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Research Article

Determination of Sowing Window for Wheat in Punjab, India using Sensitized, Calibrated and Validated CERES-Wheat Model

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ABSTRACT

Crop simulation models have been an efficient tool in determining the yield and various crop parameters under the current as well as the future predicted climate scenarios. The CERES-wheat model was sensitized for the cultivar specific parameters (CSPs) of wheat crop which were P1V, P1D, P5, G1, G2, G3 and PHINT using sensitivity index (SI), calibrated and validated for the crop parameters anthesis, maturity, yield and biomass of two common wheat cultivars in the irrigated plains of Punjab that are HD2967 and PBW725. Both mathematical and graphical approaches were used to determine the sensitivity range and this range was further utilized in calibrating the model for the year 2019 while validation was done for the year 2020 using statistical measures.The sensitivity analysis of both the wheat cultivars showed the P1V and P1D CSPs to be the most sensitive while the calibration results depicted similar CSPs with not much difference for the two cultivars. The statistical results depicted strong coefficient of determination (R^2) for anthesis (0.93, 0.90), maturity (0.74, 0.94), yield (0.74, 0.71) and biomass (0.89, 0.75), respectively for HD2967 and PBW725. The normalized root mean square error (NRMSE) was excellent (<10%) for anthesis (3.18%, 4.32%); maturity (2.93%, 2.04%), yield (0.86%, 0.90%) and biomass (10.3%, 9.3%) of HD2967 and PBW725, respectively. All the evaluation measure gave good results thus depicting the model to be accurate for further applications. The simulated sowing window on the basis of the calibrated and validated model was 20th October to 9th December with observed deviation of grain yield from the mean at early sowing (before 20th October) to be -3.86% and delayed sowing (after 9th December) to be -1.94% for HD2967. The wheat cultivar PBW725 observed the grain yield depreciation from the mean by -20.2% at early sowing (before 20th October) and by -6.7% at delayed sowing (after 14th December). Thus, the early and late sowing of these two wheat cultivars in Punjab should be avoided by the farmers while the optimum sowing date *i.e.* 24th November where the peak yield was observed should be used for better crop yield. Further, the calibrated and validated CERES-wheat model can be efficiently applied for analysing the climate change impact on wheat in the Punjab state of India.

Key words: Calibration, Crop simulation modelling, DSSAT CERES-wheat model, Sensitivity index, Validation, Wheat, Punjab, India

Introduction

Rice and wheat are the major cereal crops of India and cereals play an important role in satisfying theglobal food demand in developing nations where the nutrition and calorie intake is possible through cereal-based production system (Nikos *et al.*, 2012; Shiferow *et al.*, 2013). The cereals have been the cheapest source of energy which provides 20%

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protein and 19% calorie intake on consumption. The wheat crop in India occupies an area of 31.6 ha with a production of 109 t/ha (USDA, 2022). The productivity of wheat has shown an increase in Haryana, Punjab and Uttar Pradesh states of India (Farmer Portal, Agricultural Department, Govt. of India; 2020). At the global level, wheat occupies an area of 217 m ha and annual production of 731 m tons (USDA, 2018). India after China is the second most populated country in the world covering 2.4% and 16.9% world area and population, respectively (Census, 2011). Agriculture is the major contributor in Indian economy and the population is increasing at a decadal growth rate of 17.7% (Census, 2011) and this population pressure is leading to a decreased cultivable area. The sustainable growth of Indian economy and its development is dominated by agriculture which fulfils the nutritional requirements of 1.3 billion Indians. Wheat is a staple food of India with major population consuming the same and this has led to increased area since the green revolution from 12.8 m ha (1966-67) to 30.42 m ha (2017-18) and increased production and productivity (Sahu *et al.*, 2020). Wheat is considered as the staple and popular food among vegetarians and non-vegetarians as it is comparatively more nutritive than the other cereal crops. FAO Trade Statistics (2018) reported India as the second largest producer of wheat next to China with 11.5% share and first position in area with 12.4% share. The highest share in production was by Uttar Pradesh (31.92%) and Punjab (17.85%). Wheat crop sowing starts from the early October to the end of December with the heading starting in January and harvesting during March, April and May (Tripathi and Mishra, 2017). The fifth Assessment Report (AR5) establishes the fact of global warming by an explanation on the physical science aspects of climate change by Intergovernmental Panel on Climate Change (IPCC, 2013). The analysis of climate change is complex under highly variable topography, climate, cultivation and management practices.

The reality of climate change has been evidenced by IPCC and the global mean surface temperature is projected to increase in the ranges 1-2 and 1-3.7°C for 2046-65 and 2081-2100, respectively (IPCC, 2013). In the year 2050, high temperatures and variations in rainfall resulted in a decrease in wheat yield by 22% in sub-Saharan Africa (Ringler *et al.*, 2010).The rainfall variations and disrupting rainy season has altered the national crop production by 90 to 95% (Kidane, 2010). The impact of climate change under increased greenhouse gases is easily evaluated and assessed through crop models (White *et al.*, 2011) which are also used as inputs and options for resource management for sustainable agriculture (Aggarwal *et al.*, 2006). Decision Support System for Agrotechnology Transfer (DSSAT) model (Ritchie *et al.*, 1998) works in diverse environment and it includes CERES-wheat which is an easy management tool involving processes that can help simulate the growth, development and yield of wheat. This module of DSSAT involves the collection of experimental data from different field experiments which helps in evaluating the model, generating genetic coefficients, conducting sensitivity analysis and analysing the economic risks and uncertainties involved in taking up the alternative management options (Hoogenboom *et al.*, 2010). The application of CERES-wheat for further purposes is possible with the calibration and validation of the CERES-wheat model for a particular site with certain management inputs (Jones *et al.*, 2010).

