab, North-western India.

2. Material and methods

2.1. Environmental conditions

The experiment was carried out during two wheat growing seasons (2014–15 and 2015–16) at the research farms of Punjab Agricultural University (PAU), Ludhiana, India (30° 54′ N, 75° 48′ E, elevation 247 masl). The climate of the area is semi-arid, with average wheat season rainfall of 115 mm, daily maximum temperature of 40–45 °C in May and daily minimum temperature of 0–4 °C in January. The weather data was obtained from meteorological observatory, PAU, located 200 m from the experimental site. Seasonal weather data including mean maximum temperature, minimum temperature and relative humidity; cumulative fortnightly rainfall, sunshine hours and reference evapotranspiration recorded during 2014–15 and 2015–16 wheat growing season is presented in Figs. 1 and 2.

The mean maximum temperature, minimum temperature and RH during 2014–15 growing season were 22.3 °C, 10.4 °C and 76%

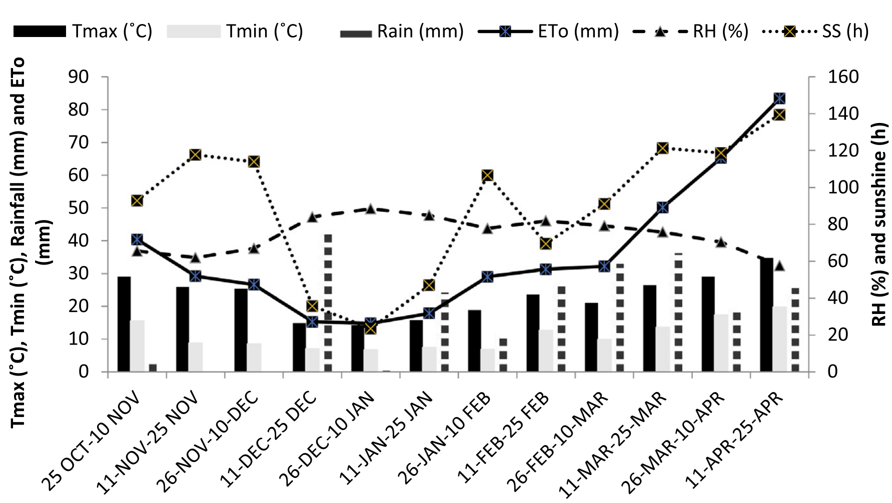

Fig. 1. Fortnightly mean maximum temperature, minimum temperature and relative humidity and cumulative fortnightly sunshine hours, potential evapotranspiration and rainfall during 2014–15.

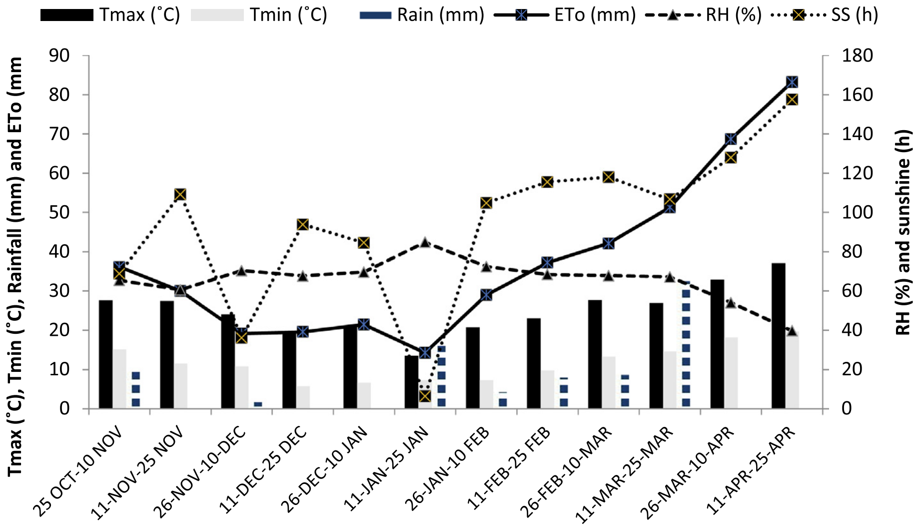

Fig. 2. Fortnightly mean maximum temperature, minimum temperature and relative humidity and cumulative fortnightly sunshine hours, potential evapotranspiration and rainfall during 2015–16.

for D_1, 21.7 ℃, 10 ℃ and 77% for D_2, 21.5 ℃, 10.3 ℃ and 78% for D_3 and 21.5 ℃, 10.9 ℃ and 79% for D_4, respectively (Fig. 1). During 2015–16, the mean maximum temperature, minimum temperature and RH were 24 ℃, 10.9 ℃ and 68.2% for D_1, 23.9 ℃, 10.7 ℃, 67.8% for D_2, 24.1 ℃, 10.9 ℃, 67.5% for D_3 and 24.3 ℃, 11.1 ℃ and 66.8% for D_4, respectively (Fig. 2). The total sunshine hours and reference ETo were higher in 2015–16 (949 h and 358 mm for D_1, 935 h and 351 mm for D_2, 883 h and 348 mm for D_3 and 856 h and 338 mm for D_4, respectively) compared to 2014–15 (938 h and 352 mm for D_1, 867 h and 322 mm for D_2, 780 h and 311 mm for D_3 and 702 h and 307 mm for D_4, respectively). Substantial variability in rainfall amount and distribution was observed for the two growing seasons (196.3 mm for D_1, 193.8 mm for D_2, 211.4 mm for D_3 and 219.4 mm for D_4 during 2014–15 and 70.2 mm for D_1, 70.6 mm for D_2, 70.6 mm for D_3 and 70.1 mm for D_4 during 2015–16.

The soil of the experimental field was sandy loam in texture, with 55–59% sand, 23–26% silt and 17–19% clay in different soil layers (Table 1). The field capacity varied from 24.3 to 25.5% and saturated hydraulic conductivity from 2.1 to 5.9 mm h^{-1}.

