Journal of the Saudi Society of Agricultural Sciences (2015) **14**, 189–199

King Saud University
Journal of the Saudi Society of Agricultural Sciences
www.ksu.edu.sa
www.sciencedirect.com

FULL LENGTH ARTICLE

Determining optimum sowing date of wheat using CSM-CERES-Wheat model

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Received 2 February 2014; revised 28 April 2014; accepted 28 April 2014
Available online 9 May 2014

KEYWORDS
CSM-CERES-Wheat;
Sowing date;
Sowing window;
Crop modeling;
Wheat

Abstract Wheat production in the south of Khuzestan, Iran is constrained by heat stress for late sowing dates. For optimization of yield, sowing at the appropriate time to fit the cultivar maturity length and growing season is critical. Crop models could be used to determine optimum sowing window for a locality. The objectives of this study were to evaluate the Cropping System Model (CSM)-CERES-Wheat for its ability to simulate growth, development, grain yield of wheat in the tropical regions of Iran, and to study the impact of different sowing dates on wheat performance. The genetic coefficients of cultivar Chamran were calibrated for the CSM-CERES-Wheat model and crop model performance was evaluated with experimental data. Wheat cultivar Chamran was sown on different dates, ranging from 5 November to 9 January during 5 years of field experiments that were conducted in the Khuzestan province, Iran, under full and deficit irrigation conditions. The model was run for 8 sowing dates starting on 25 October and repeated every 10 days until 5 January using long-term historical weather data from the Ahvaz, Behbehan, Dezful and Izeh locations. The seasonal analysis program of DSSAT was used to determine the optimum sowing window for different locations as well. Evaluation with the experimental data showed that performance of the model was reasonable as indicated by fairly accurate simulation of crop phenology, biomass accumulation and grain yield against measured data. The normalized RMSE were 3%, 2%, 11.8%, and 3.4% for anthesis date, maturity date, grain yield and biomass, respectively. Optimum sowing window was different among locations. It was opened and closed on 5 November and 5 December for Ahvaz; 5 November and 15 December for Behbehan and Dezful;and 1 November

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Peer review under responsibility of King Saud University.

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http://dx.doi.org/10.1016/j.jssas.2014.04.004

and 15 December for Izeh, respectively. CERES-Wheat model could be used as a tool to evaluate the effect of sowing date on wheat performance in Khuzestan conditions. Further model evaluations might also be needed for other cultivars which are released for this region.

1. Introduction

The Khuzestan province is one of the most important regions for wheat (*Triticum aestivum* L.) production in Iran. Wheat is cultivated on an area of approximately 700,000 ha in this province alone (Andarzian et al., 2007). Major constraints to wheat grain yield in this region are inadequate rainfall and high temperatures during grain filling at the end of the season (Radmehr et al., 2003; Andarzian et al., 2008). The choice of sowing date is an important management option to optimize grain yield in such an environment (Gomez-Macpherson and Richards, 1995; Radmehr et al., 2003; Turner, 2004). Numerous publications (Anderson and Smith, 1990; Connor et al., 1992; Owiss et al., 1999; Bassu et al., 2009; Bannayan et al., 2013) have reported an increased yield with early sowing and a reduction in yield when sowing is delayed after the optimum time. These authors reported an advantage of early sowing dates when combined with cultivars that avoid frost risk at anthesis or in regions or seasons with low frost risk, aiming at high above-ground biomass at flowering to maximize radiation interception. The delay in sowing date not only affects yield, but it affects the yield components and other aspects of the growth and development of wheat. It is generally associated with a reduced kernel weight (Jessop and Ivins, 1970; Radmehr et al., 2003), a reduced number of spikes per plant and per unit area (Spiertz et al., 1971; Stapper and Fischer, 1990), harvest index, grain number per spike, and leaf area index (Jessop and Ivins, 1970). Accurate knowledge of the sowing window of any particular variety at a particular location is critical to achieve a high grain yield (Ortiz-Monasterio et al., 1994).

In general, all reported studies for determining sowing date recommendations have been based on local field experiments that have been done periodically but for a limited number of years, and locations, and the final recommendations are extrapolated to other environments. However the response of wheat to sowing date depends on seasonal weather variability and varies a great deal across years and locations. Therefore, extrapolating the results obtained from a limited number of environments is not only difficult but may be misleading (Simane et al., 1994; Savin et al., 1995; Andarzian et al., 2008; Timsina et al., 2008). In this context, cropping system simulation models that have been evaluated with local experimental data can be valuable tools for extrapolating the short-duration field experimental results to other years and other locations (Mathews et al., 2002).

Crop simulation models integrate the interdisciplinary knowledge gained through experimentation and technological innovations in the fields of biological, physical, and chemical science relating to agricultural production system (Bannayan et al., 2007; Soler et al., 2007; Andarzian et al., 2008). Therefore, these models can increase understanding and management of the agricultural system in a holistic way. Crop simulation models have been used to investigate the performance of different cultivars at a range of sowing dates in relation to different soil-climate scenarios (Stapper and Harris, 1989; Precetti and Hollington, 1997; Ghaffari et al., 2001; Bannayan et al., 2003; Heng et al., 2007; Bassu et al., 2009). The Decision Support System for Agrotechnology Transfer (DSSAT4.5) is a comprehensive decision support system (Tsuji et al., 1998; Hoogenboom et al., 2010) that includes the Cropping System Model (CSM)-CERES-Wheat model (Ritchie and Otter-Nacke, 1985; Ritchie et al., 1998). The CSM-CERES-Wheat model can be used to simulate the growth and development of dryland and irrigated wheat across a range of latitudes in northern and southern hemispheres (Jones et al., 2003; Nain and Kersebaum, 2007; Hoogenboom et al., 2010). The model has been evaluated and applied to a range of tropical (Timsina et al., 1995), subtropical (Hundal and Kaur, 1997; Heng et al., 2000) and temperate environments in Asia (Timsina and Humphreys, 2006; Zhang et al., 2013).

