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Research Article

Assessment of Phenology and Yield of Wheat Cultivars using CERES-Wheat Model for the Northeastern Zone of Punjab, India

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ABSTRACT

For testing the CERES-wheat model, an experiment was conducted during the *rabi* 2020-21 and 2021-22 at the Regional Research Station, Ballowal Saunkhri, Punjab, India. The field data on anthesis, maturity, grain yield and biomass yield were generated from the experiment comprising two sowing dates in main plots (11th November and 15th December) and seven wheat cultivars in subplots (HD 3226, Unnat PBW 343, Unnat PBW 550, PBW Zn 1, PBW 725, PBW 660 and PBW 752) laid in split plot design. The days taken to anthesis and maturity were sensitive to the genetic coefficients P1V, P1D and P5. Likewise, the grain yield of crop was highly sensitive to G1, G2, G3 and PHINT coefficients. The model was calibrated by repeated interactions between the genetic coefficients andvalidation results showed that the CERES- wheat model predictions for phenology and yield of wheat cultivars were close to observed field data. The d-stat values for the days taken to anthesis, maturity, grain yield and biomass yield were 0.99, 0.99, 0.87 and 0.72 percent respectively. The results of NRMSE for the phenology fall in the excellent category, whereas in the good category for grain and biomass yield, indicating that the model predicted accurately phenology and yield under different environments.

Key words: CERES-wheat, Calibration, Validation, Phenology, Grain yield, Biomass yield

Introduction

Crop modeling offers an effective way to understand and analyze the consequences of management options under variable climatic conditions. Crop growth models are important tools for agricultural research, development of cropping technologies, exploration of management and policy decisions and for studying the interactions between crops and their environment (Boote *et al.*, 2018; Hammer *et al.*, 2016; Jones *et al.*, 2022). The agronomic studies that relate crop growth and yield to different on-farm conditions are normally costly in terms of both time and money. In addition, useful results are not always obtained due to uncontrollable environment factors (Aggarwal *et al.*, 2017; Amin *et al.*, 2018; Basistha *et al.*, 2018). Therefore, well calibrated and validated crop simulation models can be used as an alternative to produce reasonably reliable data under controlled conditions. Crop simulation models have been applied to a number of environments to test the hypothetical impacts of different management practices as described by Lopez-Cedron *et al.* (2018) or cultivars characteristics according to Boote *et al.* (2019) on production of biomass, biomass portioning and grain yield. However, simulation models are not meant to be replacement of field experimentation but rather, the two are complementary. Field experiments provide a data set necessary to demonstrate the accuracy of simulation models for specific soil-management-weather combinations (Hong *et al.*,

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2013; Dettori *et al.,* 2016; Sandhu *et al.,* 2019). Based upon model predictions, a decision maker can have a better idea of the consequences of the decision before even considering conducting field experimentation. Simulation modeling can enhance field experimentation, particularly if research is to be conducted over a short time period in a range of different conditions and also where resources are limiting.

Crop simulation models have been a key tool in assessing the impact of future climate change. A range of scenarios of emissions from a number of GCM ensembles and various downscaling methods are usually employed together with single-crop models as described by Gornot and Weschsung (2016). Including these projections in crop models can help to assess possible impacts and explore management strategies to adapt to climate change. Many future climate change impact assessments have been carried out using crop models for specific locations, agricultural regions and at the global scale Rosenweig and Parry (2019). However, the crop models need to be well calibrated and validated regionally before proceeding towards any kind of impact assessment research.