2.2. Experimental setup

The experiments were conducted in a split plot design comprising of four sowing dates (D_1-25 Oct, D_2-10 Nov, D_3-25 Nov and D_4-10 Dec) in main plots and five irrigation treatments in sub plots, with three replications. Four irrigation treatments based on soil water deficit from field capacity were (1) 15% depletion (2) 25% depletion (3) 35% depletion (4) 45% depletion from field capacity (FC) of the top 0–40 cm layer, and the fifth irrigation treatment was taken as conventional practice (irrigating the crop every 4–5 weeks with 75 mm water). The amount of irrigation per application was 15 mm, 25 mm, 35 mm, 45 mm and 75 mm, respectively for the five irrigation treatments. The method of irrigation for the first four treatments was drip irrigation, while the fifth was flood irrigated. The details of the treatments and number of irrigations are given in Table 2. A buffer area of 1 m was maintained between the plots (having a size of 12 m^2) to prevent the inter plot flow of water. The amount of fertilizer applied was same for all the treatments (125 kg N ha^{-1} applied in two splits, 60 kg P_2O_5 ha^{-1} and 30 kg K_2O ha^{-1}), applied as basal as Urea, Diammonium Phosphate and Muriate of Potash, respectively. Other crop management practices were as per the local package of practices of PAU (Package of practices for crops of Punjab, 2014–15).

2.3. Irrigation setup

A surface drip irrigation system was installed within a week after sowing; and managed to ensure uniform application. Polyvinyl chloride (PVC) pipeline was installed adjacent to the plots with an outlet (plot inlet) at the centre of each plot. Each plot inlet had a water-tight butterfly valve to ensure that only one plot in each replication is irrigated at a time. The pressure compensating drippers with a flow rate of 2 L h^{-1} were spaced 0.2 m apart on the laterals. Each lateral was placed in between the two crop rows. In total, there were 5 laterals in each plot with 30 drippers on each lateral. For each treatment, irrigation water was added until the requisite deficit is fulfilled. The irrigation water to be added was calculated as

Table 1
Physical properties of the experimental field.

Depth	Field capacity (m^3 m^{-3})	Bulk density (Mg m^{-3})	Saturated water content (m^3 m^{-3})	Saturated hydraulic conductivity (mm h^{-1})	Sand (%)	Silt (%)	Clay (%)
0–10	0.243	1.59	0.340	3.82	59.0	23.6	17.4
10–20	0.250	1.61	0.360	2.06	56.8	25.4	17.8
20–30	0.253	1.62	0.365	5.89	56.2	25.8	18.0
30–40	0.244	1.61	0.358	4.40	57.4	25.2	17.4
40–60	0.255	1.63	0.368	3.66	55.1	26.4	18.5
60–100	0.255	1.62	0.368	4.71	55.1	26.4	18.5

Table 2
Detail of treatments applied during 2014–15 and 2015–16 wheat growing season.

Date of sowing	Treatment (Depletion from FC (%)	No. of irrigations	Amount per application (mm)	Abbreviation
Year 2014–15				
D_1 (25th Oct.)	15	11	15	D_1 FC_{15}
	25	5	25	D_1 FC_{25}
	35	3	35	D_1 FC_{35}
	45	2	45	D_1 FC_{45}
	Conventional Practice (CP)	5	75	D_1 CP
D_2 (10th Nov.)	15	9	15	D_2 FC_{15}
	25	4	25	D_2 FC_{25}
	35	2	35	D_2FC_{35}
	45	1	45	D_2 FC_{45}
	Conventional Practice (CP)	5	75	D_2 CP
D_3 (25th Nov.)	15	7	15	D_3 FC_{15}
	25	4	25	D_3 FC_{25}
	35	2	35	D_3 FC_{35}
	45	1	45	D_3 FC_{45}
	Conventional Practice (CP)	4	75	D_3 CP
D_4 (10th Dec)	15	7	15	D_4 FC_{15}
	25	3	25	D_4 FC_{25}
	35	2	35	D_4 FC_{35}
	45	1	45	D_4 FC_{45}
	Conventional Practice (CP)	4	75	D_4 CP
Year 2015–16				
D_1 (25th Oct.)	15	16	15	D_1 FC_{15}
	25	9	25	D_1 FC_{25}
	35	6	35	D_1 FC_{35}
	45	4	45	D_1 FC_{45}
	Conventional Practice (CP)	5	75	D_1 CP
D_2 (10th Nov.)	15	15	15	D_2 FC_{15}
	25	8	25	D_2 FC_{25}
	35	5	35	D_2FC_{35}
	45	3	45	D_2 FC_{45}
	Conventional Practice (CP)	5	75	D_2 CP
D_3 (25th Nov.)	15	13	15	D_3 FC_{15}
	25	7	25	D_3 FC_{25}
	35	4	35	D_3 FC_{35}
	45	3	45	D_3 FC_{45}
	Conventional Practice (CP)	4	75	D_3 CP
D_4 (10th Dec)	15	12	15	D_4 FC_{15}
	25	6	25	D_4 FC_{25}
	35	3	35	D_4 FC_{35}
	45	2	45	D_4 FC_{45}
	Conventional Practice (CP)	4	75	D_4 CP

$$\text{Irrigation water (L/Plot)} = \frac{\theta_v \text{ at FC } (\%) - \theta_v \text{before irrigation}(\%)}{100} \times \text{Soil depth(cm)} \times \text{Plot area}(m^2) \quad (1)$$

Where, θv is volumetric moisture content; FC is the field capacity

2.4. Measurement of soil moisture

Volumetric soil moisture was measured with Delta-T Devices PR2 soil moisture profile probe (Delta-T Devices, UK) in access tubes down to 100 cm depth. However, the tubes were installed in one replication only. The moisture was measured for six soil depths (0–10, 10–20, 20–30, 30–40, 40–60 and 60–100 cm) at 3–6 days interval. The irrigation amount to each plot was measured with a water meter installed on the submain line. ETc was measured as the difference in moisture between two irrigation events.

2.5. Crop water productivity (WP)

Water productivity was calculated in accordance with Brar et al., (2012) and shown in Eq. (2)

$$CWP = \frac{GY}{ETc} \quad (2)$$

Where, CWP, is crop water productivity (kg m^{-3}), ETc is crop evapotranspiration (mm), GY is grain yield (kg ha^{-1}), I is irrigation water applied (m^3).