The overall goal of this study was specific objectives that included (1) to evaluate the performance of the CSM-CERES-Wheat model for simulating growth, development, and yield of wheat (2) to apply the CSM-CERES-Wheat model to determine optimum sowing dates on wheat yield under irrigated conditions in Khuzestan, Iran region.

2. Materials and methods

2.1. Field experiments

For evaluation of the CSM-CERES-Wheat model, data were obtained from experiments that were conducted at the Ahvaz Agricultural Research Institute Farm, Khuzestan, Iran (31°21′ N, 48°8′ E, 20 m) for five cropping seasons including, 1998–99; 1999–2000; 2000–2001 (Radmehr et al., 2003), 2003–2004; 2004–2005 (Andarzian et al., 2007). In these experiments a spring bread wheat cultivar Chamran was sown on November 5, December 5 and January 9 for 1998–99 through 2000–2001 and November 22 and December 15 for the 2003–2004 and 2004–2005 cropping seasons. In all the experiments, each plot was comprised of 12 rows, 0.2 m apart and 12 m long with a seeding rate of 400 seeds m^{-2}. Each time when 50% of the available soil water content had been lost, an average of 100 mm of water was applied. The nutrient requirements were determined based on soil analysis and were adequately met by fertilizer applications. Nutrients were applied before sowing and nitrogen was also applied as topdressing at the start of the stem elongation stage. Weeds were effectively controlled using herbicides, and almost no pests or disease infestations were observed during the actual growing seasons.

2.2. Weather and soil data

In order to determine optimum sowing dates for the Khuzestan province, we selected four locations which are representatives of different climate conditions in the region (Fig. 1). As such weather stations of Ahvaz, Behbehan, Dezful and Izeh were selected. Some specifications of these stations were illustrated in Table 1. Daily maximum and minimum air temperature, rainfall, and solar radiation data were obtained from the aforementioned weather stations (Table 1). The same soil (dominant soil in the region) was used for simulation experiments. This soil was classified as a fine carbonic hypothermic (Table 2). The parameters that were determined included soil texture, bulk density, and soil chemistry.

2.3. Model description

The CSM-CERES-Wheat, a part of DSSAT-Cropping System Model V4.5 (Hoogenboom et al., 2010), was used in this study. The model has been documented extensively since its initial development and evaluation (Ritchie and Otter-Nacke, 1985; Ritchie et al., 1998). It simulates the effects of weather, genotype, soil properties, and management on wheat growth and development, yield and soil and plant water and nitrogen dynamics.

The crop growth model considers phasic development with nine growth stages, from pre-sowing to harvest, in relation to thermal time. The model calculates biomass accumulation as the product of radiation use efficiency and photo-synthetically active intercepted radiation. The number of growing leaves is a function of leaf appearance rate (phyllochron interval, degree-days) and duration of grain filling (P5). Organ extension depends on potential organ growth, and is limited by suboptimal temperature and water and nitrogen stresses. Portioning coefficients of dry biomass in plant parts are influenced by phasic development. Grain yield is modeled as a product of grain number (G1), plant population, and grain mass at physiological maturity (G2).

Daily soil water balance is modeled in relation to rainfall/irrigation, runoff, infiltration, transpiration, and drainage from the soil profile. The model utilizes the lower and upper limit of plant extractable to apportion infiltrated water among different soil layers by a simple cascading approach. Runoff is estimated on the basis of antecedent soil water content, and drainage is controlled by the slowest draining layer of the soil profile. Runoff from rainfall is computed using soil conservation service (SCS) curve number (CN) method, and the excess water infiltrates into the soil profile. Within a horizon, each layer has a characteristic drained upper limit (DUL), a lower limit of plant extractable soil water (LL), and saturated water content (SAT). Water flow among soil layers is based on the assumption that if a layer has water content greater than DUL, saturated downward flow occurs in proportion to amount of water greater than the DUL level. If a layer has water content between LL and DUL, unsaturated upward flow between two adjacent layers occurs that is computed using soil water diffusivity and water content gradients. In the lower soil layer, drainage of excess water occurs, and is not available for later extraction. Potential evapotranspiration (ET_m) is partitioned between soil and plan surfaces using a leaf area index-based cover factor. Actual soil evaporation (E) is estimated by the two-stage model (Ritchie, 1972). Root distribution and extractable water in a soil layer modifies potential transpiration (T). Soil water deficit influences the allocation of biomass and growth and death of plant parts (Ritchie et al., 1998).

The nitrogen component of the model includes mineralization and immobilization associated with the decomposition of organic matter, transformation processes of nitrification, de-nitrification, and urea hydrolysis, movement through leaching of nitrates, and uptake of nitrogen (Godwin and Singh, 1998). This model uses the layer-wise soil water balance briefed

Table 1 Climatological characteristics during wheat growing season for the selected locations.