Crop models work as an easy simulation tool for evaluating the weather effect, genotype, soil and management effect on growth, development, yield of wheat and the water and nitrogen dynamics of plant. Phasic development from pre-sowing to harvest is considered in the crop growth model and the biomass accumulation is also calculated as the product of radiation use efficiency and photo-synthetically active radiation (Andarzian *et al.*, 2015). The study by Andarzian *et al.* (2015) indicated the simulated and measured data of crop phenology, biomass accumulation and grain yields to be near under calibration while validation indicated the statistical results to be such that the root mean square error (RMSE) for the validated data ranged from 2-11.8% for the predicted crop parameters and this justified the applicability of the models as a further research tool for assessing the climate change impact on different sowing dates in Khuzestan, Iran. The study by Andarzian *et al.* (2015) in different locations of Khuzestan province defined the optimum sowing window of wheat and determined it to be 5 November to 5 December for Ahvaz, 5 November to 15

December for Behbehan and Dezful and 1 November to 15 December for Izeh. A suitable equilibrium between the anthesis and maturity dates, grain number and grain weight and maximum LAI at optimum value resulted in high grain yields. The region of Iran identified 5 November to 15 December as the optimum time of sowing for wheat. A study at Palampur, Himachal Pradesh confirmed the utilization of DSSAT model for yield simulations in the mid hill regions of Himachal Pradesh as during the two years (2015-16 and 2016-17) farm trials the correlation coefficient between observed and simulated grain yield was high (0.76 and 0.85), normalized RMSE was also within limits (9.6 and 8.9%), mean bias error was also low (-0.5 and 77.3 kg) for the respective years (Pathania *et al.*, 2020). A study in Bangladesh (Jahan *et al.*, 2018) showed that in the wheat sown during early season (21 October-10 November) and late season (5 December-20 December), all the growth stages were under the effect of heat stress resulting in yield reduction by 2.89% per day and under late heat stress by 1.28% per day for each day delayed sowing. However, the optimum sowing window of wheat was found to be 15-30 November due to the optimum temperature conditions of 15°C-25°C prevailing in the region during day as well as night times.

Material and Methods

Wheat cultivars and field trials

The study was conducted in the central region of Punjab lying in the trans-gangetic zone of India occupying a latitudinal and longitudinal extent of $30^0$54'N and $75^0$48'E respectively with an altitude of 247m. The simulation study for the two wheat cultivars that are HD2967 and PBW725 (Anonymous, 2021) was performed at the Department of Climate Change and Agricultural Meteorology, Punjab Agricultural University (PAU), Ludhiana, Punjab for the mandatory field trials under "All India Co-ordinated Research Project on Agrometeorology". The considered six sowing dates for both the cultivars wereduring the late October and early, mid and late November for two consecutive years 2019 and 2020 using the recommended package and practices of PAU Ludhiana. The characteristics of wheat cultivars are :

Cultivar character	HD2967	PBW725
Release	2011	2015
Plant height	101 cm	105 cm
Centre	PAU, Ludhiana, India	PAU, Ludhiana, India
Maturity	157 days	154 days
Yield (q/ha)	21.4	22.9
Resistance to the main diseases	Resistance to brown rust while susceptible to new races of yellow rust	Resistance to yellow and brown rust

The input files for crop, soil and weather were extracted as per the model (DSSAT v4.7.5) format and the cultivar specific parameters (CSPs) were also determined on the basis of the crop cultivars.The details of the CSPs used in CERES-wheat models are given in Table 1.

Sensitization of the CERES-Wheat model

The sensitization of the CERES-wheat model for the CSPs was done using Sensitivity Index (Eq. 1) which was calculated as:

$$SI = ((O_2 - O_1)/O_{avg})/((I_2 - I_1)/I_{avg}) \quad \ldots(1)$$

Where, I_2, I_1 and I_{avg} are minimum, maximum and average input values of CSPs while O_2, O_1 and O_{avg} are corresponding output values of crop parameters. Lamsal *et al.* (2012) gave a mathematical and graphical approach towards determining the impact of most sensitive parameter on the growth, yield and duration of crops *i.e.,* sensitivity index.

Calibration and validation of the model

After sensitizing the model, using the 2019-20 crop year data the calibration of the model was undertaken for the two wheat cultivars using GENCALC for all the required crop parameters. The genetic coefficients were adjusted for better simulation results through trial and error method. The iterations were performed till the simulated results by the model were close to that observed on field.