2.6. The CERES-Wheat model

The CSM-CERES-Wheat model (V4.6), a part of DSSAT-cropping system model was used for simulation. The model can simulate the growth and development of wheat across a range of latitudes, and has been documented extensively throughout the northern and southern hemispheres (Jones et al., 2003; Hoogenboom et al., 2004; Timsina et al., 2008; Benli et al., 2007; Arora et al., 2007). The model computes biomass accumulation as a function of photo-synthetically active intercepted radiation and radiation use efficiency. Grain yield is modelled as the product of plant population, grain number and grain weight at maturity. Soil water balance is simulated with regard to irrigation, precipitation, run-off, infiltration, evapotranspiration and drainage from the soil profile. The model computes evapotranspiration as per FAO-56 method, photosynthesis by canopy curve method and hydrology by Ritchie water balance.

2.7. Calibration and validation

The model was calibrated for phenology, leaf area index, biomass, grain yield and seasonal evapotranspiration using observations of the experimental data of three experiments (different from the present study) conducted at Ludhiana, during the last three years (2014–16). Slight adjustments in the crop input parameters were done during the calibration procedure. The genetic coefficients that describe the specific growth and development of the crop cultivar were derived through an optimizing procedure (Alexandrov et al., 2002) until a close synchrony was observed between observed and simulated phenology and yield of well watered treatments. The final calibrated cultivar (HD 2967) parameter values were 10 for P1V (vernalization sensitivity coefficient (%/d of unfulfilled vernalization), 45 for P1D (photoperiod sensitivity coefficient (% reduction/h near threshold), 690 for P5 (thermal time from the onset of linear fill to maturity (°C d), 19 for G1 (kernel number per unit stem + spike weight at anthesis (#/g), 45 for G2 (potential kernel growth rate (mg/(kernel.d)), 4.2 for G3 (tiller death coefficient; standard stem + spike weight when elongation ceases (g) and 85 for PHINT (thermal time between the appearance of leaf tips (°C d).

The evaluation was done by comparing the observed data of phenology, yield and evapotranspiration during 2014–15 and 2015–16 wheat growing season with the model results. Different measures used to evaluate the performance of the model like correlation coefficient; root mean square error (RMSE), normalized RMSE (nRMSE), mean bias error (MBE) and mean absolute percentage error (MAPE) were computed as follows:

S. No.	Statistical parameter	Formula	Reference
1.	Mean bias error	$\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)$	(Panda et al., 2003)
2.	Mean absolute percentage error	$\frac{1}{N}\sum_{i=1}^{N}\left\|100\frac{(P_i-O_i)}{O_i}\right\|$	(Panda et al., 2003)
3.	Root mean square error	$\sqrt{\frac{\sum_{i=1}^{N}(P_i-O_i)^2}{N}}$	(Thomann 1982)
4.	Normalized Root mean square error	$\sqrt{\frac{\sum_{i=1}^{N}(P_i-O_i)^2}{N}}x100/\bar{O}$	(Loague and Green 1991)
5.	Correlation coefficient	$\frac{\sum_{i=1}^{N}(O_i-\bar{O})\sum_{i=1}^{N}(P_i-\bar{P})}{\sqrt{\sum_{i=1}^{N}(O_i-\bar{O})^2\sum_{i=1}^{N}(P_i-\bar{P})^2}}$	(Kirch 2008)

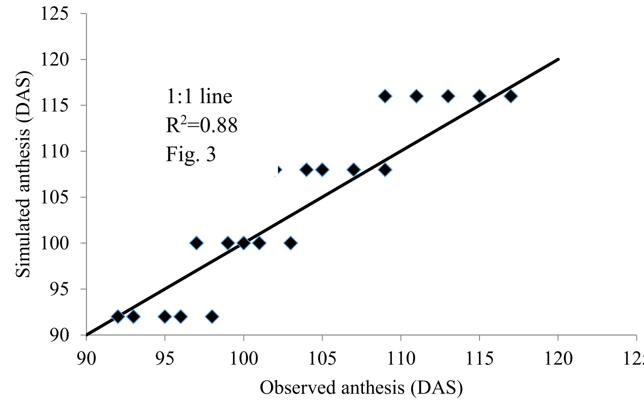

Fig. 3. Regression analysis (1:1 line) between simulated and observed anthesis for the year 2014–15.

Where O_i and P_i are observed and predicted values, respectively, $\bar{O}$ is the observed mean and $\bar{P}$ is the predicted mean. In addition a regression procedure was used to test the nature of relationship between simulated and observed values.

3. Results

3.1. Simulated and observed phenology and leaf area index (LAI)

The simulated and observed number of days taken to anthesis was 116 and 113 in D_1, 108 and 105 in D_2, 100 and 100 in D_3 and 92 and 95 in D_4 (Fig. 3) during 2014–15. For 2015–16, the respective number of days taken to anthesis was 115 and 113 in D_1, 109 and 107 in D_2, 100 and 101 in D_3 and 90 and 96 in D_4 (Fig. 4). Similarly, the simulated and observed number of days taken to maturity was 161 and 163 in D_1, 152 and 149 in D_2, 141 and 138 in D_3 and 131 and 128 in D_4 (Fig. 5) during 2014–15. For 2015–16, the respective number of days taken to maturity was 158 and 162 in D_1, 149 and 150 in D_2, 138 and 142 in D_3 and 127 and 128 in D_4 (Fig. 6).

The simulated and the observed data for leaf area index revealed deviation of – 0.4 to + 0.5 and – 0.4 to + 0.7 between observed and simulated LAI in different treatments during 2014–15 and 2015–16, respectively. However the overall variation in LAI was quite low, ranging from 3.4 to 4.4 for the simulated data and 3.0–4.8 for the observed data across different treatment com-

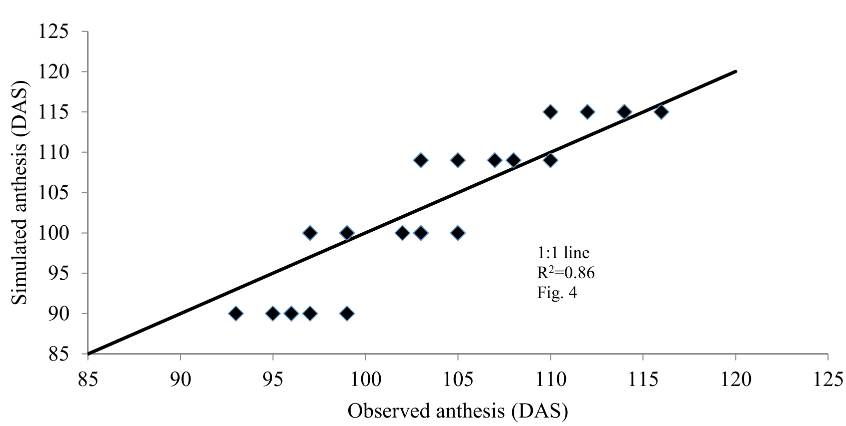

Fig. 4. Regression analysis (1:1 line) between simulated and observed anthesis for the year 2015–16.