Location	Longitude	Latitude	Elevation (m)	T_{max} (°C)	T_{min}(°C)	Total annual rainfall (mm)	Number of study years
Ahvaz	48° 4′ E	31° 12′ N	23	23.5	11.3	213	30
Behbehan	50° 14′ E	30° 36′ N	313	23.2	10.2	330	14
Dezful	48° 25′ E	32° 16′ N	83	22.8	9.2	348	18
Izeh	49° 52′ E	30° 50′ N	827	19	7.6	599	17

T_{max}: annually average of maximum temperature; T_{min}: annually average of minimum temperature.

Table 2 Soil properties for experiments conducted in Ahvaz and used in simulation studies.

Soil properties	Depth(cm)			
	0–15	15–30	30–60	60–90
Texture	Silty clay	Silty clay	Clay	Sand clay loam
Sand (%)	17	5	12	57
Silt (%)	43	42	35	16
Clay (%)	40	53	53	27
Bulk density ($g\,cm^{-3}$)	1.4	1.2	1.2	1.5
Field capacity($cm^3\,cm^{-3}$)	0.39	0.44	0.44	0.26
Permanent Wilting point ($cm^3\,cm^{-3}$)	0.25	0.31	0.31	0.16
Saturated Soil Water Content ($cm^3\,cm^{-3}$)	0.48	0.53	0.52	0.40
Saturated Hydraulic conductivity($cm\,h^{-1}$)	0.21	0.18	0.12	0.63
Organic carbon (%)	0.94	0.50	0.38	0.16
pH	7.2	8	8.2	8.3
EC($dS\,m^{-1}$)	4.5	3.5	2.3	2

above. Nitrates and urea movement in the soil profile are dependent on water movement. The nitrogen uptake is controlled by crop demand for nitrogen and soil supply of nitrogen and the lesser of the two is used to compute the actual rate. Effects of water and nitrogen deficits on crop and growth and development are taken into account by computing water and nitrogen stresses factors, and the lesser of the two controlling a given process.

2.4. Evaluation of the CSM-CERES-Wheat model

The growth and development modules of the CERES model use different sets of species, ecotype and cultivar coefficients (P1V, P1D, P5, G1, G2, G3 and PHINT (Table 3), which define the phenology and crop growth in time domain. The CSM-CERES-Wheat model was calibrated for Chamran cultivar with data obtained from the experiments of 1998–1999 cropping year (Radmehr et al., 2003) and evaluated with data obtained from experiments of 1999–2001 and 2003–2005 cropping years (Radmehr et al., 2003; Andarzian et al., 2007). For calibration, the cultivar coefficients were obtained sequentially, starting with the phenological development parameters related to flowering and maturity dates (P1V, P1D, P5 and PHINT) followed by the crop growth parameters related with kernel filling rate and kernel numbers per plant (G1, G2 and G3), (Hunt and Boot, 1998; Hunt et al., 1993). However, for better model calibration some parameters of ecotype and species files were adjusted. The trial and error method was used to determine genetic coefficients manually (Godwin and Singh, 1998). These parameters values were adjusted to minimize root mean square error (RMSE) between simulated and measured data. A detailed description of the cultivar coefficients used by CSM-CERES-Wheat model is presented in Table 3. For calibration and evaluation, the simulated dates of anthesis and physiological maturity as well as yield and yield components were compared with the observed data. Different statistic indices were employed, including Coefficient of Determination (r^2), Regression 1:1, absolute and normalized Root Mean Square Error (RMSE), and index of agreement (d-index). The RMSE expressed in percent, calculated according to Loague and Green (1991) with Eq. (2).

Absolute RMSE equation is:

$$RMSE = \left[\sum_{i=1}^{n} \frac{(P_i - O_i)^2}{n}\right]^{0.5} \tag{1}$$

$$RMSE = \left[\sum_{i=1}^{n} \frac{(P_i - O_i)^2}{n}\right]^{0.5} \times \frac{100}{M} \tag{2}$$

where P_i and O_i refer to simulated and observed values for the studied variables, respectively, e.g., days from sowing to anthesis, days from anthesis to physiological maturity, leaf area index (LAI), biomass, grain yield and yield components. M is the mean of the observed variable. Normalized RMSE gives a measure (%) of the relative difference of simulated versus observed data. The simulation is considered excellent with a normalized RMSE is less than 10%, good if the normalized RMSE is greater than 10% and less than 20%, fair if normalized RMSE is greater than 20 and less than 30%, and poor if the normalized RMSE is greater than 30% (Jamieson et al., 1991).

Table 3 Genetic coefficients fitted for cultivar Chamran.

Crop file	Parameter	Calibrated value
Species		
	TRGFW	
	T_{base}	9.5
	T_{opt1}	16
	T_{opt2}	25
	T_{max}	35
Ecotype		
	P1	235
	P2	300
	P3	200
	P4	200
	SLAS	180
	PARUE	4.6
	PARU2	4.6
Genotype		
	P1V	0
	P1D	103
	P5	700
	G1	11
	G2	45
	G3	1
	PHINT	100

TRGFW: temperature response, grain filling, dry weight (°C).
T_{base}: base temperature, below which increase in grain weight is zero.
T_{opt1}: 1 st optimum temperature, at which increase in grain weight is most rapid.
T_{opt2}: 2 nd optimum temperature, highest temperature at which increase in grain weight is still at its maximum.
T_{max}: maximum temperature, at which increase in grain weight is zero.
P1: duration of phase end juvenile to terminal spikelet (GDD, Growing Degree Days).
P2: duration of phase terminal spikelet to end leaf growth (GDD).
P3: duration of phase end leaf growth to end spike growth (GDD).
P4: duration of phase end spike growth to end grain fill lag (GDD).
SLAS: specific leaf area ($cm^2\ g^{-1}$).
PARUE: PAR conversion to dry matter ratio before the last leaf stage ($g\ MJ^{-1}$).
PARU2: PAR conversion to dry matter ratio after the last leaf stage ($g\ MJ^{-1}$).
P1V: Days at optimum vernalizating temperature required to complete vernalization.
P1D: Percentage reduction in development rate in a photoperiod 10 h shorter than the optimum relative that optimum.
P5: Grain filling (excluding lag) period duration (GDD).
G1: Kernel number per unit canopy weight at anthesis (g^{-1}).
G2: Standard kernel size under optimum condition (mg).
G3: Standard non-stressed dry weight (total, including grain) of a single tiller at maturity (g).
PHINT: Phyllochron interval (GDD).

