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Yield Gap Analysis under Different Water and Nitrogen Management Practices in Wheat Crop using CSM-CROPSIM-CERES –Wheat Model in *Tarai* Region of Uttarakhand

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A B S T R A C T

Water and nitrogen are two primary limiting factors for wheat yield. In consonance with this, field experiment was conducted at Norman Ernest Borlaug Crop Research Centre in Pantnagar (Uttarakhand) during *Rabi* season of 2017-18 to analyze the performance of CSM-CROPSIM-CERES-wheat model for wheat cultivar (PBW-502) grown under different stress conditions characterized by inducing different water and nitrogen levels. 27 treatment combinations consisted of 3 DOS (12th December, 22nd December and 02nd January), 3 irrigation levels (100% irrigations, 75% irrigations and 50% irrigations) and 3 nitrogen levels (100%, 75% and 50% of recommended nitrogen doses) laid in a Factorial RBD with 3 replications. The results revealed good agreement between simulated and measured data of crop phenology, LAI and grain yield. The simulated and observed yield ranged between 1.5 to 4.95 t/ha and 1.42 to 4.73 t/ha, respectively. RMSE was found to be 11.61% with R^2 value of 0.90, which is found significant. The model performance was validated with the experimental dataset of year 2007-2008 by using genetic coefficients obtained during calibration process. Degree of stress in wheat crop was analyzed in terms of yield gap, which was found higher (68. 28 %) under lowest levels of irrigation (2 irrigation) and nitrogen (75 kg ha^{-1}).

Introduction

Wheat (*Triticum aestivum* L.) is the most important cereal crop all over the world and it ranks firstboth in aspects of area (225.07 million hectares) and production which was about 735.70 million tonne during 2015-2016 (FAO, 2017). In India, wheat is second most important cereal crop with production of 93.50 million tonnes after rice and ranks second in the queue after China (FAOSTAT, 2016). Highest yield is usually attained with favorable soil conditions, optimum water and fertilizer input, and good management practices (Cui *et al.*, 2005; Zhang *et al.*, 2013). Overall, the increase in wheat yield is more pertaining to substantial rise in irrigation and nitrogen application.

Decision making and planning in agriculture essentially execute various model-based decision support systems in relation to changing climate scenarios and management activities. The models applied needs to be thoroughly calibrated for the particular set of conditions and then only they can be applied to assess the impact of different environmental and management conditions in crop yield. DSSAT (Decision support system for Agrotechnology transfer) is a software application program which comprising of variety of crop simulation model has been frequently used to assess the yield response under different environmental conditions (Rinaldi, 2004; Yang *et al.*, 2010). Crop models simulate growth and development processes as a function of soil, weather, management practices and crop cultivar.

Considering the capability of CERES-wheat for determining quantitative effects of varied environmental and managerial parameters on production of wheat, by choosing different strategies such assessing different varieties, different planting dates, assessing the amount and time of nitrogen application and simulation may evaluate the effects of these factors with the long term meteorological data, growth, reproduction and yield of wheat in the regional and national levels (Boote *et al.*, 2001). After a thorough evaluation of CSM-CROPSIM-CERES-Wheat, the model was able to judiciously quantify wheat development, growth and yield responses to within-season variability in plant population and nitrogen application rate and to seasonal variation in weather and management practices (Thorp *et al.*, 2010). In the recent years, DSSAT has been extensively utilized to analyze yield gap under different water and nitrogen limiting conditions (Lobell and Monasterio, 2007; Anderson, 2010; Torabi *et al.*, 2011).

The objective of the present study is to simulate yield of wheat cultivar (PBW-502) under different irrigation and nitrogen levels using CSM-CROPSIM-CERES-Wheat model, and also to assess stress levels through yield gap analysis.