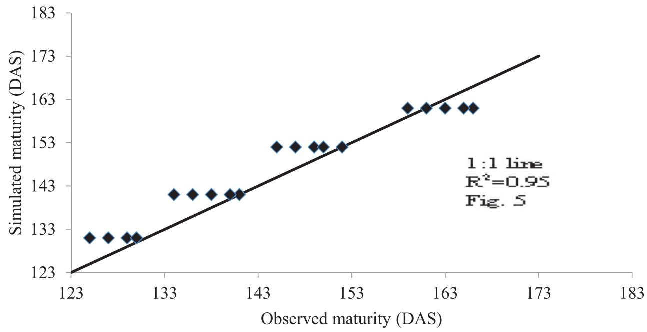

Fig. 5. Regression analysis (1:1 line) between simulated and observed maturity for the year 2014–15.

binations during 2014–15 (Fig. 7). The respective LAI during 2015–16 was 3.3–4.5 for the simulated data and 2.9–5.1 for the observed data (Fig. 8).

3.2. Simulated and observed grain and biological yield

The simulated and the observed data regarding grain and biological yield (t ha^{-1}) as given in Figs. 9 and 10 revealed deviation of – 0.3 to + 0.2 t ha^{-1} between observed and simulated grain yield in different treatments during both the years. The overall range was 4.4–5.4 t ha^{-1} for the simulated yield and 4.1–5.6 t ha^{-1} for the observed yield across different treatment combinations during 2014–15 (Fig. 9). The respective range during 2015–16 was 4.4–5.4 t ha^{-1} for the simulated yield and 4.5–5.5 t ha^{-1} for the observed yield (Fig. 10). The deviation of – 0.6 to + 0.8 and – 0.7 to + 0.8 t ha^{-1}, was recorded between observed and simulated bio-

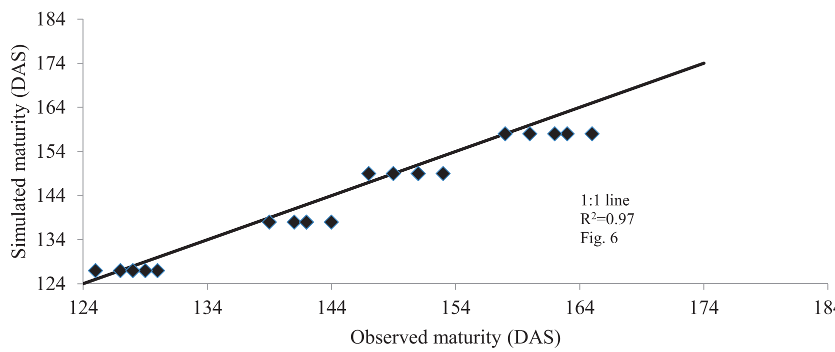

Fig. 6. Regression analysis (1:1 line) between simulated and observed maturity for the year 2015–16.

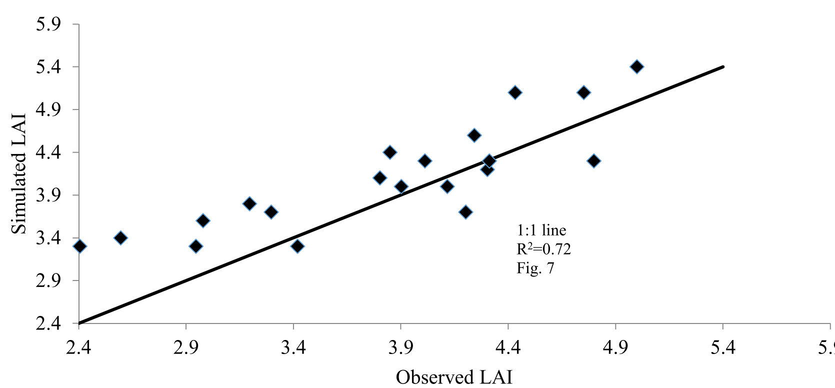

Fig. 7. Regression analysis (1:1 line) between simulated and observed leaf area index for the year 2014–15.

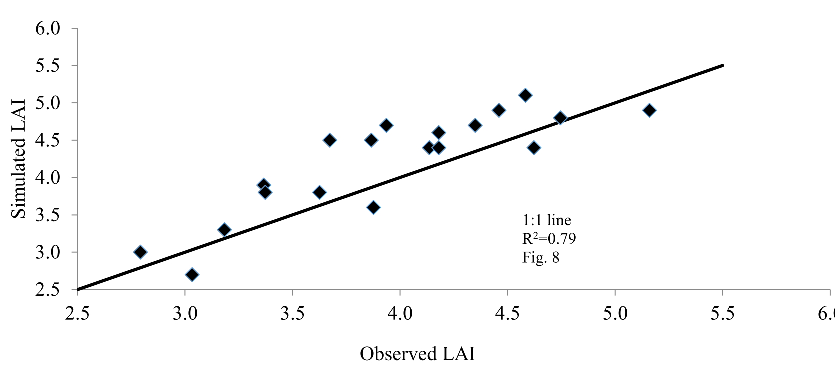

Fig. 8. Regression analysis (1:1 line) between simulated and observed leaf area index for the year 2015–16.

