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Research Article

Comparative Assessment of CERES and InfoCrop Models to Evaluate Phenology and Yield of Maize Cultivars for the Northeastern Zone of Punjab, India

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ABSTRACT

The CERES-Maize and InfoCrop-Maize models were calibrated and validated using two cultivars (JC-4 and PMH-13) grown under four sowing dates (1st June, 15th June, 30th June and 15th July) during the years 2021 and 2022. The study was conducted at the Punjab Agricultural University Regional Research Station, Ballowal Saunkhri, Punjab. The models were calibrated by repetitive interactions among the genetic coefficients of maize genotypes. The different test criteria , *viz.,* mean of observed and simulated values, root mean square error (RMSE), coefficient of determination (R^2), mean absolute error (MAE), Nash-Sutcliffe efficiency (NSE) and normalized root mean square error (NRMSE) were used to evaluate the performance of models in terms of simulating phenology and yield attributes of maize cultivars. The CERES-Maize model showed close agreement between observed and simulated data for anthesis date (RMSE= 1.09 days, NSE=1.00 and R^2= 0.82), maturity date (RMSE= 0.97 days, NSE=1.00 and R^2= 0.97), grain yield (RMSE=431.63 kg/ha, NSE=0.80 and R^2= 0.84) and biomass yield (RMSE= 778.29 kg/ha, NSE=0.70 and R^2= 0.74). On the other hand, the data simulated by InfoCrop-Maize model showed more error and less efficiency for anthesis date (RMSE= 1.85 days, NSE=0.70 and R^2= 0.76), maturity date (RMSE= 2.26 days, NSE=0.80 and R^2= 0.77), grain yield (RMSE= 673.95 kg/ha, NSE=0.60 and R^2= 0.69) and biomass yield (RMSE= 1197.16 kg/ha, NSE=0.30 and R^2= 0.61). The CERES-Maize model demonstrated greater proficiency in simulating phenological and yield parameters than the InfoCrop-Maize model.

Key words: CERES-Maize, InfoCrop-Maize, Sensitivity analysis, Calibration, Validation, Statistical evaluation

Introduction

The impact of climate change on crop production varies regionally, with positive effects in some parts of the world and negative effects in hot, dry areas (Ewert *et al.,* 2005; Parry *et al.,* 2004; Gregory *et al.,* 2005). The rainfed *Shivalik* foothills of Punjab have experienced reduced rainfall during *kharif*, affecting agriculture due to unreliable irrigation (Kaur *et al.*, 2022). Maize, a primary cereal crop in this region, faces challenges from rising temperatures, which increase water demand and thereby affect crop growth and reduce yields (Singh *et al*., 2012; Song *et al*., 2016). Studies project a 7.4%

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decrease in maize yield for every degree rise in global mean temperature, indicating the significant impact of temperature and rainfall extremes on maize production (Dogra *et al.,* 2000; Yousuf *et al.*, 2017; Zhao *et al.*, 2017; Kaur *et al*., 2022).

Crop modelling techniques have been used to simulate the effects of climate change on crops by using climate projections to drive process-based or statistical crop models that predict crop yield (Lobell *et al.,* 2008; Lobell and Burke, 2010; Devkota *et al*., 2013). Crop modelling can be used as an efficient tool in utilising agronomic management practices to reduce the adverse effects of future climatic changes, especially in the resource-constrained Kandi region of Punjab. The CERES-Maize model and InfoCrop are crop growth models capable of simulating the influence of various factors such as weather, soil conditions, agronomic practices (including planting methods, nitrogen application, residue management, and irrigation), as well as the impact of significant pests on crop growth and eventual yield (Aggarwal *et al.,* 2006). Sensitivity and uncertainty analyses are required to determine the influence and uncertainty of model input parameters. The modelling work in agriculture has expanded to encompass multi-model comparisons, assessing genotypic, agronomic and climate change impacts on crop growth and productivity, while reducing model uncertainties. These models may also serve as decision support tools for crop management under current and future climates (DeJonge *et al.,* 2012; Patil *et al.,* 2019). Keeping all these in mind, CERES-Maize (DSSAT v 4.8) and InfoCrop-Maize models were used to check their performance and suitability for the region.