The index of agreement (d) proposed by Willmott et al. (1985) was estimated in (Eq. (3)). According to the d-statistic, the closer the index value is to one, the better the agreement between the two variables that are being compared and vice versa.

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|P'_i| + |O'_i|)^2}\right] \tag{3}$$

where n is the number of observations, P_i the predicted observation, O_i is a measured observation, $P'_i = P_i - M$ and $O'_i = O_i - M$ (M is the mean of the observed variable).

2.5. Model application

An analysis of the effect of different sowing dates on yield and yield components of wheat was conducted using long term historically available daily weather data for each station. 8 different sowing dates were simulated using the seasonal analysis tool of DSSAT Version 4.5 under irrigated conditions. The sowing dates started on 25 October and were repeated every 10 days until 5 January. This period is the regional sowing window, however the early and late sowing dates are not suitable to obtain high grain yields, but due to the limitation of the available water, wheat may be sown early and due to delay in harvesting previous crops such as maize it may be sown at last of the window.

3. Results

3.1. Model calibration

In order to coincidence of simulated and measured developmental stages, leaf area expansion, biomass production, grain yield and yield components of wheat, in addition to the determination of cultivar genetic coefficients, some ecotype and species parameters were adjusted (Table 3). However, most of the published literatures about CERES-wheat model calibration have been focused on determining cultivar genetic coefficients. We found that after determining cultivar genetic coefficients, model well predicted anthesis and physiological maturity dates but there were significant discrepancies between predicted and observed terminal spiklet initiation and flag leaf emergence stages. Therefore, P1, P2, P3 and P4 parameters (Ecotype file) were tuned for coinciding predicted and observed aforementioned stages (Johenen et al., 2012). Taking into consideration climate conditions of the region and cultivar characteristics, adjustment of SLAS and PARUE parameters (Ecotype file) were needed for better simulation of leaf area expansion and biomass production, respectively. Occurrence of high temperatures during grain filling period particularly in late sowing dates is conventional in the region. Under such circumstances, grain weight would be reduced. Hence, for better simulation of grain weight response to temperature TRGF parameter (Species file) was adjusted based on cardinal temperatures of wheat grain filling stage (Porter and Gawith, 1999; Zahedi and Jenner, 2003; Spiertz et al., 2006; Wahid et al., 2007; Farooq et al., 2011).

The best genetic coefficient combination that reduced the difference between simulated and observed data for phenology and grain yield for cultivar Chamran is shown in Table 3. The vernalization coefficient (P1V) was set zero owing to this cultivar is spring-type and has no sensitivity to vernalization (Ritchie, 1991). The P1D and P5 values obtained for cultivar Chamran were 103 and 700 GDD, respectively. The kernel number coefficient (G1), the kernel weight coefficient (G2) and the optimal value for spike number coefficient (G3) for this cultivar were 11 g^{-1}, 45 and 1.5 g, respectively. The phyllochron interval coefficient (PHINT) value for this cultivar was 100 GDD. The simulated and observed values for phenology, grain and biomass yields, and maximum leaf area index (LAI_{max}), after calibration, are presented in Table 4. There was a good agreement between measured and simulated values.

3.2. Model evaluation

The performance of the CSM-CERES-Wheat model was evaluated with independent data sets obtained from experiments of 1999–2001 (Radmehr et al., 2003) and 2003–2005 (Andarzian et al., 2007) cropping years which were not used for model calibration. The variables that were evaluated included crop phenology, biomass, leaf area index (LAI) and grain yield.

3.2.1. Phenological stages

The model was able to predict the anthesis date well as shown in Table 5, and Fig. 2a. The values for RMSE, normalized RMSE, index of agreement (d) and r^2 for anthesis date were 3.5 d (days), 3%, 0.72 and 0.60, respectively. There was, also, a close match between predict and observed physiological maturity dates. The values for RMSE, normalized RMSE, index of agreement (d) and r^2 for physiological maturity date were 3 d (days), 2%, 0.91 and 0.96, respectively. All of the indices imply that there was a good agreement between simulated and measured durations (days, d) from sowing to anthesis and from sowing to physiological maturity stages. Based on these results it can be concluded that the model was very robust in predicting the critical phenological growth stages.

3.2.2. Time-course of LAI and above-ground biomass

Temporal changes in LAI accumulation (Fig. 3) indicate that the correspondence between simulated and measured LAI was very well during the 2003–2004 growing season. The values of statistic indices were RMSE = 1, D-index = 0.89, r^2 = 0.77. Fig. 3 also shows the reasonably very good agreement between simulated and measured above-ground biomass of wheat during the 2003–2004 growing season. The values of statistic indices were RMSE = 0.9 t ha^{-1}, D-index = 0.99, r^2 = 0.99.