Then using the 2020-21 crop year data the validation of the model was done. The statistical measures involved in the validation process were coefficient of determination (R^2), Root Mean Square

Table 1. Sensitivity index (SI)for Anthesis (ANT), Maturity (MAT), Grain yield (GY) and genetic coefficients of CSPs forwheat cultivars (HD2967 and PBW725)

CSPs	HD2967				Genetic coefficient	PBW725				Genetic coefficient
	ANT	MAT	GY	RANGE		ANT	MAT	GY	RANGE	
P1V	0.19	0.08	0.40	0-20	1	0.19	0.08	0.38	0-20	1
P1D	0.45	0.21	0.44	60-80	69	0.45	0.21	0.38	60-80	63
P5	0	0.25	0	900-990	950	0	0.25	0	900-990	950
G1	0	0	1.00	10-30	23	0	0	1.00	10-30	23
G2	0	0	1.00	30-50	40	0	0	1.00	30-50	40
G3	0	0	0	0.1-4.6	2.1	0	0	0	0.1-4.5	2.0
PHINT	0	0	0.14	40-60	50	0	0	0.14	40-60	50

Details of CSPs

Genetic Coefficient	**Definition**
P1V	Days, Optimum temperature for vernalization
P1D	Photoperiod response (% reduction in rate/10 h drop in pp)
P5	Grain filling phase (duration excluding lag) (°C.d)
G1	At anthesis the number of kernels per unit weight of canopy (#/g)
G2	Optimum conditions for standard kernel size (mg)
G3	Weight of standard and non-stressed mature tiller (including grain in g dwt)
PHINT	Phylochron interval, the interval (°C.d) between successive leaf tip appearance

Error (RMSE), Normalized Root Mean Square Error (NRMSE), index of agreement (d-stat) and Nash-Sutcliffe model efficiency (EF). The R^2 (Eq. 1) value near to 1 represents a good fit and RMSE (Eq. 2) represents the amount of error which if low indicates a good fit. The NRMSE value needs to be low for good accuracy and it ranges as <10% that represents excellent fit, >10% to <20% indicates good fit, >20% to <30% indicates a fair fit and >30% indicates a poor fit (Jamieson *et al.*, 1991). The d-stat is the single index indicator of the model performance and is the better indicator of 1:1 prediction than the R^2 (Wilmott and Wilmott, 1982) as it covers the variance and biasness in the model (Eq. 5) and lies between 0 and 1 with 1 representing a best fit. EF is dimensionless with 1 indicating a perfect match between the observed and simulated values (Nash and Sutcliffe, 1970).

The evaluation parameters have been listed below:

$$R^2=1-\frac{\sum_{i=1}^{n}(m_i-s_i)^2}{\sum_{i=1}^{n}(m_i-\bar{m})^2} \quad \text{...(2)}$$

$$\text{RMSE}=\sqrt{\frac{\sum_{i=1}^{n}(m_i-s_i)^2}{n}} \quad \text{...(3)}$$

$$\text{NRMSE}=\frac{RMSE*100}{\bar{m}} \quad \text{...(4)}$$

$$\text{d-stat}=1-\frac{\sum_{i=1}^{n}(m_i-s_i)^2}{\sum_{i=1}^{n}(|s_i|+|m_i|)^2} \quad \text{...(5)}$$

$$\text{EF}=\frac{\sum_{i=1}^{n}(m_i-\bar{m})^2-\sum_{i=1}^{n}(s_i-m_i)^2}{\sum_{i=1}^{n}(m_i-\bar{m})^2} \quad \text{...(6)}$$

EasyGrapher v4.7 was used to represent the evaluation results on 1:1line graphs.

Optimization of sowing window for Wheat

The calibrated and validated DSSAT CERES-wheat model was used to simulate yield and biomass for the considered sowing window of Wheat in Punjab *i.e.* mid October to late November which helped in deciding the optimum dates for wheat sowing and what would be the results of late sowing of wheat.

Results and Discussion

Sensitivity analysis

Sensitivity analysis is an important step in determining the response of a particular CSPs towards the plant parameters that are anthesis, maturity and yield. The sensitivity analysis of a model can be done by two approaches that are mathematical and graphical approach for easy understanding. The mathematical approach (Table 1) showed P1V and P1D to be a sensitive CSP towards all the three crop parameters while G1, G2 and PHINT while P5 was found sensitive to only the maturity parameter of wheat crop. Both the wheat cultivars showed similar results with G3 being the insensitive parameter towards all the crop parameters. The sensitivity results for HD2967 (Fig. 1) and PBW725 (Fig. 2) were also represented through graphical approach which clearly explains the linear