Materials and Methods

Study area

The study was carried out at the Regional Research Station, Ballowal Saunkhri, located in the northeastern zone of Punjab, commonly known as the Kandi region. Ballowal Saunkhri is situated at 30°07′N, 76°23′E and lies 355m above mean sea level. The area has a subtropical climate with very hot and dry summer from April to June, hot and humid conditions from July to September, frigid winters in December and January, and mild climate during October, November, February and March.

Field experiment

The data for the calibration and validation of the model were generated from the experiment conducted during the *kharif* season of 2021 and 2022, comprising two maize cultivars (PMH-13 and JC-4) under four sowing dates (1st June, 15th June, 30th June, and 15th July).

Model description

CERES-Maize and InfoCrop-Maize models were developed to simulate daily crop growth, development, and yield under diverse climate and soil conditions with different agricultural management. Both models involve a multitude of input parameters that directly or indirectly affect the accuracy of their outputs. Therefore, it is crucial to conduct sensitivity and uncertainty analyses to understand the influence and associated uncertainty of these input parameters. The required data set and the process for running the CERES-Maize and InfoCrop-Maize models are illustrated in Figures 1 and 2.

Weather data

The minimum weather data set required for running the CERES-Maize model is daily maximum temperature (°C), daily minimum temperature (^{0}C), daily precipitation (mm) and daily solar radiation (MJ m^{-2} day^{-1}), whereas the InfoCrop-Maize model requires an additional data set including wind speed and vapour pressure along with the data set required for the CERES-Maize model.

Site information

The CERES-Maize and InfoCrop-Maize models require latitude, longitude, and altitude-related site information to run.

Soil data

The soil data required to run the models are the upper and lower horizon depths (cm), percentage sand, silt, and clay content, bulk density (g cm^{-3}), organic carbon (per cent), and pH in water.