There was generally a good agreement between the model predictions and measured biomass data at the end of cropping seasons (Fig. 4a; Table 5). The model simulates biomass values at harvest quite well. The calculated values of statistic indices, RMSE, normalized RMSE, D-index, and r^2 are 0.47 t ha^{-1}, 3.4%, 0.92 and 0.86, respectively.

3.2.3. Grain yield

Grain yield was very well simulated by the CERES-Wheat model. (Fig. 4b; Table 5). The RMSE, normalized RMSE,

Table 4 Calibration results for CERES-wheat model for cultivar Chamran using data of experiment over 1998–1999 cropping years.

Crop trait	Predicted	Observed
Anthesis(DAP)	104	104
Maturity (DAP*)	143	143
Grain yield (t ha^{-1})	5.2	5
Biomass at harvest (t ha^{-1})	16.2	15
LAI_{max}	6.1	5.2

* Day after sowing.

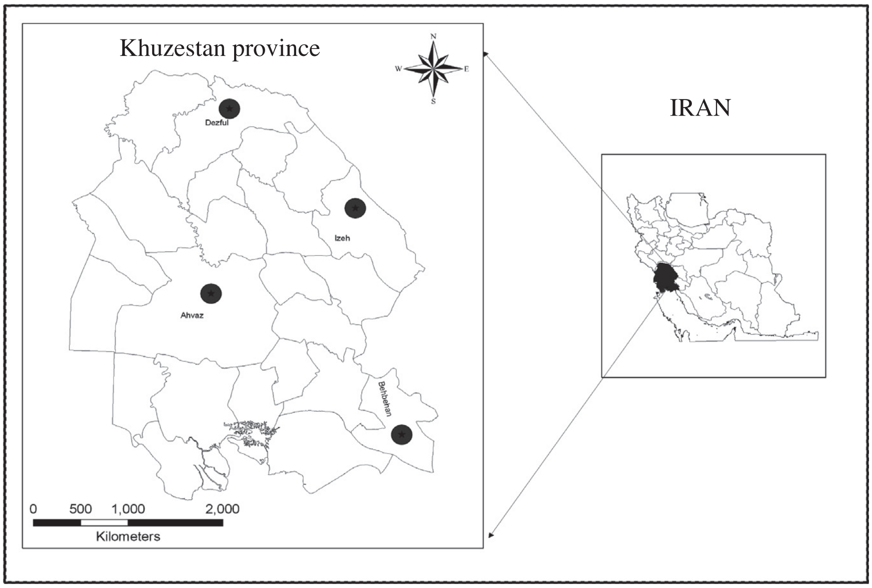

Figure 1 Study locations in Iran.

Table 5 Statistical indices of evaluating the performance of CERES-Wheat model in predicting phenological dates and simulating grain yield and biomass production.

Cropping year	Anthesis (DAP)		Maturity (DAP)		Grain yield (t ha^{-1})		Biomass (t ha^{-1})	
	Predicted	Observed	Predicted	Observed	Simulated	Measured	Simulated	Measured
1999–2000	104	106	137	140	6.1	5.4	15.2	14.6
2000–2001	106	103	128	125	5.8	5.3	15	14.7
2003–2004	112	107	130	128	4.9	4.3	13	13.3
2004–2005	100	102	133	136	5.2	4.7	13.5	12.9
Index								
RMSE (day)[a]	3.5		3		0.58		0.47	
Normal – RMSE (%)[b]	3		2		11.8		3.4	
D-Index[c]	0.72		0.91		0.71		0.92	
r^2(1:1)[d]	0.60		0.96		0.97		0.86	

[a] Root mean square error.
[b] Normalized root mean square error.
[c] Wilmot's index of agreement.
[d] Coefficient of determination for the 1 to 1 line.

d-index, and r^2 were 0.58 t ha^{-1}, 11.8%, 0.71 and 0.97, respectively. Aforementioned indexes imply the robustness of the model in simulating wheat grain yield.

3.3. Model application: determining optimum sowing date of wheat

3.3.1. Ahvaz

In Ahvaz location long-term simulated yield ranged from 3.9 to 7.3 t ha^{-1} depending upon the sowing date. The highest yield was attained through sowing on 15 November and the lowest yield through sowing on 25 October. Considering yield response to sowing date follows a quadratic equation, the simulated yield in early and late sowing dates was lower than that ones in the normal sowing date (Fig. 5). Delay in sowing date from 25 October to 15 November has resulted in an yield increase. On average, the expense of each day delay in sowing date grain yield was increased by 0.169 t ha^{-1}. Grain yield was decreased by a delay in the sowing date from 15 November to 5 January. In this case, due to a delay in sowing date, on average, grain yield was approximately decreased 0.05 t ha^{-1} d^{-1} (5% per week).

3.3.2. Behbehan

Average long-term simulated yield in this location varied from 3.9 to 7.7 t ha^{-1}. Maximum and minimum yields were simulated for 15 November and 25 October sowing dates, respectively (Fig. 5). With a delay in sowing date from 25 October to 15 November, yield was approximately increased by 0.178 t ha^{-1} d^{-1}, whereas, a delay in sowing date from 15 November to 5 January resulted in a yield reduction about 0.046 t ha^{-1} d^{-1} (4% per week).