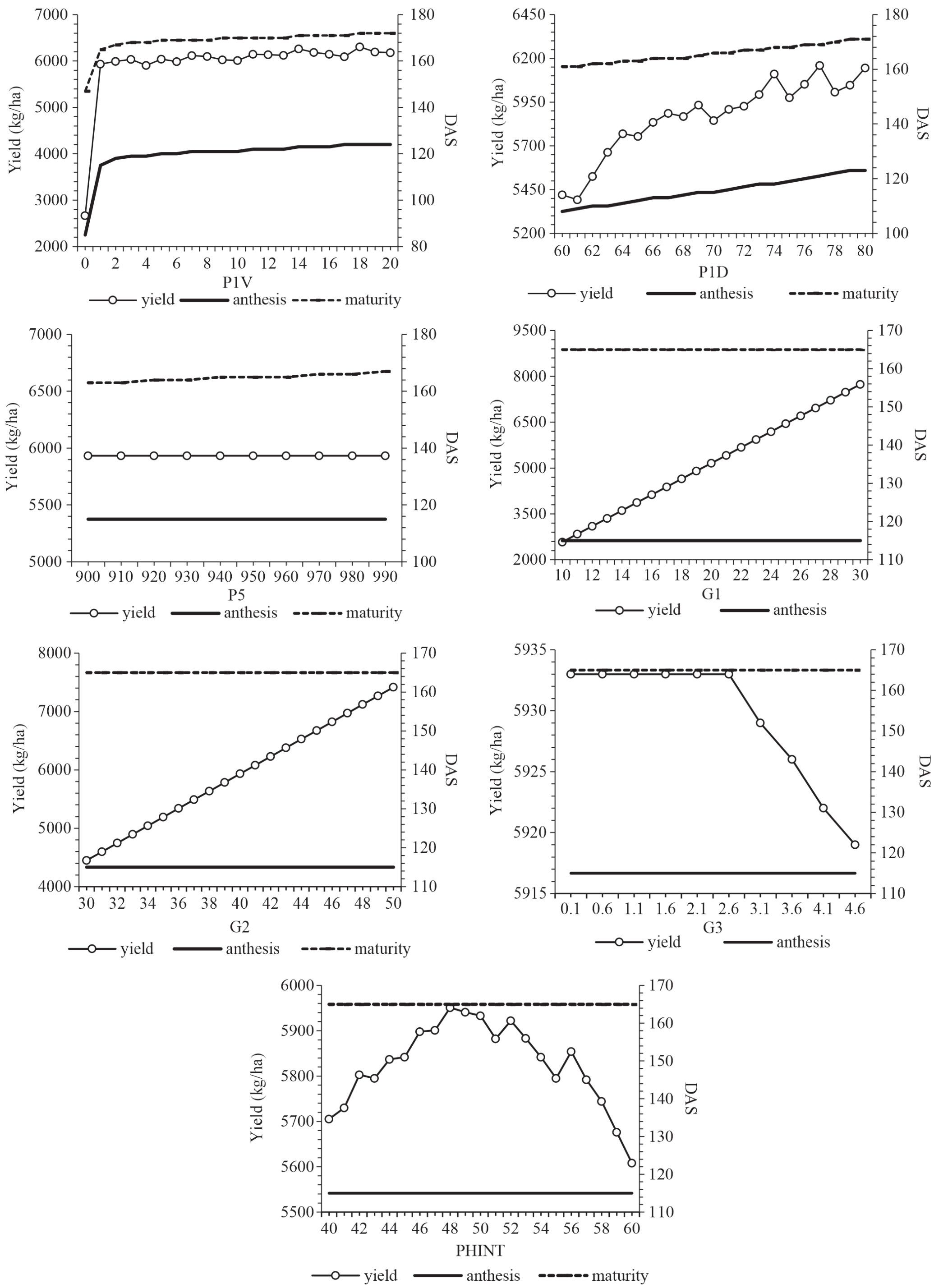

Fig. 1. Variations in grain yield (kg/ha), anthesis and maturity (DAS) of HD2967 to changes in CSPs. (a)P1V1 (b)P1D1 (c)P5 (d)G1 (e)G2 (f)G3 and (g)PHINT