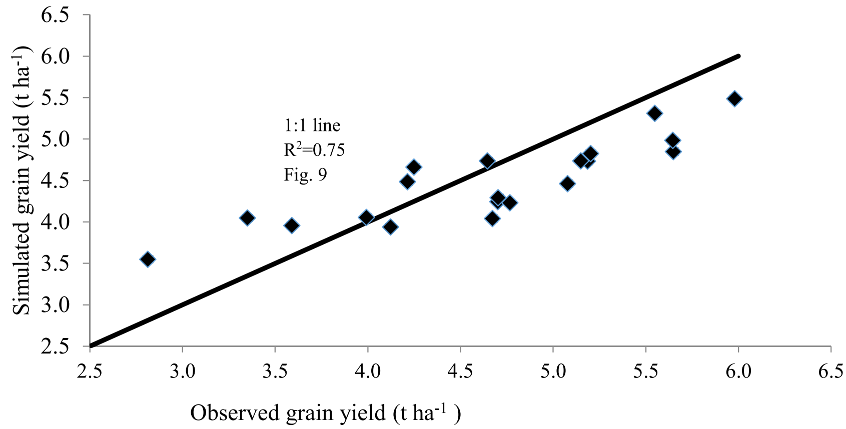

Fig. 9. Regression analysis (1:1 line) between simulated and observed grain yield for the year 2014–15.

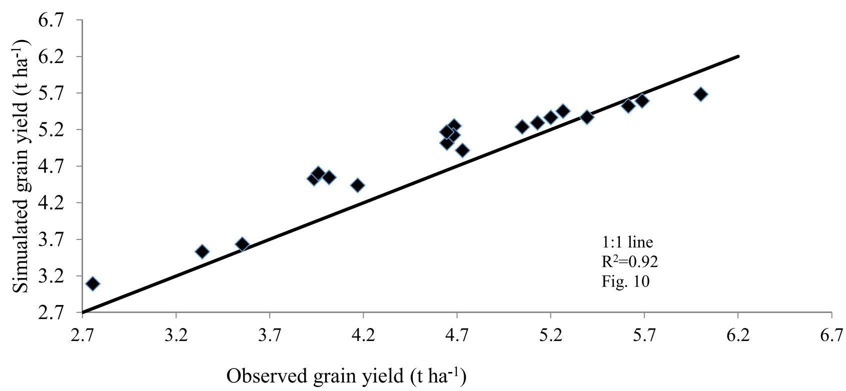

Fig. 10. Regression analysis (1:1 line) between simulated and observed grain yield for the year 2015–16.

logical yield in different treatments during 2014–15 and 2015–16, respectively. The overall range of biological yield was 10.6–11.7 t ha^{-1} for the simulated data and 10.0–12.6 t ha^{-1} for the observed data across different treatment combinations during 2014–15 (Fig. 11). The respective range during 2015–16 was 10.9–12.1 t ha^{-1} for the simulated data and 10.3–12.9 t ha^{-1} for the observed data (Fig. 12).

3.3. Simulated and observed crop evapotranspiration (ETc) and crop water productivity (CWP)

The simulated and the observed data regarding ETc (mm) and CWP (kg m^{-3}) as given in Fig. 13 and Fig. 14 revealed deviation of – 14.4 to + 10.8 and – 6.7 to + 27.9 mm between observed and simulated ETc in different treatments during 2014–15 and 2015–16, respectively. The overall range of ETc was 330–421 mm for the simulated data and 318–406 mm for the observed data across different treatments during 2014–15. The respective range during 2015–16 was 265–374 mm for the simulated ETc and 258–396 mm for the observed ETc.

The deviation of – 0.06 to + 0.09 and – 0.15 to + 0.01 kg m^{-3} was recorded between observed and simulated CWP in different treatments during 2014–15 and 2015–16, respectively (Figs. 15 and 16). The overall range of CWP was 1.29–1.48 kg m^{-3} for the simulated data and 1.35–1.43 kg m^{-3} for the observed data across different treatment combinations during 2014–15. The respective range during 2015–16 was 1.44–1.69 kg m^{-3} for the simulated CWP and 1.40–1.65 kg m^{-3} for the observed CWP.

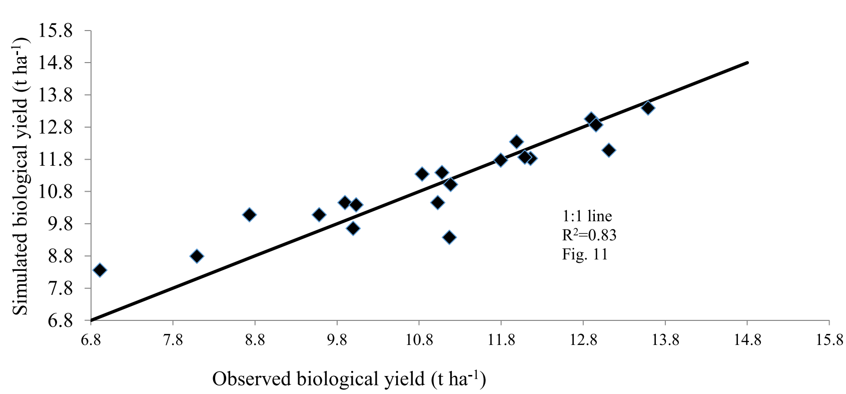

Fig. 11. Regression analysis (1:1 line) between simulated and observed biological yield for the year 2014–15.

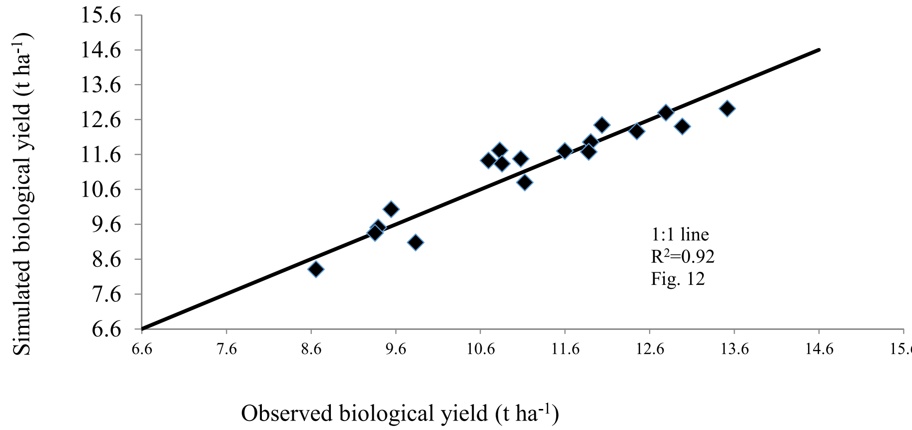

Fig. 12. Regression analysis (1:1 line) between simulated and observed biological yield for the year 2015–16.