In this study, CERES- wheat model was calibrated and validated using the observed field experiment data so that the model could be used to simulate phenology and yield of wheat crop under the futuristic climate change scenarios. This is a component of DSSAT crop growth simulation model developed under the USDA-ARS wheat yield project and U.S. government multiagency AGRI-STARS program (Hoogenboom *et al.*, 2020; Ritchie, 2019). The CERES-wheat model simulates growth, development and yield of wheat under different weather conditions, soil and crop management practices (Bannayan and Crout, 2021; Hunt *et al.*, 2020; Jamiesin *et al.*, 2021; Ritchie *et al.*, 2020). The genetic coefficients are sensitive to photoperiod, grain filing duration, conversion of mass to grain number, stem size, vernalization requirements, and cold hardiness (Hunt *et al.*, 2020). The model simulates phenology, biomass, yield, leaf area index, water and N balance of soil and plants its sowing to maturity (Kaur *et al.*, 2021; Sandhu *et al.*, 2016). Therefore, present research for the northeastern region of Punjab was planned to evaluate of the CERES-wheat model for simulating growth and yield for seven wheat cultivars as affected by different sowing dates and cultivars.

Materials and Methods

Study area

The study was carried out for Regional Research Station, Ballowal Saunkhri located in northeastern zone of Punjab which is commonly known as Kandi region of Punjab. Ballowal Saunkhri has been situated at 30°07′ N, 76°23′ E and lies 355m above mean sea level (Talukder *et al.*, 2018). The area represents semi arid climate with very hot and dry summer from April to June, hot and humid conditions from July to September, cold winters from November to January and mild climate during February and March.

Field experiment

The experiment comprising two sowing dates (11^{th} November and 15^{th} December) in main plots and seven wheat cultivars (HD 3226, Unnat PBW 343, Unnat PBW 550, PBW Zn 1, PBW 725, PBW 660 and PBW 752) in subplots was laid in a split plot design at Regional Research Station, Ballowal Saunkhri in the *Rabi* season of 2020-21 and 2021-22. All the package of practices recommended by Punjab Agricultural University, Ludhiana were followed for raising the crop.

Model description

CERES-Wheat model was developed by Joe Ritchie and colleagues in 1970s. This model has capability to simulate daily crop growth, development and yield under diversified climate and soil conditions with different agronomical management and thus it was selected for the study. The minimum data 2.3. set required for running the model is as follows:

Weather data

The minimum weather data set required for running the model is the daily maximum temperature (°C), daily minimum temperature (°C), daily precipitation (mm) and daily solar radiation (MJ m^{-2} day^{-1}). The weather files with extension *.WTH was used for operating the model simulations.

Site information

The CERES-wheat model requires latitude, longitude and altitude-related site information for running the model.

Soil data

The soil data requires to run the model are upper and lower horizon depth (cm), percentage sand, silt and clay content, bulk density (g cm^{-3}), organic carbon (percent) and PH in water. The soil file for soil data for operating crop model has the extension *.SOL

Crop management and yield

The crop management includes information on planting dates, dates when soil condition were measured prior to planting, planting density, row spacing, planting depth, crop variety, date and amount of irrigation and date and amount of fertilizer application. For wheat crop, the management files with extension *.WHX is used for operating the model simulations. The yield files with extension *.WHA is requires for operating the model which includes data regarding the yield and yield attributes recorded at the time of harvest.

Genetic coefficients

These genetic coefficients of the cultivars describe characteristics in terms of phenology and grain development and are required to run the model. Detailed description of genetic coefficients of CERES-Wheat model are P1V (Days, optimum vernalizing temperature required for vernalization), P1D (Photoperiod response (percent reduction in rate/10h drop in pp)), P5 (Grain filling phase duration), G1 (Kernel number/unit canopy weight at anthesis (g)), G2 (Standard kernel size under optimum conditions (mg)), G3 (Standard non-stressed mature tiller weight) and PHINT (Interval between successive leaf tip appearance).

Model calibration

Model calibration is the process of adjusting some model parameters according to the climatic and geographical conditions of the study area. It is also necessary to obtain the genetic coefficients of the new cultivars used in modeling studies. Therefore, the model was calibrated with observed field data of phenology, grain yield and biomass yield components for the *rabi* 2020-21 by repeated iterations of the genetic coefficients. Cultivar coefficients P1V, P1D, P5, and PHINT deals with vegetative growth and phenology of plant, whereas G1, G2 and PHINT affect the grain yield of cultivars.