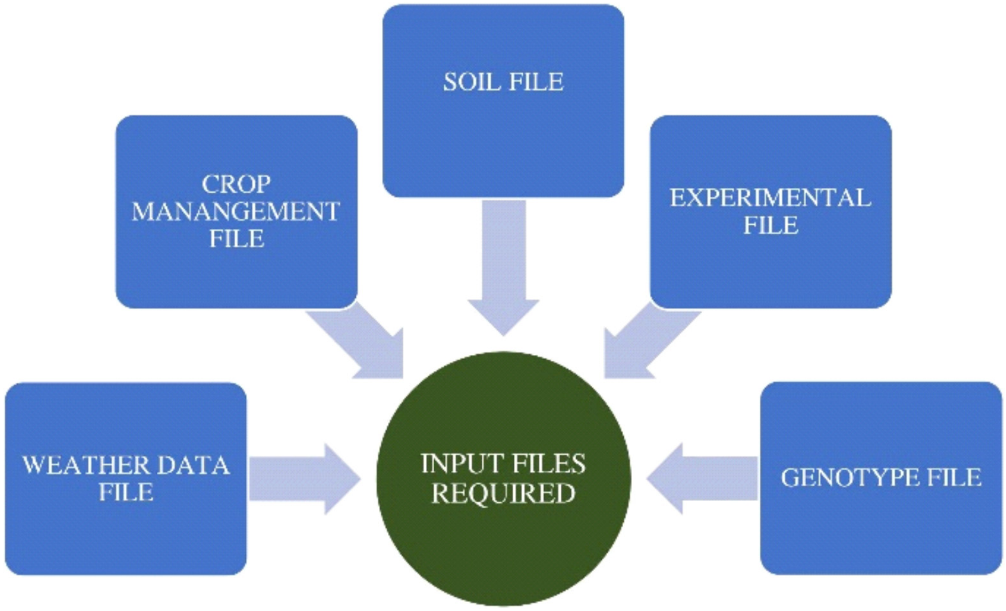

Fig. 1. Minimum data set required to run the model

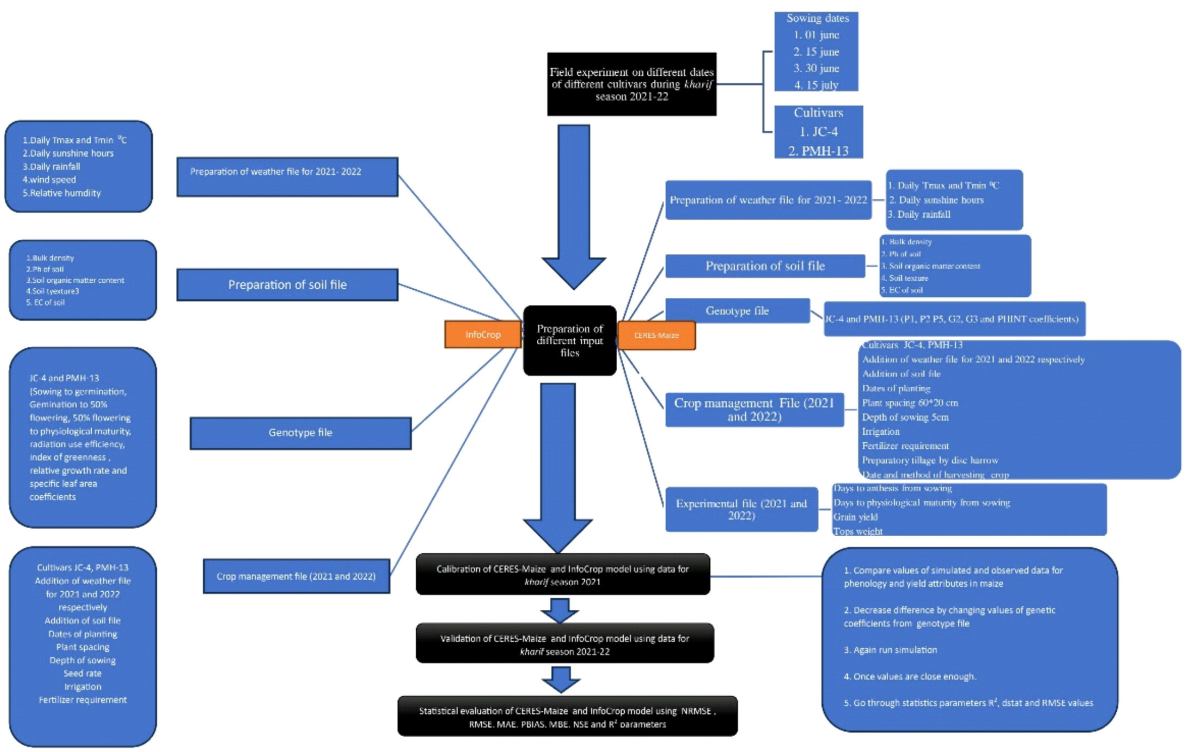

Fig. 2. Flow chart representation of the modelling process using CERES-Maize and InfoCrop-Maize models

Crop management and yield

The crop management includes information on planting dates, dates when soil conditions were measured prior to planting, planting density, row spacing, planting depth, crop variety, date and amount of irrigation and fertiliser application.

Genetic coefficients

These genetic coefficients describe cultivar characteristics in terms of phenology and grain development and are required to run the model. The genetic coefficients for CERES-Maize model are G2 (Maximum possible number of kernels per plant), G3 (Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day), PHINT (Phyllochron interval; the interval in thermal time (degree days) between successive leaf tip appearances), P1 (Juvenile phase (expressed in degree days), P2 (Photoperiod sensitivity) and P5 (Thermal time from silking to physiological maturity (in degree days). Likewise, the genetic coefficients for InfoCrop-Maize model are sowing to germination, germination to 50% flowering, 50% flowering to physiological maturity, relative growth rate of leaf area (°C/day), specific leaf area(dm^2/mg), index of greenness of leaves and radiation use efficiency (g/MJ/day).

Sensitivity analysis

To understand how the models work, a sensitivity analysis of the CERES-Maize and InfoCrop-Maize models was conducted to determine the sensitivity of the model output to changes in 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, indicating the need for accuracy in determining that particular parameter. The Sensitivity tests were performed by altering the values of genetic coefficients.