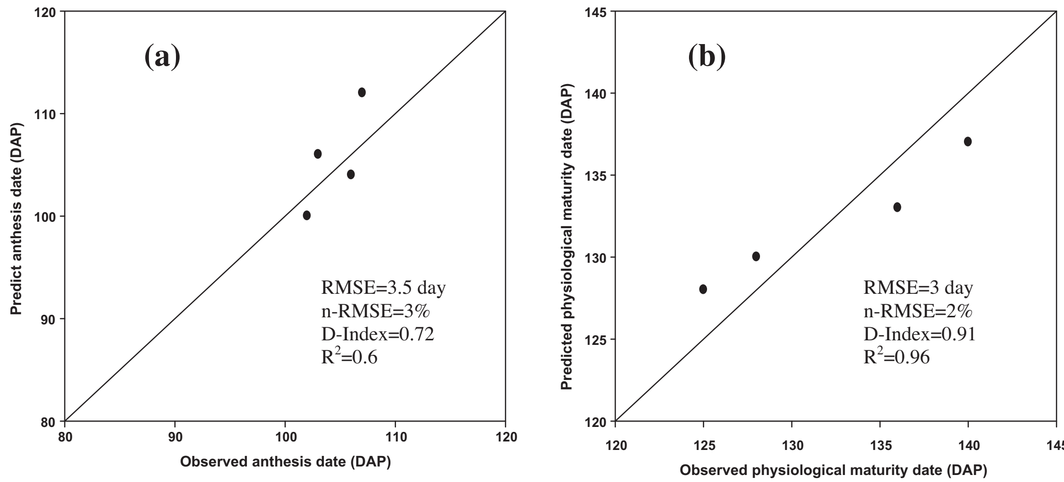

Figure 2 Comparision of predicted and observed days from sowing to anthesis (a) and to maturity (b).

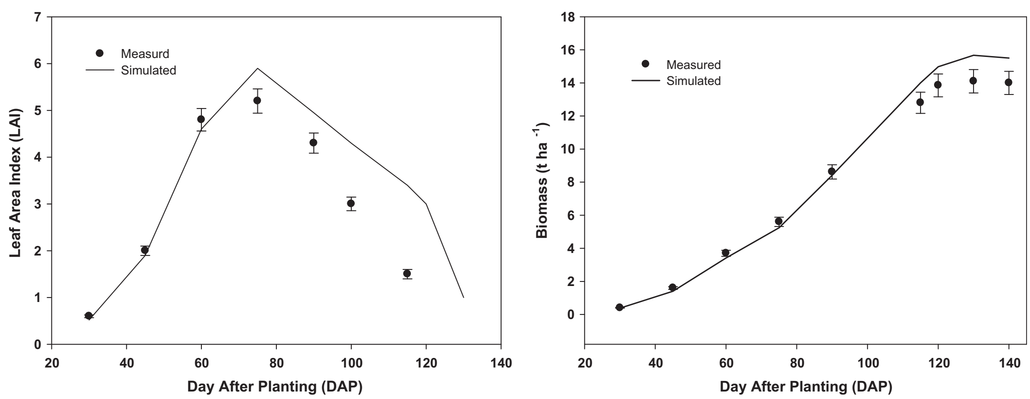

Figure 3 Simulated and measured seasonal leaf area index (LAI) and above-ground biomass of cultivar Chamran sown on 22 November 2003 at Ahvaz.

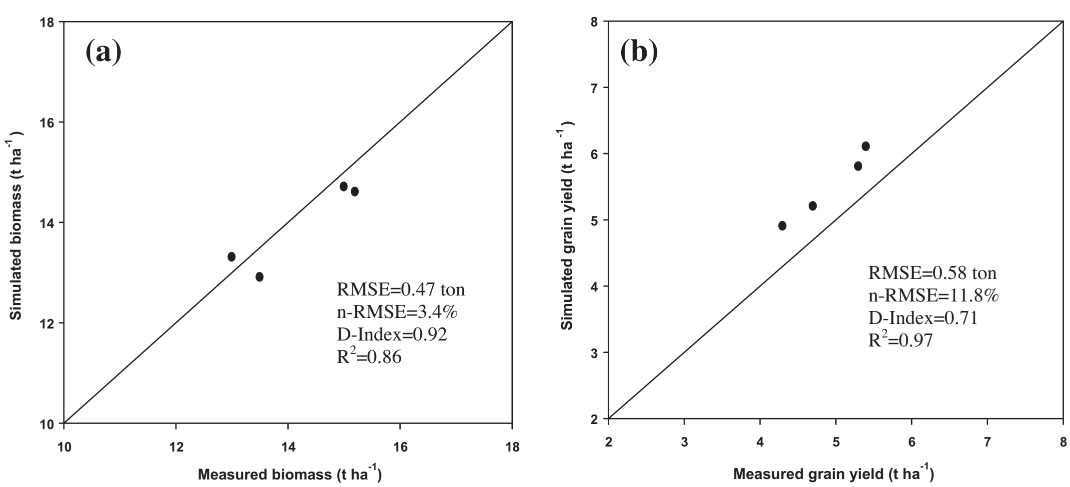

Figure 4 Comparison of simulated and measured biomass production (a) and grain yield (b).