Model validation and statistical evaluation

The purpose of the validation is to use the well calibrated crop growth model for comparing the simulated and observed yield of the different season that were not the part of calibration process. Data from *rabi* 2021-2022 was used for validation. Simulation performance after model validation is evaluated using a variety of statistics such as Root Mean Square Error (RMSE), R^2, Normalized root mean square error (NRMSE), d-stat etc. Regression analysis in combination with the 1:1line graphs between simulated and observed data (2021-22) were used to evaluate model accuracy.

Sensitivity analysis

To understand how the model works, a sensitivity analysis is performed on the model to determine the sensitivity of the model output to changes in the input parameters. If a small change in an input parameter results in a relatively large change in the output, the model is said to be more sensitive to that parameter. This means that the parameters involved need to be determined more accurately. The CERES wheat model has a genotype file that contains information in the form of genetic coefficients. Sensitivity tests were performed by altering the values of these genetic coefficients.

Normalized root mean square error (NRMSE) (percent)

Normalized root mean square error (NRMSE) provides a measure (percent) of relative difference of predicted versus observed data .The simulation is considered excellent, good, fair and poor if NRMSE is less than 10, 10-20, 20-30 and more than 30 percent, respectively, (Jamieson *et al.*, 1991). NRMSE was calculated as follow:

$$\text{NRMSE} = \frac{[\Sigma in = 1 \ (Pi - Oil) \ 2/n]}{\bar{O}} \times 100$$

Where, *P* is value predicted by the model, *O* is observed value; *n* is total number of observations and Ōis mean of observed values.

Deviation

The deviation between the model simulated and observed values for phenology, growth and yield of wheat was calculated as given below:

Phenology

Deviation (Number of days) = Simulated date – Observed date

Yield

Deviation (percent) = ((Simulated yield – Observed yield) / Observed yield) *100

Results and Discussion

Sensitivity analysis of CERES-Wheat model

The sensitivity analysis was performed for 7 cultivar specific coefficients (P1V, P1D, P5, G1, G2, G3 and PHINT) which controls the phenological development and yield of the wheat crop by increasing or decreasing their values to determine their effect on the phenology and grain yield. The data presented in Table 1 to Table 4 indicated the sensitivity of model to theses genetic coefficients for cv. HD 3226, Unnat PBW 343, Unnat PBW 550, PBW Zn 1, PBW 725, PBW 660 and PBW 752 respectively. The G1, G2, G5 and PHINT did not affect the days taken to maturity in all the cultivars (Table 2).

Calibration of CERES-Wheat model

Crop simulation models need some calibration before they can be used in an area other than where they were originally made, especially when the model is to be used to predict future climate change scenarios. The CERS-Wheat model was calibrated for the wheat crop cultivars, i.e., HD 3226, Unnat PBW 343, Unnat PBW 550, PBW Zn 1, PBW 725, PBW 660 and PBW 752. The model simulated and observed value of anthesis and physiological maturity dates, grain yield, biomass yield was tabulated and the differences between the two values were compared. CERES-Wheat requires a set of seven genetic coefficients for the simulation of phenology, growth and grain yield of cultivars. Since such data were not available, the genetic coefficients of different hybrids were estimated by repeated iterations until a close match between simulated and observed phenology, growth and yield was obtained. The value of each genetic coefficient which minimized the differences between the observed and simulated values was selected for using in the model separately for the seven cultivars. The genetic coefficients for calibrated CERES-Wheat model for all the wheat cultivars have been given in Table 5. The cv. HD 3226 had higher value for P1D, i.e., 60 (°day) followed by PBW 660, i.e., 40 (°day). The Cv. PBW 752 had higher value of P5 520 (˚day) followed by PBW Zn 1 and Unnat PBW 343, i.e., 510 (°day) and 460 (°day) respectively indicates that it was longer duration hybrid as compared to other hybrids. Minor differences were recorded in G1 values that were 30.3, 32.6, 32.3, 30, 31.4, 29.3 and 29.8 (day) for HD 3226, Unnat PBW 343, Unnat PBW 550, PBW Zn 1, PBW 725, PBW 660 and PBW 752, respectively. The value of G2 was 25, 25, 30, 27, 27.27, 25 and 29 for HD 3226, Unnat PBW 343, Unnat PBW 550, PBW Zn 1, PBW 725, PBW 660 and PBW 752, respectively. Both genetic coefficients of G1 and G2 controlled the yield by increasing and decreasing the values of it. Unnat PBW 343 had lower kernel filling rate (G3), i.e., 2.0 mg day^{-1} as compared to other cultivars which was varied from 7.0 to 7.5 mg day^{-1}. PHINT (Phylochron interval) value varied from 56 for HD 3226, 90 for Unnat PBW 343, 60 for Unnat PBW 550, 50 for PBW Zn 1, 70 for PBW 725, 120 for PBW 660 and 58 for PBW 752.