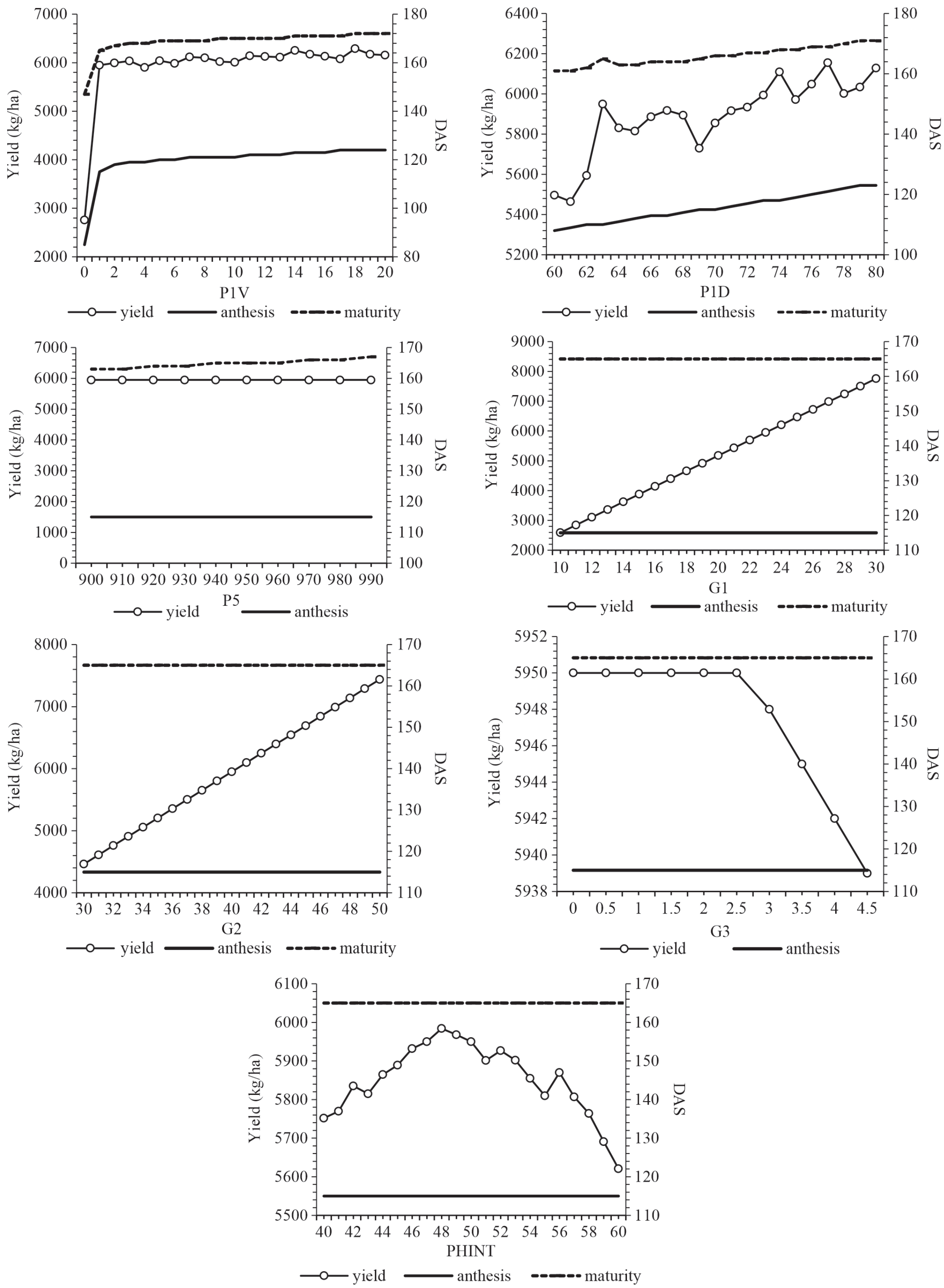

Fig. 2. Variations in grain yield (kg/ha), anthesis and maturity (DAS) of PBW725 to changes in CSPs (a) P1V1 (b) P1D1 (c) P5 (d) G1 (e) G2 (f) G3 and (g) PHINT

relationship between the anthesis, maturity and yield with different CSPs. The graphical representation clearly shows the P1V and P1D CSPs to be the most sensitive for all the three crop parameters while G1, G2, G3 and PHINT were sensitive to the yield parameter only. The sensitization of the crop model is very important for the calibration and validation process of the model.

Calibration

The CERES-wheat model after sensitization was calibrated using the 2019-20 crop year data for the CSPs which determined a close agreement between the simulated and observed crop growth parameters. Not much difference (Table 1) was observed between the CSPs of the two wheat cultivars

Validation

The calibrated CERES-wheat model was validated using the crop year 2020-21 data and the statistical measures were evaluated for determining the accuracy of the model (Table 2). The observed and simulated mean for anthesis of HD2967 was 112 and 108, respectively and for PBW725 was 109 and 105, respectively while for maturity the mean was 153 and 156, respectively and 150 and 153, respectively for the respective cultivars. The ratio for both anthesis and maturity were similar for both the wheat cultivars *i.e.* 0.96 and 1.02, respectively. The model showed accuracy under all the dates of sowing for the anthesis with a strong R^2 value of 0.93 and 0.90, respectively for HD2967 and PBW725 while for maturity these were 0.74 and 0.94 for the respective cultivars. The RMSE valuefor anthesis was low as 3.56 for HD2967 and 4.71 for PBW725 while for maturity was as low as 4.49 for HD2967 and 3.05 for PBW725. The d-stat value was higher for anthesis and maturity (0.88) for HD2967 and for PBW725 too these values were 0.73 (anthesis) and 0.93 (maturity). The NRMSE for anthesis; maturity of cultivars was excellent with 3.18 and 4.32; 2.93 and 2.04 for HD2967 and PBW72, respectively. The model efficiency for both the wheat cultivars and crop parameters was good.

The evaluation results for the grain yield were good for both the cultivars as the observed and simulated mean did not show much difference and the ratio was observed to be 1 (Table 2). The R^2 value was good with 0.74 for HD2967 and 0.71 for PBW725 while the RMSE was also low with 375.61kg/ha and 253.2 kg/ha for respective wheat cultivars. The d-stat value was high for HD2967 (0.86) and PBW725 (0.90) and NRMSE represented an excellent fit with 6.96 and 4.98 values for HD2967 and PBW725, respectively. The model efficiency was also good with values 0.66 and 0.48 for HD2967 and PBW725, respectively. The statistical evaluation for biomass yield of the two wheat cultivars gave similar results with observed and simulated mean to be 14356 kg/ha and 13038 kg/ha, respectively for HD2967 and 13708 kg/ha and 13331 kg/ha, respectively for PBW725. The ratio for the two cultivars was 0.90 and 0.97, respectively for HD2967 and PBW725 while the R^2 value was also high as 0.89 and 0.75 for respective wheat cultivars. The RMSE value for HD2967 was 1482.2 kg/ha and for PBW725 was 1282.7 kg/ha and the d-stat value was high as 0.84 and 0.75 for the respective cultivars. The NRMSE represented a good fit (10.3%) for HD2967 and excellent fit (9.3%) for PBW725. The model efficiency was low for the crop parameter.

The simulated and observed data points along with the statistically evaluated parameters were clearly plotted on 1:1 line graphs for the crop year 2020 for all the crop parameters, i.e., anthesis (DAS), maturity (DAS), yield (kg/ha) and biomass (kg/ha) under different environments (Fig. 3).