3.3.3. Dezful

In Dezful location, average long-term predicted yield was between 4.9 and 7.9 t ha^{-1} depending on the sowing date (Fig. 5). In this location same as the other ones, the highest and lowest yields were obtained for 15 November and 25 October sowing dates, respectively. Delay in the sowing date from 25 October to 15 November led to an yield increase of about 0.192 t ha^{-1} d^{-1}. In contrast, a delay in sowing date from 15

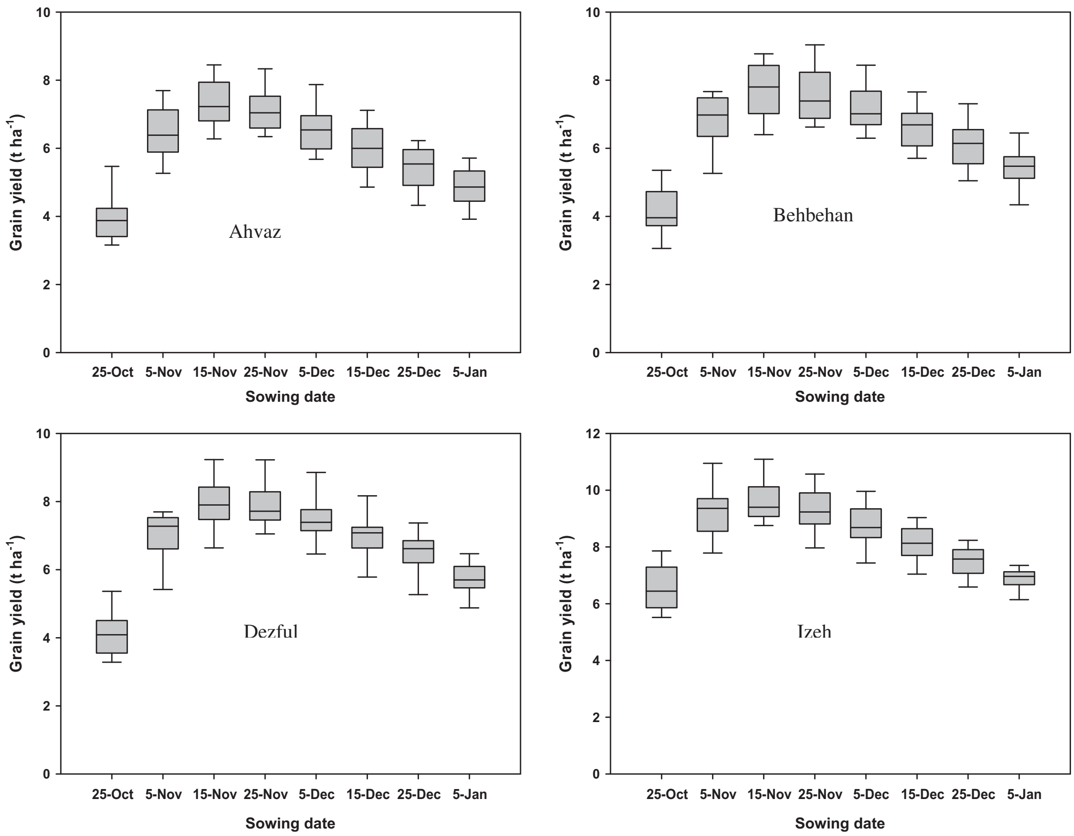

Figure 5 Simulated yield for different sowing dates for Ahvaz, Behbehan, Dezful and Izeh locations.

November to 5 January resulted in a yield decrease of about 0.046 t ha^{-1} d^{-1} (4% per week).

3.3.4. Izeh

Average yield obtained on the basis of long-term historical daily weather data in this location ranged from 6.5 to 9.6 t ha^{-1} depending on the sowing date (Fig. 5). The simulated yield for this location was higher than the other locations. However, same as the other locations the highest and lowest yields were predicted for 15 November and 25 October sowing dates, respectively. Delaying sowing date from 25 October to 15 November resulted in an increase in yield of 0.153 t ha^{-1} d^{-1}, but delaying the sowing date from 15 November to 5 January caused to decreased yield of 0.057 t ha^{-1} d^{-1} (4% per week).

3.3.5. Determining sowing window

Annually yield variability ranged from 10% to 15% of average of long-term yield, approximately near to standard division, for all locations. We assumed that the date on which 85% of the maximum yield could be obtained and located between 25 October and 15 November as the opening sowing window and the date on which 85% of the maximum yield could be obtained and located between 15 November and 5 January as the closing sowing window. For Ahvaz, the sowing window started on 5 November and finished on 5 December, in other words the length of optimum sowing duration was 30 days. Sowing window for Behbehan and Dezful locations was similar. It began on 5 November and ended on 15 December. The length of the optimum sowing window for these two locations was 40 days. For the Izeh location, sowing window commenced on 1 November and closed on 15 December. The length of optimum sowing duration for this location was 45 days.

4. Discussion

Our finding showed that the CERES-Wheat model can be used as a suitable tool to investigate farm management options and to determine the best ones to apply in crop production. The ability of the CERES-Wheat model to predict biomass at harvest in the sub–tropical environment was verified by previous studies (Hundal and Kaur, 1997; Heng et al., 2000; Arora et al., 2007; Timsina et al., 2008; Kumar et al., 2002; Andarzian et al., 2009). Evaluation of CERES-Wheat for grain yield showed reasonable predictive ability of the model in tropical (Arora et al., 2007; Timsina et al., 2008; Andarzian et al., 2009), sub-tropical (Timsina et al., 1995; Hundal and Kaur, 1997; Kaur et al., 2007) and Mediterranean (Dettori et al., 2011) environments.