Similar type of findings was also reported by Sandhu *et al*. (2016) and Talukder *et al*. (2018). The values for NRMSE for wheat cutivars were on excellent range. Mall *et al*. (2016) observed a nice agreement between the observed and simulated values of days taken to anthesis with RMSE and R^2 values 4.4 and 0.68 for wheat crop.

Table 1. Sensitivity analysis for days taken to anthesis by different wheat cultivars using CERES-Wheat model

S.No.	GC	HD3226		Unnat PBW343		Unnat PBW550		PBW Zn1		PBW 725		PBW 660		PBW 752	
		Range	DTA	Range	DTA	Range	DTA	Range	DTA	Range	DTA	Range	DTA	Range	DTA
1	P1V	65	98	30	99	30	95	30	97	30	99	45	100	30	95
		60*	98	25	98	27	95	20	96	25	98	40	100	25	95
		55	98	20	97	24	94	10	93	20	97	35	99	20	93
2	P1D	85	101	90	102	85	98	85	97	90	102	90	104	90	102
		82*	98	85	98	80	95	83	96	85	98	85	100	80	95
		79	96	80	95	75	91	81	94	80	95	80	96	70	88
3	P5	450	98	470	98	400	95	550	96	460	98	430	100	550	95
		430*	98	460	98	370	95	510	96	450	98	420	100	520	95
		410	98	450	98	340	95	470	96	440	98	410	100	490	95
4	G1	30.3	98	32.6	98	32.3	95	30	96	31.4	98	29.3	100	29.8	95
		28.3*	98	29.6	98	30.3	95	27	96	26.4	98	26.3	100	27.8	95
		26.3	98	26.6	98	28.3	95	24	96	21.4	98	23.3	100	25.8	95
5	G2	25	98	25	98	30	95	27	96	30	98	30	100	31	95
		21*	98	21	98	27	95	24	96	27	98	25	100	29	95
		17	98	17	98	24	95	21	96	24	98	20	100	27	95
6	G3	9.5	98	3.0	98	9.5	95	10	96	10	98	10.	100	10	95
		7.5*	98	2.0	98	7.5	95	7.0	96	7.0	98	7.0	100	7.0	95
		5.5	98	1.0	98	5.5	95	4.0	96	4.0	98	4.0	100	4.0	95
7	PHINT	60	98	95	98	70	95	60	96	80	98	130	100	60	95
		56*	98	90	98	60	95	50	96	70	98	120	100	58	95
		52	98	85	98	50	95	40	96	60	98	110	100	56	95

*GC= Genetic coefficient
*DTA= Days taken to anthesis

Table 2. Sensitivity analysis for days taken to maturity by different wheat cultivars using CERES-Wheat model