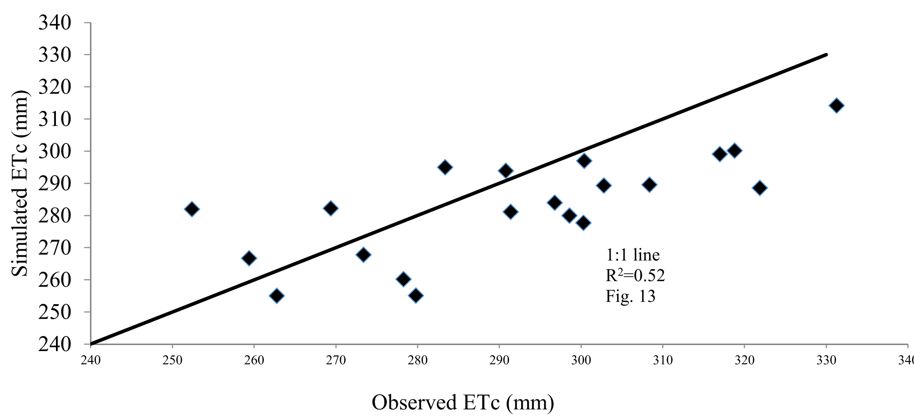

Fig. 13. Regression analysis (1:1 line) between simulated and observed crop evapotranspiration for the year 2014–15.

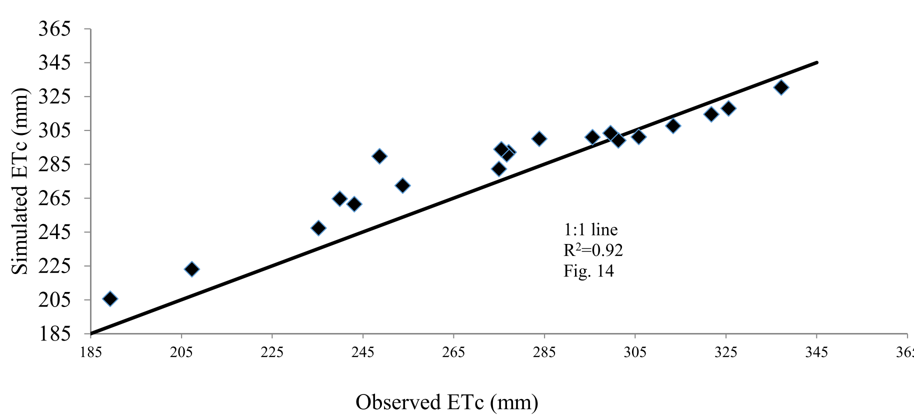

Fig. 14. Regression analysis (1:1 line) between simulated and observed crop evapotranspiration for the year 2015–16.

4. Discussion

The mean number of days taken to anthesis across different sowing dates and irrigation treatments was 104.0 and 103.5 days after sowing (DAS) for the simulated data and 103.3 and 104.3 DAS for the observed data (Table 3) with a standard deviation (SD) of 9.2 and 7.3 days (d) and coefficient of variation (CV) of 8.8 and 7.1% for the simulated and observed days to anthesis during 2014–15. During, 2015–16, the SD was 9.7 and 7.0 d, and CV was 9.4 and 6.7%, respectively for the simulated and observed data. The model performance was found to be good in simulating the days to anthesis as revealed by high correlation coefficient, r (0.94 and 0.93) and low RMSE (3.40 and 4.10 d), nRMSE (3.3 and 3.9%), MAE (2.70 and 3.50 d), MBE (0.70 and −0.75 d) and MAPE (2.60 and 3.4%) during 2014–15 and 2015–16, respectively, between the simulated and observed days taken to anthesis (Table 3). Also, a good line of fit (1:1) was found between the simulated and observed days taken to anthesis with R^2 of 0.88 and 0.86 during 2014–15 and 2015–16, respectively (Figs. 3 and 4). Similarly, the mean number of days taken to maturity across differ-

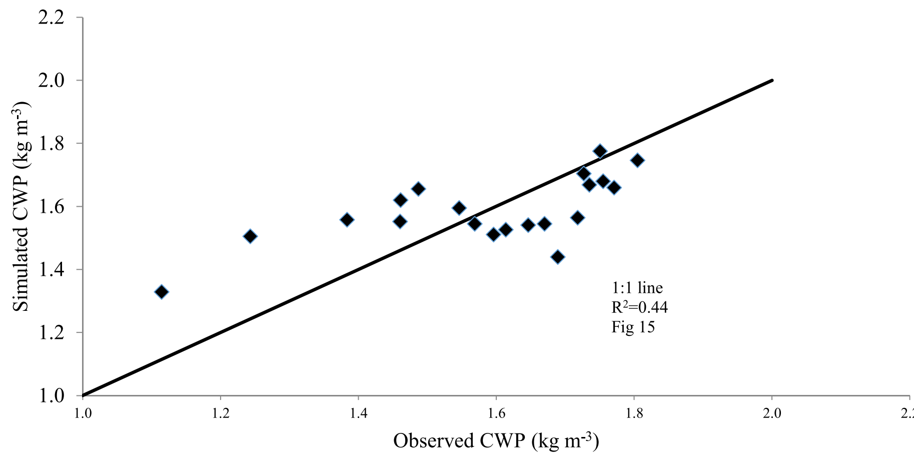

Fig. 15. Regression analysis (1:1 line) between simulated and observed crop water productivity for the year 2014–15.

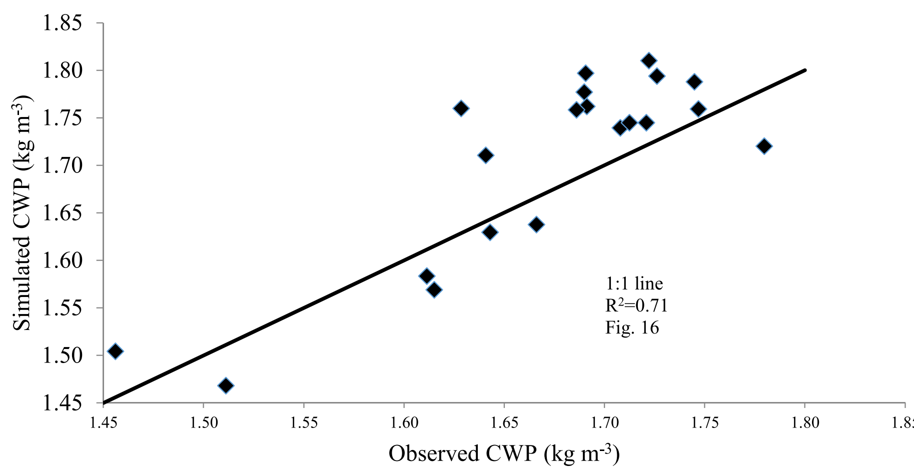

Fig. 16. Regression analysis (1:1 line) between simulated and observed crop water productivity for the year 2015–16.