Model calibration

The CERES-Maize and InfoCrop-Maize models were calibrated using observed field data on phenology and yield components for the *kharif* season of 2021, using repeated interactions of the genetic coefficients.

Model validation and statistical evaluation

The purpose of the validation is to use the well-calibrated crop growth model to compare the simulated and observed yields across seasons that were not part of the calibration process. Data from the *kharif* season 2022 was used for validating the CERES-Maize and InfoCrop-Maize model, which was then evaluated using a variety of statistical tests.

Statistical methods for evaluation of model

The performance of the simulation of CERES-Maize and InfoCrop-Maize model was evaluated using various statistical indices, including the root mean square error (RMSE) (Rani *et al*., 2016), Normalized root mean square error (NRMSE), Nash-Sutcliffe efficiency (NSE), Percent bias index (PBIAS), Mean absolute error (MAE) and Mean bias error (MBE).

Results and Discussions

Sensitivity analysis and calibration of CERES-Maize and InfoCrop-Maize model

The sensitivity analysis for cultivar specific coefficients of CERES-Maize and InfoCrop-Maize (Table 1) models was performed by increasing or decreasing their values to determine their effect on the phenology and yield. Increasing values of P1 led to enhancements in phenology and yield parameters in JC-4 (from 195 to 210) and PMH-13 (from 197 to 210), while decreases (from 195 to 175 in JC-4 and 197 to 190 in PMH-13) resulted in yield reductions. Altering P2 demonstrated varied effects; in JC-4, phenology increased (from 0.5 to 0.6) while yield parameters decreased, whereas in PMH-13, both increased. Decreasing P2 in JC-4 led to reduced phenology but increased biomass yield up to 0.3, after which subsequent decreases affected both biomass and grain yield. Decreasing P2 in PMH-13 resulted in reduced phenology and yield parameters. Altering P5 showed similar effects: increasing values (from 630 to 650 in JC-4 and from 730 to 810 in PMH-13) led to enhancements, while decreasing values (from 630 to 510 in JC-4 and from 730 to 610 in PMH-13) led to reductions in phenology and yield parameters. Increasing G2 values (from 650 to 680 in JC-4 and from 825 to 835 in PMH-13) improved yield

Table 1. Sensitivity test for genetic coefficients in the CERES-Maize model

S. No.	Genetic coefficients	JC-4					PMH-13				
		Range	Anthesis (Days)	Maturity (Days)	Grain yield (kg/ha)	Biomass (kg/ha)	Range	Anthesis (Days)	Maturity (Days)	Grain yield (kg/ha)	Biomass (kg/ha)
1	P1	175	47	80	2665	10818	190	50	90	4552	12386
		195*	48	82	2600	11017	197 *	51	91	4646	12499
		210	50	84	2488	10940	210	52	92	4646	12646
2	P2	0.40	48	82	2610	10969	0.40	50	90	4588	12320
		0.50*	48	82	2600	11017	0.55*	51	91	4646	12499
		0.60	49	83	2543	10941	0.70	51	91	4645	12498
3	P5	610	48	81	2504	10918	710	51	90	4475	12410
		630*	48	82	2600	11017	730*	51	91	4646	12499
		650	48	84	2708	11142	750	51	92	4773	12629
4	G2	610	48	82	2490	10928	810	51	91	4575	12456
		650*	48	82	2600	11017	825*	51	91	4646	12499
		680	48	82	2713	11152	835	51	91	4693	12527
5	G3	8.5	48	82	2557	10996	9.10	51	91	4497	12407
		8.7*	48	82	2600	11017	9.40*	51	91	4646	12499
		8.9	48	82	2678	11116	9.70	51	91	4794	12588
6	PHINT	38	48	82	2637	10981	45.68	51	90	4426	12380
		39*	48	82	2600	11017	46.68*	51	91	4646	12499
		40	49	83	2588	10972	47.68	52	91	4686	12560

parameters, while decreasing values (from 650 to 610 in JC-4 and from 825 to 810 in PMS-13) had opposite effects. Similar trends were observed with alterations in G3 (from 8.7 to 8.9 in JC-4 and from 9.4 to 9.7 in PMH-13), where increasing values improved yield parameters and decreasing values (from 8.7 to 8.5 in JC-4 and from 9.4 to 9.1 in PMH-13) had opposite effects. Increasing PHINT values in JC-4 (from 39 to 40) decreased yield but increased phenology, whereas in PMH-13 (from 46.68 to 47.68), yield parameters increased with no significant effect on phenology. Decreasing PHINT values reduced both parameters across both cultivars. The following Table represent the sensitivity analysis in CERES-Maize (Table 1).