Optimization of sowing window

Optimization of the sowing window for the wheat cultivars HD2967 and PBW725was taken up after sensitising, calibrating and validating the crop model which confirmed a good agreement between the observed and simulated crop parameters that were anthesis, maturity, grain yield and biomass yield. The good evaluation results helped us in determining the usefulness of the crop model for further operations like optimizing the sowing window and climate change studies. The evaluated sowing window for the two wheat cultivars in Punjab region was taken up from 20th October to 31st January at an interval of 5 days. The simulated results have been represented in Fig. 4.

Table 2. Statistical measures for evaluation of CERES-Wheat v4.7.5 simulation performance

Parameters	HD2967			PBW725		
	Observed		Simulated	Observed		Simulated
			Anthesis			
Mean (DAS)	112		108	109		105
Ratio		0.97			0.96	
Standard Deviation	4.79		4.78	3.39		4.07
R^2		0.93			0.90	
RMSE (DAS)		3.56			4.71	
d-stat		0.88			0.73	
NRMSE (%)		3.18			4.32	
Model efficiency		0.45			-0.93	
			Maturity			
Mean (DAS)	153		156	150		153
Ratio		1.02			1.02	
Standard Deviation	6.82		6.11	5.68		6.01
R^2		0.74			0.94	
RMSE (DAS)		4.49			3.05	
d-stat		0.88			0.93	
NRMSE (%)		2.93			2.04	
Model efficiency		0.57			0.71	
			Grain yield			
Mean (kg/ha)	5397		5334	5089		5062
Ratio		1.00			0.99	
Standard Deviation	645.0		386.2	350.5		464.9
R^2		0.74			0.71	
RMSE (kg/ha)		375.61			253.2	
d-stat		0.86			0.90	
NRMSE (%)		6.96			4.98	
Model efficiency		0.66			0.48	
			Biomass yield			
Mean (kg/ha)	14356		13038	13708		13331
Ratio		0.90			0.97	
Standard Deviation	1568.2		1909.7	764.2		1828.7
R^2		0.89			0.75	
RMSE (kg/ha)		1482.2			1282.7	
d-stat		0.84			0.75	
NRMSE (%)		10.3			9.3	
Model efficiency		0.11			-1.82	

The deviation of grain yield and harvest index (HI) from their mean has been depicted graphically in Fig. 4 where depreciation has been observed in the HI with the grain yield of wheat cultivars HD2967 and PBW725. The yield and HI deviation varied between +35.3% to -38.4% and +24.5% to -23.0%, respectively for HD2967 (Fig. 4a) while between +42.5% to -39.2% and +23.7 to -24.5, respectively for PBW725 (Fig. 4b).The grain yield observed a depreciation from its mean before 20th October by -3.86% and after 9th December by -1.94% for HD2967 while depreciation observed for PBW725 was by -