ent sowing dates and irrigation treatments was 146.3 and 143.0 days after sowing (DAS) for the simulated data and 144.4 and 145.3 DAS for the observed data (Table 3) with a standard deviation (SD) of 11.6 and 13.4 days (d) and coefficient of variation (CV) of 7.9 and 9.3% for the simulated and observed days to maturity during 2014–15. During, 2015–16, the SD was 11.9 and 12.8 d, and CV was 8.4 and 8.8%, respectively for the simulated and observed data. The model performance was found to be good in simulating the days to maturity as revealed by high correlation coefficient, r (98 and 0.98) and low RMSE (3.7 and 3.3 d), nRMSE (2.6 and 2.3%), MAE (3.0 and 2.7 d), MBE (1.9 and −2.3 d) and MAPE (2.1 and 1.8%) during 2014–15 and 2015–16, respectively, between the simulated and observed days taken to maturity (Table 3). Also, a good line of fit (1:1) was found between the simulated and

Table 3
Performance of DSSAT CSM CERES-Wheat model (V4.6) for simulating phenology, yield and water use of wheat during 2014–15 and 2015–16.

Parameters*	Simulated			Observed			Simulated vs Observed					
	Mean	SD	CV (%)	Mean	SD	CV (%)	r	RMSE	nRMSE (%)	MAE	MBE	MAPE (%)
2014–15												
Anthesis (DAS)	104.00	9.18	8.82	103.30	7.33	7.09	0.94	3.40	3.30	2.70	0.70	2.60
Maturity (DAS)	146.25	11.59	7.93	144.35	13.43	9.30	0.98	3.70	2.60	3.00	1.90	2.10
LAI	4.10	0.69	17.00	3.80	0.74	19.30	0.82	0.47	12.40	0.40	0.30	11.70
Grain yield (kg ha^{-1})	4481.1	675.3	15.10	4663.5	822.8	17.60	0.87	489.70	10.50	445.60	−182.40	10.00
Biological yield (kg ha^{-1})	11030.2	1569.3	14.20	10958.1	1752.0	16.00	0.91	726.30	6.60	549.80	72.10	5.60
ETc (mm)	282.90	19.40	6.80	291.90	21.90	7.50	0.72	17.30	5.90	15.40	−8.90	5.30
CWP (kg m^{-3})	1.59	0.10	9.30	1.60	0.19	11.70	0.66	0.14	8.80	0.12	−0.11	7.74
2015–16												
Anthesis (DAS)	103.50	9.69	9.36	104.25	6.98	6.70	0.93	4.10	3.90	3.50	−0.75	3.40
Maturity (DAS)	143.00	11.94	8.35	145.30	12.83	8.83	0.98	3.30	2.30	2.70	−2.30	1.80
LAI	4.100	0.83	20.20	3.90	0.70	17.90	0.90	0.43	11.00	0.40	0.22	10.20
Grain yield (kg ha^{-1})	4867.6	787.8	16.20	4623.2	845.3	18.30	0.96	351.50	7.60	297.80	244.40	6.92
Biological yield (kg ha^{-1})	10634.5	1935.7	18.20	10755.5	1779.0	16.50	0.96	650.70	6.00	486.80	−121.10	5.20
ETc (mm)	284.90	35.60	12.50	275.30	39.60	14.40	0.96	15.80	5.70	13.10	9.60	5.20
CWP (kg m^{-3})	1.700	0.090	5.36	1.68	0.08	4.70	0.84	0.06	3.60	0.10	0.03	3.30

* SD = standard deviation, CV = coefficient of variation, r = Correlation coefficient, RMSE = Root mean square error, nRMSE = Normalized root mean square error (%), MAE = Mean absolute error, MBE = Mean bias error and MAPE = Mean absolute percentage error (%).

observed days taken to maturity with R^2 of 0.95 and 0.97 during 2014–15 and 2015–16, respectively (Figs. 5 and 6). The mean LAI across different treatments was 4.1 and 4.1 for the simulated data and 3.8 and 3.9 for the observed data during 2014–15 and 2015–16, respectively (Table 3). The standard deviation (SD) of 0.69 and 0.74 and coefficient of variation (CV) of 17.0 and 19.3% was found for the simulated and observed LAI during 2014–15. During, 2015–16, the SD was 0.83 and 0.70 and CV was 20.2 and 17.9%, respectively for the simulated and observed data. The model performance was found to be good in simulating the leaf area index as revealed by high correlation coefficient, r (0.82 and 0.90) and low RMSE (0.47 and 0.43), nRMSE (12.4 and 11.0%), MAE (0.40 and 0.40), MBE (0.30 and 0.22) and MAPE (11.7 and 10.2%) during 2014–15 and 2015–16, respectively, between the simulated and observed data (Table 3). Also, a good line of fit (1:1) was found between the simulated and observed LAI with R^2 of 0.72 and 0.79 during 2014–15 and 2015–16, respectively (Figs. 7 and 8). The variation between simulated and observed days to anthesis and maturity has been quoted by several researchers viz., Andarzian et al., (2015) reported RMSE of 3.5 and 3.0 days for time to anthesis and maturity as compared to observed data. Similarly, Timsina et al., (1995) reported that the time to anthesis and maturity was over estimated by the model with an RMSE of 8.6 and 8.7 days, respectively, for variety RR21 and HD2009 at Pantnagar. While Hundal ad Kaur (1997) reported RMSE of 4.0 and 3.8 days between simulated and observed days to anthesis and maturity. Arora et al., (2007) reported RMSE of 0.1, 0.5, 0.9 between simulated and observed LAI for different sampling dates.