S.No.	GC	HD3226		Unnat PBW343		Unnat PBW550		PBW Zn1		PBW 725		PBW 660		PBW 752	
		Range	DTM	Range	DTM	Range	DTM	Range	DTM	Range	DTM	Range	DTM	Range	DTM
1	P1V	65	131	30	132	30	125	30	133	30	132	45	132	30	132
		60*	131	25	132	27	125	20	132	25	132	40	131	25	132
		55	130	20	131	24	125	10	130	20	130	35	131	20	131
2	P1D	85	132	90	135	85	128	85	133	90	135	90	135	90	138
		82*	131	85	132	80	125	83	132	85	132	85	131	80	132
		79	128	80	129	75	123	81	131	80	129	80	128	70	127
3	P5	450430*	132131	470460	132132	400370	126125	550510	134132	460450	132132	430420	132131	550520	133132
		410	130	450	132	340	124	470	130	440	131	410	131	490	130
4	G1	30.3	131	32.6	132	32.3	125	30	132	31.4	132	29.3	131	29.8	132
		28.3*	131	29.6	132	30.3	125	27	132	26.4	132	26.3	131	27.8	132
		26.3	131	26.6	132	28.3	125	24	132	21.4	132	23.3	131	25.8	132
5	G2	25	131	25	132	30	125	27	132	30	132	30	131	31	132
		21*	131	21	132	27	125	24	132	27	132	25	131	29	132
		17	131	17	132	24	125	21	132	24	132	20	131	27	132
6	G3	9.5	131	3.0	132	9.5	125	10	132	10	132	10.	131	10	132
		7.5*	131	2.0	132	7.5	125	7.0	132	7.0	132	7.0	131	7.0	132
		5.5	131	1.0	132	5.5	125	4.0	132	4.0	132	4.0	131	4.0	132
7	PHINT	60	131	95	132	70	125	60	132	80	132	130	131	60	132
		56*	131	90	132	60	125	50	132	70	132	120	131	58	132
		52	131	85	132	50	125	40	132	60	132	110	131	56	132

*GC= Genetic coefficient

*DTM= Days taken to maturity

Table 3. Sensitivity analysis for grain yield by different wheat cultivars using CERES-Wheat model

S.No.	GC	HD3226		Unnat PBW343		Unnat PBW550		PBW Zn1		PBW 725		PBW 660		PBW 752	
		Range	GY	Range	GY	Range	GY	Range	GY	Range	GY	Range	GY	Range	GY
1	P1V	65	3581	30	3980	30	4920	30	3858	30	4481	45	4252	30	4841
		60*	3583	25	3905	27	4778	20	3746	25	4397	40	4259	25	4710
		55	3647	20	3923	24	4791	10	3627	20	4420	35	4190	20	4629
2	P1D	85	3586	90	3953	85	4965	85	3861	90	4446	90	4285	90	4936
		82*	3583	85	3905	80	4778	83	3746	85	4397	85	4259	80	4710
		79	3498	80	3770	75	4572	81	3687	80	4253	80	4066	70	4191
3	P5	450	3583	470	3905	400	4778	550	3746	460	4397	430	4259	550	4710
		430*	3583	460	3905	370	4778	510	3746	450	4397	420	4259	520	4710
		410	3583	450	3905	340	4778	470	3746	440	4397	410	4259	490	4710
4	G1	30.3	3837	32.6	4301	32.3	5093	30	4162	31.4	5230	29.3	4744	29.8	5049
		28.3*	3583	29.6	3905	30.3	4778	27	3746	26.4	4397	26.3	4259	27.8	4710
		26.3	3330	26.6	3509	28.3	4462	24	3329	21.4	3565	23.3	3773	25.8	4371
5	G2	25	4266	25	4649	30	5309	27	4214	30	4886	30	5110	31	5035
		21*	3583	21	3905	27	4778	24	3746	27	4397	25	4259	29	4710
		17	2901	17	3161	24	4247	21	3277	24	3909	20	3407	27	4385
6	G3	9.5	3583	3.0	3904	9.5	4777	10	3745	10	4397	10.	4259	10	4710
		7.5*	3583	2.0	3905	7.5	4778	7.0	3746	7.0	4397	7.0	4259	7.0	4710
		5.5	3584	1.0	3908	5.5	4778	4.0	3747	4.0	4398	4.0	4260	4.0	4712
7	PHINT	60	3605	95	3911	70	4862	60	3841	80	4447	130	4262	60	4719
		56*	3583	90	3905	60	4778	50	3746	70	4397	120	4259	58	4710
		52	3546	85	3895	50	4651	40	3579	60	4333	110	4248	56	4696