The results of simulations showed that the yield of early sowing dates (before 15 November) was lower than the yield of normal sowing date (e.g. 15 November) in all locations. It was because of decreasing crop growth cycle particularly the time from sowing to the anthesis stage (Fig. 6). The high temperature in early sowing dates (data not shown) has resulted in accelerating crop development stages, reducing crop canopy (leaves and tillers) and decreasing biomass production which

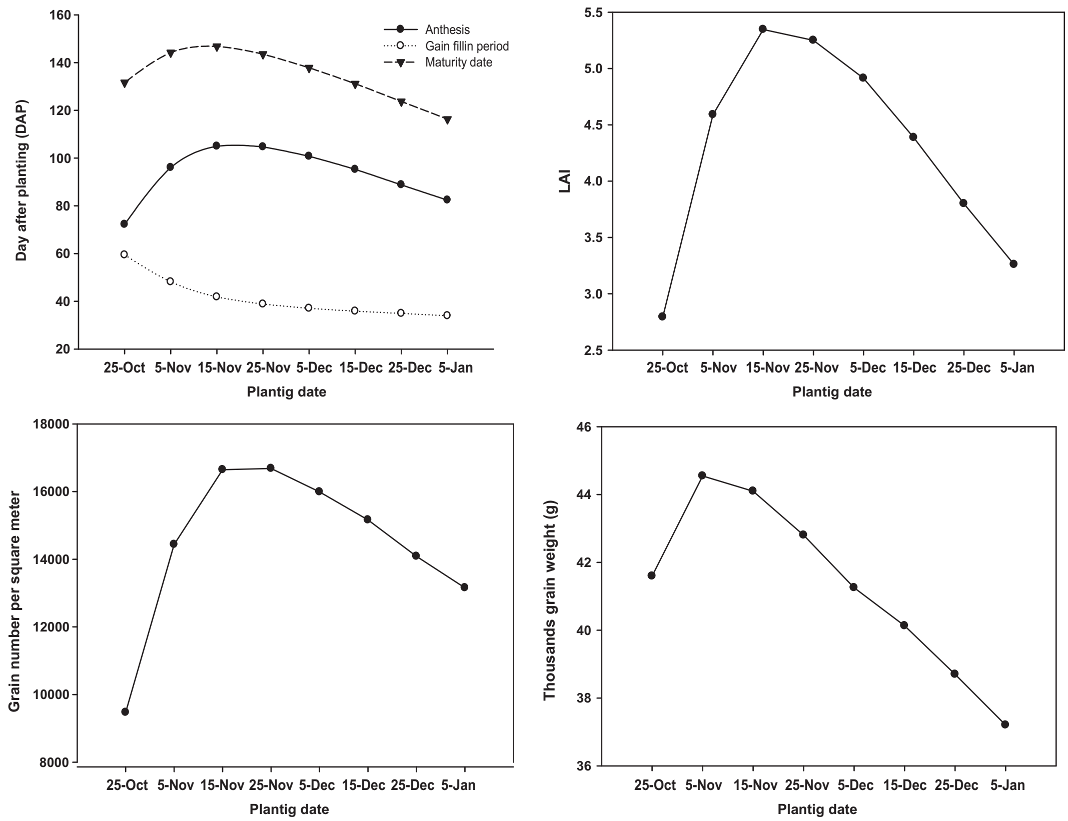

Figure 6 Average simulated anthesis date, maturity date, grain filling period, maximum LAI, seed number per unit area, thousand grain weight of wheat for different sowing dates.

in turn have led to reduce the yield and its components. It has been suggested that decreasing duration of the stem elongation phase (end of tillering to anthesis stages) would result in a lower number of fertile florets (Slafer et al., 2001). The rational was that the number of fertile florets is strongly related to stem dry weight at anthesis (Gonzalez et al., 2003). In spite of the findings of Stapper and Harris (1989), early sowing dates in these locations decrease the interception of solar radiance of a crop and reduce the accumulation of dry matter.

We found that in late sowing dates (beyond 15 November) the length of the time from sowing to anthesis and physiological maturity stages, maximum LAI, the number of grains per square meter, grain weight and harvest index were reduced compared to the normal sowing date (Fig. 6). In all locations, environment temperature usually increases from February to the end of the wheat cropping season. Same as the early sowing date, high temperatures resulted in accelerating crop development and shortening crop growth cycle. Under these circumstances cumulative intercepted solar radiance and biomass production were decreased (Heng et al., 2007; Stapper and Harris, 1989). Delaying the sowing date beyond the optimum sowing date led to reduced grain weight because of the existence of high temperatures during grain filling which decreases the length of the grain filling period as it was simulated by the CERES-Wheat model. This coincides with the findings of Fischer (1975), Sofield et al. (1977), Evans (1978) and Ortiz-Monasterio et al. (1994), who found that the post anthesis temperature was most important in determining grain weight.

5. Conclusions

It can be concluded from the obtained results that the CERES-wheat model was reasonable as indicated by correspondence between simulated crop phenology, biomass accumulation, and grain yields with measured data. The normalized RMSE ranged between 2% and 11.8% for crop parameters which were predicted. The validated CERES-Wheat model was used as a research tool to provide estimates of climatically driven potential yield for different sowing dates in Khuzestan, Iran conditions. The model was run using the seasonal analysis option of the DSSAT software to define the optimum sowing window for wheat in different locations of the Khuzestan province. Optimum sowing window was different among locations. It was opened and closed on 5 November and 5 December for Ahvaz; 5 November and 15 December for Behbehan and Dezful; 1 November and 15 December for Izeh, respectively. The highest grain yields were generally obtained from sowing dates which have suitable equilibrium between anthesis and maturity dates and between grain number and grain weight as well, and maximum LAI is at optimum value. As a result, the simulated optimum sowing window for wheat in this region is between 5 November to 15 December. As such models can be used to drive best management options in proportion with environmental conditions. Further model evaluations might also be needed for other cultivars which are released for this region.

Acknowledgements

We would like to thank Seed and Plant Improvement Institute (SPII), Iran, for providing logistical support during the implementation of trials.

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