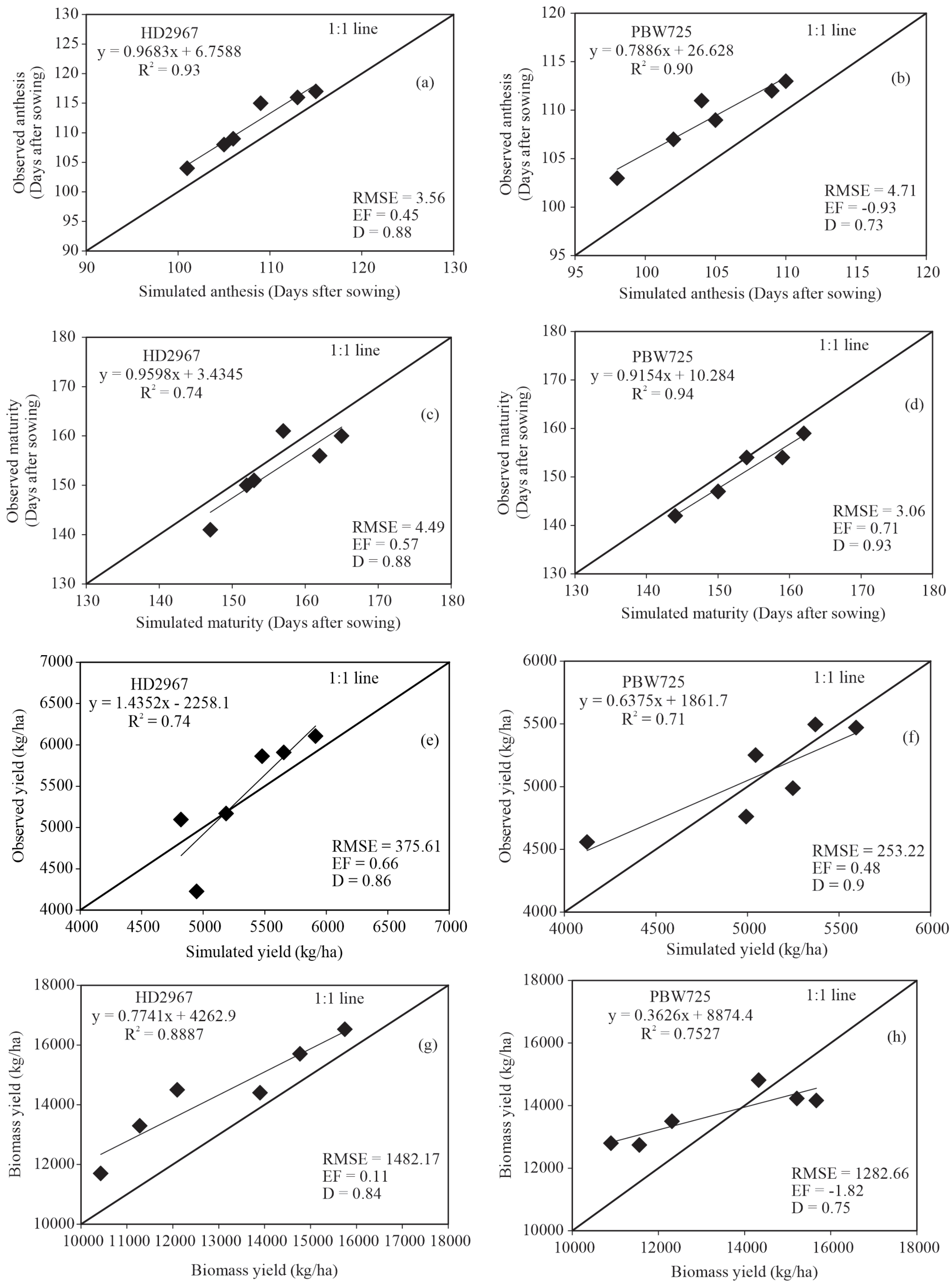

Fig. 3. Evaluation results for anthesis (a & b), maturity (c & d), grain yield (e & f) and biomass yield (g & h) of wheat cultivars

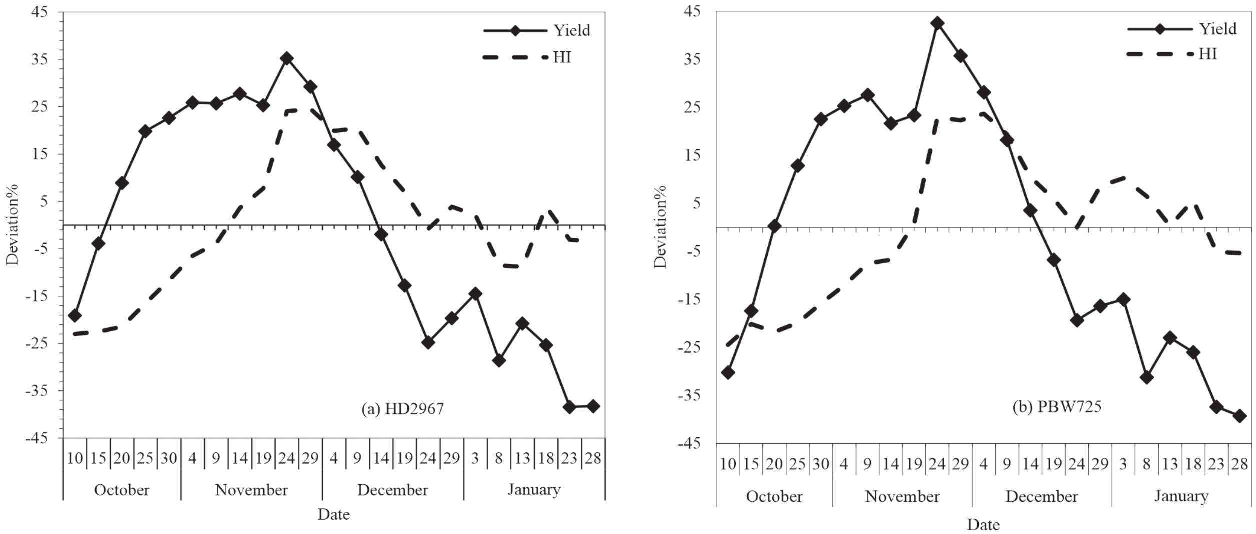

Fig. 4. Yield and harvest index (HI) relation with the sowing window for (a) HD2967 and (b) PBW725

20.2% before 20th October and by -6.7% after 14th December. The depreciation dates clearly state the sowing window for both the varieties to be best between 20th October to 9th December with highest peak observed on 24th November.

Discussions

In the present study coefficients G1 and G2 CSP were found to be most sensitive towards the grain yield and so small change in these parameter during calibration will adjust the observed and predicted yield. Changes in coefficients P1V and P1D would result in adjustment of all the three crop parameters, i.e. phenology and yield in both the wheat varieties. In another study by Abera (2019) conducted in Ethopia showed the genetic coefficients P1V, P1D and P5 to be sensitive towards the crop development and its phenology while G1, G2 and G3 were sensitive towards the growth and yield attributes of the wheat. According to the various limits for different regions the genetic coefficients as determined by a study in Faisalabad, Pakistan were 35 day, 60%, 650 GDD, 15 k/g, 100 mg, 1.00 g and 85 GDD for P1V, P1D, P5, G1, G2, G3 and PHINT, respectively (Farid *et al*., 2015). The model using these CSPs revealed good results with low percent difference between the observed and simulated values of 1.54 and -2.99, respectively for grain and biological yield. The calibration results as per the study by Andarzian *et al.* (2015) in Iran conditions showed that the P1V was adjusted to zero due to no vernalization requirement of the Chamran cultivar while the other genetic coefficients were observed to be 103 GDD, 700 GDD, 11 g^{-1}, 45 and 1.5 g for P1D, P5, G1, G2, G3 and PHINT, respectively. A research study by Patel *et al*. (2017) on calibration and validation of DSSAT CERES-wheat model (V-4.6) in Varanasi region of Uttar Pradesh was performed on the experimental data (2008-2014) for cultivars (HUW 234, Kundan, HUW 510 and PBW 373) and the simulated yields were found close to those observed with R^2 value of 0.96, NRMSE of 4.92% and D-index of 0.99. The accuracy between the simulated and observed phenological events and yield attributes determined the applicability of the model for irrigation scheduling which worked well under three, four and five irrigation scheduling.