The observed trends in altering genetic coefficients for InfoCrop-Maize revealed that increasing the sowing-to-germination genetic coefficient from 20 to 30 in JC-4 resulted in increased yield parameters with no effect on phenology, whereas in PMH-13, increasing the coefficient from 75 to 80 led to decreased phenology and increased yield. Decreasing these values in JC-4 to 15 caused a reduction in yield, with no effect on phenology, whereas in PMH-13, decreasing them to 65 led to reductions in both yield and phenology parameters. In both JC-4 and PMH-13, increasing germination to 50% flowering (697 to 710 and 770 to 790) increased both parameters, whereas decreasing these values (697 to 670 and 770 to 670) decreased both parameters. Increasing values of 50% flowering to physiological maturity (495 to 510 and 575 to 590) increased yield parameters with no effect on phenology in JC-4 and PMH-13, respectively, while decreasing these values (495 to 470 and 575 to 470) caused yield parameter reductions with no effect on phenology (Table 2).

Variations in grain yield and biomass were observed with increasing relative growth rate from 0.0011 to 0.002 in JC-4, with no effect on phenology, whereas in PMH-13, phenology decreased while yield increased. Decreasing these values in JC-4 to 0.0009 led to increased yield with no effect on phenology, whereas in PMH-13, both yield and

Table 2. Sensitivity analysis for genetic coefficients of cultivars using the InfoCrop-Maize model

S. No.	Genetic coefficients	JC-4					PMH-13				
		Range	Anthesis (Days)	Maturity (Days)	Grain yield (kg/ha)	Biological yield (kg/ha)	Range	Anthesis (Days)	Maturity (Days)	Grain yield (kg/ha)	Biomass (kg/ha)
1	Sowing to germination	15	48	84	2528	10367	65	48	83	3919	13281
		20*	48	84	2682	10750	75*	51	89	4071	13465
		30	48	84	2740	10851	80	48	83	4108	13965
2	Germination to 50% flowering	670	45	79	2603	10258	670	47	84	3671	12972
		697*	48	84	2682	10750	770*	51	89	4071	13465
		710	51	87	2910	10911	790	54	92	4578	14225
3	50% flowering to physiological maturity	470	48	84	2581	10278	470	51	89	3649	12987
		495.0*	48	84	2682	10750	575.0*	51	89	4071	13465
		510	48	84	2885	10874	590	51	89	4379	15051
4	Relative growth rate of leaf area (^{0}C/day)	0.0009	48	84	2572	11452	0.0006	48	83	3784	13322
		0.0011*	48	84	2682	10750	0.0011*	51	89	4071	13465
		0.002	48	84	2546	10230	0.002	48	83	4045	13944
5	Specific leaf area(dm^2/mg)	0.0011	48	84	2499	9753	0.0011	51	89	3567	12813
		0.0015*	48	84	2682	10750	0.0020*	51	89	4071	13465
		0.0025	48	84	2982	10858	0.0025	51	89	4280	13972
6	Index of greenness of leaves	1.00*	48	84	2682	10750	1.00*	51	89	4071	13465
		0.9	48	84	2722	11358	0.9	49	89	4058	13455
		0.79	48	87	2705	10844	0.79	51	87	3973	13347
7	Extinction coefficient of leaves at flowering	0.6	48	84	2838	10933	0.6	51	89	3706	13097
		0.7*	48	84	2682	10750	0.7*	51	89	4071	13465
		0.75	48	87	2559	10550	0.75	51	90	3827	13364
8	Radiation use efficiency (g/MJ/day)	2.9	44	81	2428	9550	3.2	46	85	3513	10959
		3.31*	48	84	2682	10750	3.51*	51	89	4071	13465
		4	50	88	2879	11550	4	55	93	4347	14246