The mean grain yield across different treatments was 4481 and 4868 kg ha^{-1} for the simulated data and 4664 and 4623 kg ha^{-1} for the observed data (Table 3) with a standard deviation (SD) of 675 and 823 kg and coefficient of variation (CV) of 15.1 and 17.6% for the simulated and observed grain yield during 2014–15. During, 2015–16, the SD was 788 and 845 kg and CV was 16.2 and 18.3%, respectively, for the simulated and observed grain yield. The model performance was found to be good in simulating the grain yield as indicated by high correlation coefficient, r = 0.87 and 0.96 and low RMSE (490 and 352 kg), nRMSE (10.5 and 7.6%), MAE (446 and 230 kg), MBE (−182.4 and 244.4 kg) and MAPE (10.0 and 6.9%) during 2014–15 and 2015–16, respectively, between the simulated and observed data (Table 3). Also, a good line of fit (1:1) was found between the simulated and observed grain yield with R^2 of 0.75 and 0.92 during 2014–15 and 2015–16, respectively (Figs. 9 and 10). The grain yield in higher moisture regimes was better simulated as compared to lower irrigation regimes because the model was calibrated for the favourable growing conditions. The simulated and observed grain yield was higher when sowing was done on 25th October, with irrigation applied at 15% depletion from field capacity as compared to all other sowing date and irrigation treatment combinations. Thus it can be concluded that delayed planting reduces the grain yield of wheat, particularly under deficit irrigation regimes (Figs. 9 and 10). The mean biological yield across different treatments was 11,030 and 10635 kg ha^{-1} for the simulated data and 10,958 and 10756 kg ha^{-1} for the observed data (Table 3) with a standard deviation (SD) of 1569 and 1752 kg and coefficient of variation (CV) of 14.2 and 16.0% for the simulated and observed biological yield during 2014–15. During, 2015–16, the SD was 1936 and 1779 and CV was 18.2 and 16.5%, respectively, for the simulated and observed data. The model performance was found to be good in simulating the grain yield as revealed by high correlation coefficient, r = 0.91 and 0.96 and low RMSE (726 and 651 kg), nRMSE (6.6 and 6.0%), MAE (550 and 487 kg), MBE (72 and −121 kg) and MAPE (5.6 and 5.2%) during 2014–15 and 2015–16, respectively, between the simulated and observed data (Table 3). Also, a good line of fit (1:1) was found between the simulated and observed biological yield with R^2 of 0.83 and 0.92 during 2014–15 and 2015–16, respectively (Figs. 11 and 12). The biological yield in higher moisture regimes was better simulated as compared to lower irrigation regimes because the model was calibrated for the favourable growing conditions. Andarzian et al., (2015) reported RMSE of 580 and 470 kg ha^{-1} between simulated and observed grain and biological yield as compared to observed data. While, Timsina et al., (1995), Hundal and Kaur (1997), Heng et al., (2000), Nain et al., (2002) and Godwin et al., (2002) reported RMSE of 270, 310, 370, 80 and 80 kg ha^{-1}, respectively, between simulated and observed grain yield. Similarly, Hundal and Kaur (1997) and Heng et al., (2000) reported RMSE of 1110 and 1500 kg ha^{-1} between simulated and observed biological yield.

The mean ETc across different treatments was 283 and 285 mm for the simulated data and 292 and 275 mm for the observed data (Table 3) with a standard deviation (SD) of 19.4 and 21.9 mm and coefficient of variation (CV) of 6.8 and 7.5% for the simulated and observed ETc during 2014–15. During, 2015–16, the SD was 35.6 and 39.6 mm and CV was 12.5 and 14.4%, respectively, for the simulated and observed data. The model performance was found to be good in simulating the ETc as revealed by high correlation coefficient, r = 0.72 and 0.96 and low RMSE (5.9 and 5.7 mm), nRMSE (5.9 and 5.7%), MAE (15.4 and 13.1 mm), MBE (- 8.9 and 9.6 mm) and MAPE (5.3 and 5.2%) during 2014–15 and 2015–16, respectively, between the simulated and observed data (Table 3). Also, a good line of fit (1:1) was found between the simulated and observed ETc with R^2 of 0.92 (Fig. 13) during 2015–16, but R^2 was less (0.52) during 2014–15 (Fig. 14), due to wide variations in precipitation during the two crop seasons.

The mean CWP across different treatments was 1.59 and 1.70 kg m^{-3} for the simulated data and 1.60 and 1.68 kg m^{-3} for the observed data (Table 3) with a standard deviation (SD) of 0.10 and 0.19 kg m^{-3} and coefficient of variation (CV) of 9.3 and 11.7% for the simulated and observed CWP during 2014–15. During, 2015–16, the SD was 0.09 and 0.08 kg m^{-3} and CV was 5.4 and 4.7%, respectively, for the simulated and observed data. The model performance was found to be good in simulating the CWP as revealed by high correlation coefficient, r (0.66 and 0.84) and low RMSE (0.14 and 0.06 kg m^{-3}), nRMSE (8.8 and 3.6%), MAE (0.12 and 0.10 kg m^{-3}), MBE (-0.11 and 0.03 kg m^{-3}) and MAPE (7.74 and 3.30%) during 2014–15 and 2015–16, respectively, between the simulated and observed CWP (Figs. 15 and 16. Also, a good line of fit (1:1) was found between the simulated and observed ETc with R^2 of 0.71 (Fig. 15) during 2015–16, but R^2 was less (0.44) during 2014–15 (Fig. 16), due to wide variations in simulated and observed ETc. Arora et al., (2007) also reported that simulated water loss has a good correspondence with the measured water loss. The range of simulated ETc was 241–332 mm and 221–316 mm for 6th Nov and 3rd Dec sowing, respectively. The respective range of observed ETc was 228–331 mm and 227–261 mm.

5. Conclusion

The simulated (5.6 t ha^{-1}) and observed grain yield (6.0 t ha^{-1}) was higher when sowing was done on 25th October, with irrigation applied at 15% depletion from field capacity. It was further revealed that model performed well in simulating the days to anthesis, maturity, LAI, grain yield and crop evapotranspiration. Although, there were some over and under estimations, but the error was within the acceptable limits (±10%). Thus the latest version (V4.6) of DSSAT-CSM-CERES-Wheat can be reasonably used as valuable option for optimising planting dates and irrigation schedules across North-west, India.

Declaration of Interest

There is no conflict of interest and all the authors have significantly contributed in the overall manuscript preparation.

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