The CERES-Wheat model showed a good accuracy under all the dates of sowing for cv HD2967 and PBW725 for the anthesis (R^2 value of 0.93 and 0.90, respectively) and maturity (R^2 value of 0.74 and 0.94, respectively). Similarly, Abera (2019) reported the calibration results of CERES-Wheat model in Ethiopia with a strong correlation between the simulated and observed values with R^2 values for anthesis, maturity and yield of 96, 79 and 79%, respectively for wheat var. Tay and 75, 75 and 92%, respectively for var. Senkegna. The performance of Tay variety for anthesis was accurate and in good agreement than that for maturity and grain yield. The regression coefficients for grain yield, anthesis and maturity were observed to be 0.8, 2.1 and 0.65, respectively of Tay variety and 0.67, 1.5 and 0.37, respectively for var. Senkegna. In the present study the NRMSE for anthesis /maturity of cultivars was excellent with 3.18 and 4.32/ 2.93 and 2.04 for HD2967 and PBW72, respectively. The model efficiency for both the wheat cultivars and crop parameters was good. Similarly, the validation results for different management zones of Faisalabad, Pakistan showed close agreement between the CERES-Wheat simulated yield and observed grain yield with a low percent difference of -4.83 while the modelling efficiency and root mean square error was within the limits (Farid *et al.*, 2015). In a study by Andarzian *et al.* (2015) the normalised RMSE for all the crop parameters ranged between 2% and 11.8%. The validated observed and simulated crop parameters were also showed on 1:1 line graphs by Abera (2019) because linear regression results close to 1 describes the model simulations better. A study in the Ludhiana district of Punjab confirmed the application of CERES-wheat model for pre-harvest yield forecast with a good level of confidence as the percent deviation of predicted yield from observed was between -3.7 to -10.9 while the NRMSE and MBE values were 5.80% and -271.38 kg ha^{-1} in the pre harvested wheat yield prediction performed for 20th March. The predicted and observed yield comparison showed that the average deviation of predicted wheat yield was observed as -5.35% and the R^2 value was high as 0.945 (Gill *et al.*, 2018).

A research study by Rani *et al*. (2017) in the sub-tropical semi-arid climate of New Delhi on validated DSSAT 4.6 model for cultivar HD2967 confirmed its applicability in simulating the nitrogen uptake and yield under different farm management scenario resulting in efficient usage and selection of practices for sustainable wheat production in the Indo-gangetic region. In the present study the best sowing window for both the varieties was simulated to be between 20th October to 9th December with highest peak observed on 24th November. In Iran Andarzian *et al. (*2015) used CERES-wheat model and reported the yield of early sowing dates (before 15th November) was lesser in comparison to normal sowing date (15th November) due to the decreasing crop growth cycle from sowing to anthesis. The late sowing dates (after 15th November) in the region observed a shortening in the time period from sowing to anthesis and maturity, maximum LAI, number of grains per metre square, grain weight as well as harvest index reduction than that in normal sowing dates. Findings by Jahan *et al.* (2018) in Bangladesh on CERES-wheat model was used to determine sowing window for wheat as the short winter season in Bangladesh is a major role player in wheat yield. During the early sowing (21st October to 10th November) of wheat, various phenological stages were affected under early heat stress thus reducing the yield by 2.89% per day for every one day early sowing and similar scenario was observed during late sowing (5th December to 20th December) where the yield depreciation was by 1.28% per day for every one day delay of sowing due to late heat stress. The grain yield for the region were higher for optimum sowing dates (15th November to 30th November) which might be due to optimum temperatures (15-25°C) during day as well as night time.

Conclusions

Crop simulation model is a tool used for prediction of yield and other crop parameters under the existing and predicted climatic conditions. But significant results can be obtained only if the prior steps, i.e. sensitivity analysis, calibration and validation for the model are done accurately. In the present study these prior requirements for the crop model were done using the datasets collected during 2019-20 and 2020-21 crop years. The CERES-Wheat model predicted 20th October to 9th December to be an optimum sowing window for both the cultivars with the peak yield simulated during 24th November. The early and late sowing of wheat showed high yield depreciation and thus these practices should be avoided by the Punjab farmers. The decrease in HI during early and late dates of sowing is a clear indicator of abrupt distribution of photosynthates. The initial steps of sensitization and calibration of the crop model are important for ascertaining the truthfulness of the model and it also helps in accurate quantification of the parameters. The usefulness of the model is determined through its validation which is done using evaluated measures and after the perfect fit of the simulated and observed crop parameters the model is now easily and accurately applicable for further studies. The results of the present study ascertain that the CERES-wheat model is useful in optimizing the crop management practices such as shift in sowing dates, rate of fertilizer application, irrigation scheduling, yield prediction under current as well as future climatic conditions. Wheat is a staple cereal crop of India and the Punjab state is a leading contributor of wheat in central pool of food grains in the country. So a sensitized, calibrated and well validated simulation model like CERES-Wheat is an efficient and economical tool for understanding the climate change impact on the wheat crop.

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