*GC= Genetic coefficient
*GY= Grain yield

Table 4. Sensitivity analysis for biomass yield by different wheat cultivars using CERES-Wheat model

S.No.	GC	HD3226		Unnat PBW343		Unnat PBW550		PBW Zn1		PBW 725		PBW 660		PBW 752	
		Range	BY	Range	BY	Range	BY	Range	BY	Range	BY	Range	BY	Range	BY
1	P1V	65	12225	30	12940	30	11661	30	12461	30	12602	45	12734	30	12715
		60*	12230	25	13018	27	11670	20	12390	25	12632	40	12732	25	12659
		55	12237	20	13085	24	11627	10	12219	20	12596	35	12873	20	12569
2	P1D	85	12042	90	13077	85	11712	85	12469	90	12728	90	12834	90	13056
		82*	12230	85	13018	80	11670	83	12390	85	12632	85	12732	80	12659
		79	12082	80	13048	75	10752	81	12220	80	12644	80	12824	70	11683
3	P5	450	12309	470	13462	400	11900	550	12543	460	12690	430	13069	550	12893
		430*	12230	460	13018	370	11670	510	12390	450	12632	420	12732	520	12659
		410	12143	450	12786	340	11464	470	12321	440	12556	410	12585	490	12446
4	G1	30.3	12230	32.6	13018	32.3	11670	30	12390	31.4	12632	29.3	12732	29.8	12659
		28.3*	12230	29.6	13018	30.3	11670	27	12390	26.4	12632	26.3	12732	27.8	12659
		26.3	12230	26.6	13018	28.3	11670	24	12390	21.4	12632	23.3	12732	25.8	12659
5	G2	25	12230	25	13018	30	11670	27	12390	30	12632	30	12732	31	12659
		21*	12230	21	13018	27	11670	24	12390	27	12632	25	12732	29	12659
		17	12230	17	13018	24	11670	21	12390	24	12632	20	12732	27	12659
6	G3	9.5	12221	3.0	12987	9.5	11662	10	12382	10	12626	10.	12727	10	12651
		7.5*	12230	2.0	13018	7.5	11670	7.0	12390	7.0	12632	7.0	12732	7.0	12659
		5.5	12245	1.0	13077	5.5	11683	4.0	12401	4.0	12639	4.0	12737	4.0	12670
7	PHINT	60	12321	95	13074	70	11908	60	12756	80	12792	130	12742	60	12696
		56*	12230	90	13018	60	11670	50	12390	70	12632	120	12732	58	12659
		52	12083	85	12926	50	11326	40	11754	60	12417	110	12694	56	12606

*GC= Genetic coefficient

*BY= Biomass yield

Table 5. Genetic coefficients derived for different wheat cultivars using CERES-Wheat model

Cultivar	Genetic coefficients						
	P1V	P1D	P5	G1	G2	G3	PHINT
HD3226	60	82	430	28.3	21	7.5	56
Unnat PBW343	25	85	460	29.6	21	2.0	90
Unnat PBW550	27	80	370	30.3	27	7.5	60
PBW Zn1	20	83	510	27	24	7.0	50
PBW725	25	85	450	26.4	27	7.0	70
PBW660	40	85	420	26.3	25	7.0	120
PBW752	30	80	520	27.8	29	7.0	58

Validation of CERES-Wheat model

The validation of model explained the association of CERES-Wheat model simulated parameters with the observed observations for growth development and yield of wheat cultivars. The statistical assessment of the validation results between observed and simulated data of the phenological events and yield of wheat cultivars sown under two dates of sowing have been given in Table 6. The CERES-Wheat model was able to simulate phenological events, i.e., anthesis date (RMSE= 0.5 day, d-stat= 0.99), maturity day (RMSE= 0.5 day, d-stat= 0.99) and yield parameters, i.e., grain yield (RMSE= 362.9 kg/ha, d-stat= 0.87) and biomass yield (RMSE=1026.2 kg/ha, d-stat= 0.72) for wheat cultivars under different sowing dates during *rabi*, 2021-2022.