phenology decreased. Increasing the specific leaf area coefficient from 0.0015 to 0.0025 in JC-4 and from 0.0020 to 0.0025 in PMH-13 resulted in increased yield parameters with no effect on phenology, while decreasing these values caused yield reductions with no effect on phenology. Increasing the greenness index in JC-4 altered the trend, except for the days to anthesis. In PMH-13, increasing values from 0.9 to 1.0 led to increasing trends in both parameters, while decreasing values to 0.79 caused a decrease in the yield parameter. Increasing radiation use efficiency from 3.3 to 4.0 in JC-4 and from 3.5 to 4.0 in PMH-13 resulted in increases in both parameters, while decreasing these values to 2.9 and 3.2 in JC-4 and PMH-13, respectively, caused decreases in both parameters. It was observed that in CERES-Maize, altering P1, P2, P5, and PHINT affected yield and phenology in maize, whereas altering G1 and G2 affected only yield. Likewise, in the InfoCrop-Maize model, yield was affected by altering all coefficients, whereas phenology was affected by sowing to germination, germination to 50% flowering, and radiation use efficiency coefficients. Similar results were reported in studies indicating that all six genetic coefficients (P1, P2, P5, G2, G3, and PHINT) affect and contribute to the simulation of crop growth and production in the CERES-Maize model (Song *et al*., 2016; Kothiyal *et al.,* 2022).

The genetic coefficients derived for CERES-Maize model for JC-4 (P1=195.00, P2=0.50, P5=630.00, G2=650.00, G3=8.70 and PHINT= 39.00) and PMH-13 (P1=197.00, P2=0.55, P5=730.00, G2=825.00, G3=9.40 and PHINT= 46.68) cultivars are given in Table 3. For InfoCrop-Maize model genetic coefficients for JC-4 (sowing to germination=20.00, germination to 50% flowering=697.00, 50% flowering to physiological maturity=495.00, relative growth rate of leaf area=0.0011, specific leaf area=0.0015, index of greenness of leaves=1.00, extinction coefficient of leaves at flowering=0.7 and radiation use efficiency=3.31) and PMH-13 cultivar (sowing to germination=75.00, germination to 50% flowering=770.00, 50% flowering to physiological maturity=575.00, relative growth rate of leaf area=0.0011, specific leaf area=0.0020, index of greenness of leaves=1.00, extinction coefficient of leaves at flowering=0.7 and radiation use efficiency=3.51) are given in Table 4.

Validation of the CERES-Maize and InfoCrop-Maize models

The validation of the CERES-Maize and InfoCrop-Maize models explained the association between simulated parameters and observed growth, development, and yield of maize cultivars. The statistical assessment of the validation results comparing observed and simulated data for the growth and yield of maize cultivars is presented in Table 4. The CERES-Maize model demonstrated proficiency in simulating phenological events, as evidenced by close alignment with observed values for anthesis date (RMSE=1.09 days, R^2=0.82) and maturity date (RMSE=0.97 days, R^2=0.97). Furthermore, the model exhibited competency in estimating yield parameters, with simulated values closely matching observed data for grain yield (RMSE=431.63 kg/ha, R^2=0.84) and biomass yield (RMSE= 778.29 kg/ha, R^2=0.74) whereas, InfoCrop-Maize model showed less alignment with observed values for anthesis date (RMSE= 1.6 days, R^2=0.76) and maturity date (RMSE=2.3 days, R^2=0.77). Furthermore, the model exhibited competency in estimating yield parameters, with simulated values closely matching observed data for grain yield (RMSE=673.9 kg/ha, R^2=0.69) and biomass yield (RMSE=1197.2 kg/ha, R^2=0.61) across various maize cultivars and sowing dates during *kharif* (2021-22). The study conducted by Rani *et al.* (2016) calibrated and validated the CERES-Maize model and found good agreement between observed and simulated phenology and yield attributes in maize. The model showed RMSE of 0.87 days for phenology. A study by Kaur *et al*. (2021) calibrated and validated the InfoCrop-Maize model and found good agreement between observed and simulated yield attributes in maize. The model showed R^2 values of 0.84, 0.79, and 0.81 for simulated yield in the Punjab, Haryana, and Delhi regions.