Crop phenology

The CERES-Wheat model for simulating the duration from sowing to anthesis evaluating with data from 2021 and 2022 experiment revealed that similar average values for wheat between observed and simulated values, i.e., 96 days for observed and also 96 days for simulated Table 6. The coefficient of determination (R^2) between the simulated and observed data for both anthesis and maturity was 0.99 which means that the model explained 99 per cent variation in the simulated data which is due to a linear relationship with the observed data (Table 6). In addition to this, the d-stat between the simulated and observed data for both anthesis and maturity was 0.99 which was good for explaining accurate model predictions. Furthermore, the NRMSE between the simulated and observed data for both anthesis and maturity was 0.55 and 0.41percent which fall in excellent category (Table 6). It means model did an excellent job in predicting the simulated phenology in the model.

The 1:1 line and its linear regression graph plotted between observed and CERES-Wheat model simulated the days taken to anthesis, days taken to maturity, grain yield and biomass yield for the different wheat cultivars, respectively under different conditions have been shown in Figure 1 (a) and 1 (b). The model simulated the phenological stages of anthesis and physiological maturity of three cultivars in close agreement with those observed in the field. However, the CERES-Wheat model more realistically simulated the days taken to anthesis and maturity. The simulated anthesis days of the linear regression model between observed and simulated accounted for 100 per cent variations whereas simulated physiological maturity accounted for 99 per cent variations (Fig. 1 (a) and 1 (b)) due to observed data. This showed that model is able to will be perfectly validated and simulated more realistically.

Similar studies were conducted by Rai *et al.* (2022) showed that agreement between simulated and observed days taken to anthesis and maturity reasonably good with NRMSE of 94 and 91 percent.

The coefficient of determination (R^2), d-stat and NRMSE between the simulated and observed data of grain yield and biomass yield were 0.82 and 0.72, 0.87 and 0.72 and 9.0 and 8.4 percent, respectively (Table 6). All the statistical tools indicate that CERES-Wheat model was validated with good degree of accuracy and further it can be used under