Table 3. Genetic coefficients of maize cultivars used for the CERES-Maize model

Cultivar	P1	P2	P5	G2	G3	PHINT
JC-4	195	0.50	630	650	8.70	39.00
PMH-13	197	0.55	730	825	9.40	46.68

Table 4. Genetic coefficients of maize cultivars used for the InfoCrop-Maize model

Genetic coefficients	Cultivars	
	JC-4	PMH-13
Sowing to germination	20	75
Germination to 50% flowering	697	770
50% flowering to physiological maturity	495	575
Relative growth rate of leaf area (^{0}C/day)	0.0011	0.0011
Specific leaf area (dm^2/mg)	0.0015	0.0020
Index of greenness of leaves	1.00	1.00
Extinction coefficient of leaves at flowering	0.7	0.7
Radiation use efficiency (g/MJ/day)	3.31	3.51

Table 5. Statistical evaluation of both the crop growth models

Models	Crop attributes	Statistical parameters						
		MAE	MBE	RMSE	PBIAS	NSE	NRMSE	R^2
CERES-Maize	Anthesis	0.06	-1.06	1.09	0.01	1.00	0.02	0.82
	Maturity	0.06	-0.44	0.97	0.01	1.00	0.01	0.97
	Grain yield	18.13	-17.75	431.62	0.01	0.80	0.11	0.84
	Biomass yield	97.94	-276.06	778.29	0.02	0.70	0.06	0.74
InfoCrop-Maize	Anthesis	0.06	-1.06	1.85	0.02	0.70	0.03	0.76
	Maturity	0.13	-0.38	2.26	0.01	0.80	0.02	0.77
	Grain yield	96.69	-325.93	673.95	0.08	0.60	0.18	0.69
	Biomass yield	122.72	-408.19	1197.16	0.03	0.30	0.09	0.61

Statistical evaluation

The CERES-Maize model's evaluation metrics highlight its accuracy in predicting critical aspects of maize growth (Table 5). It shows strong performance in estimating grain yield (MAE=18.13, RMSE=431.62, NSE=0.8), while biomass yield predictions, though less accurate (MAE=97.94, RMSE=778.29, NSE=0.7), still remain reasonably efficient. Moreover, the model accurately forecasts both maturity and anthesis days, with minimal error (MAE=0.06) and high efficiency (NSE=1.0), demonstrating its reliability in predicting these pivotal growth stages in maize cultivation. InfoCrop-Maize model's performance varies across parameters. It moderately predicts grain yield with (MAE=96.69, RMSE=673.95, NSE=0.6) and biomass yield with higher errors and less efficiency (MAE=122.72, RMSE=1197.16, NSE=0.30). However, it reasonably forecasts maturity and anthesis days with lower errors (MAE=0.13 and 0.06, respectively) and moderate efficiencies (NSE=0.8 for maturity and NSE=0.7 for anthesis), indicating its decent capability to predict these vital growth stages in maize cultivation, as depicted in Table 5.

Conclusion

CERES-Maize and InfoCrop-Maize models were calibrated and validated for two maize cultivars (JC-4 and PMH-13) under four sowing dates (1st June, 15th June, 30th June, and 15th July). It was observed that in CERES-Maize, phenology and yield were sensitive to P1, P2, P5 and PHINT, whereas G2 and G3 coefficients affected the yield only. In the InfoCrop-Maize model, yield was affected by all parameters, whereas phenology was affected by time of sowing to germination, 50% flowering to germination and radiation use efficiency. CERES-Maize predicted grain yield more efficiently (MAE=18.13, NSE=0.8) compared to InfoCrop-Maize (MAE=96.69, NSE=0.6). Thus, CERES-Maize may be used to simulate growth and yield parameters for the Shivalik foothills of Punjab, making it suitable for investigating the impact of genotypes, agronomic practices, soil conditions, and changing climatic conditions on yield, and for aiding the adoption of agronomic management practices to mitigate adverse effects on crop growth and yield.

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