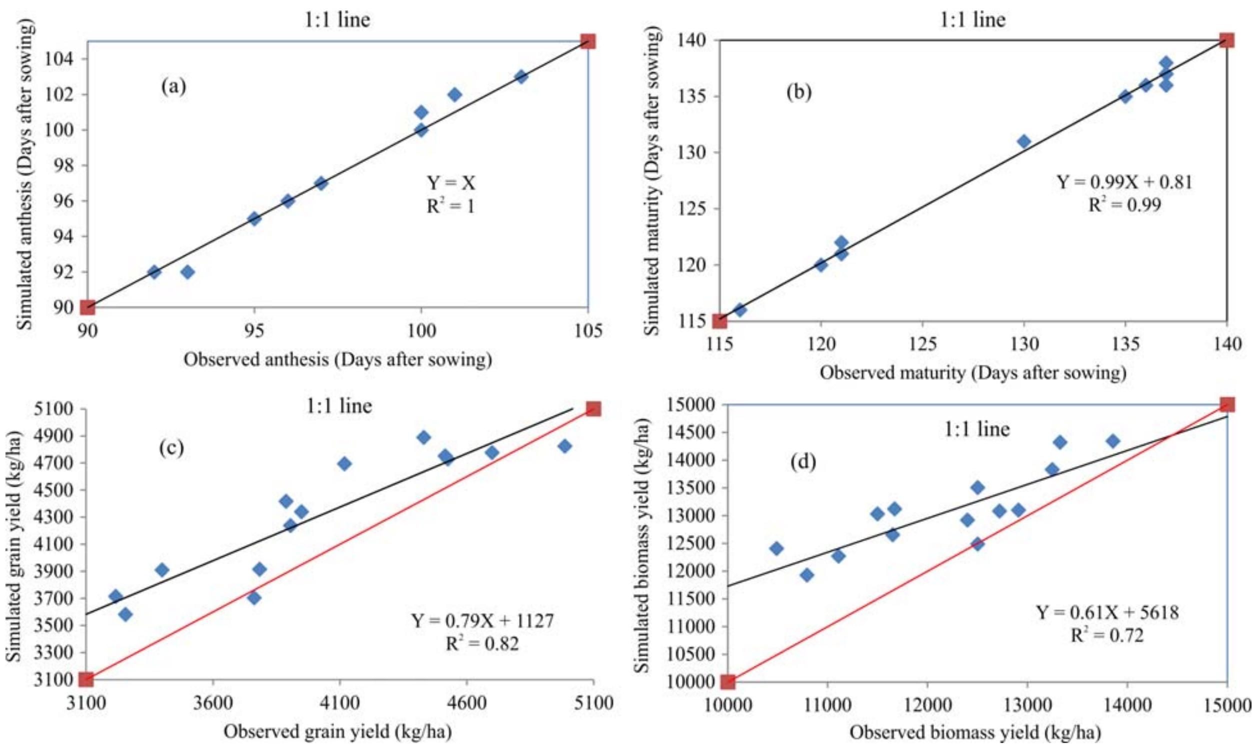

Fig. 1. Comparison of simulated and observed phenology and yield (kg/ha) for wheat cultivars under different environments, *Rabi* 2020-2022

different climate change conditions for simulation guided management practices for yield maximization of wheat.

The 1:1 line and its linear regression graph between simulated and observed grain and biomass yield of the wheat cultivars under different sowing dates has been shown in Fig. 1 (c) and 1 (d). The simulated grain and biomass yield of linear regression model accounted for 82 and 72 percent variations due to observed grain and biomass yield. The similar findings were reported by Mall *et al.* (2018) during validation of CERES-Wheat model and observed R^2 value of 0.56 and NRMSE of 0.78 percent for grain yield of wheat. Hlavinka *et al.* (2020) observed R^2 values ranged between 0.97 to 0.99 for wheat grain yield.

Conclusions

The CERES-Wheat model showed that the phenology of wheat crop was sensitive to the three coefficients, i.e., P1V, P1D and P5. However, the grain yield of crop was highly sensitive to G1, G2, G3 and PHINT genetic coefficients. The validation results showed that the CERES- wheat model predictions for phenology and yield of wheat cultivars were close to observed field data with slight overestimations and underestimations. The d-stat values for the days taken to anthesis, maturity, grain yield and biomass yield were 0.99, 0.99, 0.87 and 0.72 percent, respectively. The results of NRMSE for the phenology and yield gave good estimates for grain and biomass yield, indicating that model can be used accurately to predict phenology and yield under different environments for the northeastern zone of Punjab. The CERES-Wheat model provided rather reliable estimates of phenology and grain yield of wheat cultivars. This study also showed that the calibrated CERES-Wheat model could be used as a promising research tool for yield forecasting as well as grower's tool for before sowing and within season management decisions for wheat cultivars under different growing environments. The results may be useful for estimating the crop production and to evaluate the effect of climate change on phenological events and grain yield of wheat cultivars under northeastern region of Punjab.

Table 6. Statistics of the observed and simulated phenology and yield of wheat (*Rabi* 2021-2022)

Variable name	Mean		Ratio	Standard deviation		r-square	Mean diff.	RMSE	d-stat	Total obs.	NRMSE
	Observed	Simulated		observed	simulated						
Anthesis day	96	96	1	4.3	4.6	0.99	0	0.53	0.99	14	0.55
Maturity day	128	128	1	7.9	7.9	0.99	0	0.53	0.99	14	0.41
Grain yield (kg/ha)	4031	4320	1.07	523.8	456.8	0.82	289	362.9	0.87	14	9.0
Biomass yield (kg/ha)	12190	13069	1.07	973.8	701.0	0.72	879	1026.2	0.72	14	8.4

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