Materials and Methods

Study site

In order to evaluate the performance of CROPSIM-CERES-Wheat crop simulation model under stress conditions for a wheat variety (PBW-502), a 3-factorial randomized block design with 81experimental plots was laid out at Norman Ernest Borlaug Crop Research Centre (NEBCRC), Pantnagar (Uttarakhand) during *Rabi* season of 2017-18. Eighty one experimental plots consists of 3 dates of sowing [12^{th} December (D_1), 22^{nd} December (D_2) and 02^{nd} January (D_3)], 3 levels of irrigation [100% irrigations (I_1), 75% irrigations (I_2) and 50% irrigations (I_3)] and 3 levels of nitrogen [100% (N_1), 75% (N_2) and 50% (N_3) of recommended nitrogen doses] with 3 replications.

Considering the convenience aspect, in rest of the document, treatment combinations will be described on the basis of abbreviations used for them, e.g., $I_1N_1D_1$ implies first level of irrigation (100% = full irrigation), nitrogen (100%= 150 kg N/ha) and date of sowing (first sowing = 12^{th} December). The description of number of irrigation and amount of nitrogen doses is given in Table 1.

Model description

In this study, we deployed CERES-Wheat cropping system model (CSM-CERES-Wheat model) embedded under DSSAT software application program for simulation of wheat performance under different stress conditions induced by varying water and nutrient (specifically in terms of nitrogen). DSSAT model primarily operated on the 3 databases; one corresponds to the weather and soil information of the area under study, as well as agronomic management and physiological traits of each variety selected for the study.

Weather and soil database

Laboratory measurement of soil's physico-chemical properties from a portion of the experimental area at different depths were included in the DSSAT soil. sol file and was used to construct soil database. Weather information was provided by the Automatic Meteorological Station (AWS) located at the close proximity to the experimental area in GBPUAT, Pantnagar (29^0N, 79.3^0E) and includes maximum and minimum temperature, solar radiation and precipitation on daily basis. Observed weather data was incorporated in the DSSAT WeatherMan module in order to generate WTH file.

Crop characteristics database

Managerial information includes specifications of plant spacing, planting depth, method of seed application, variety used, amount, method and time of irrigation, type of fertilizer used and its amount and time of application. Observation of physiological characters under different treatments is also needed which includes planting date, emergence, crown root initiation, tillering, jointing, milking, physiological maturity and harvesting. Taking into consideration the essential input data for proper execution of the model, parameters such as plant height, plants m^{-2}, leaf area index, number of grains per spike, 1000 grain weight (g) was measured via all stages.

Implementation, calibration and validation of model

DSSAT model v.4.7 was used for analysis. AT Create module based on crop information was used to create three files for PBW-502, i.e., WHX, WHT, and WHA. The first is experimental file (.WHX) containing information on all above specified experimental conditions. Secondly, the WHA file includes average performance data and information on phenological observations such as anthesis date, flowering data, number of spikes m^{-2} and maturity data (Hoogenboom *et al.*, 2003) while WHT file incorporates the progression of the field data over time such as growth analysis data.

Calibration and validation of model

Calibration of the model was accomplished by using measured values from experimental area for *Rabi* season of 2017-2018, comprising of 27 treatment combinations. In order to calibrate and validate the model, it is indispensable to determine the "genetic coefficients" of the wheat genotype (PBW-502) under study. Seven genetic coefficients for wheat was considered, which were obtained in a sequential manner, commencing with the coefficients which mainly deal with phenological development (P1V, P1D, P5, PHINT) followed by the coefficients primarily dealing with growth factors (G1, G2, G3) (Hunt *et al.*, 1993; Hunt and Boot, 1998).

An iterative approach was applied to derive the genetic coefficients by performing trial and error adjustments until there occur a close match between simulated and observed data for the traits under consideration. Subsequent validation was performed for PBW-502 for the year 2007-2008.

Based on the above mentioned dataset, we used some indices to evaluate the fitting of the model such as root mean square error (RMSE), coefficient of determination (R^2), index of agreement (d-index).

All the indices measures degree of fitting between simulated and measured data (Geng *et al.*, 2017). R^2 and RMSE are used to address the degree of dispersion (RMSE) and degree of association (R^2) between observed and simulated data. Value of d-index as 1 represents good fitting of model while the value of d-index close to 0 indicates bad model fitting between simulated and observed data.

$$d - \text{index} = 1 - \frac{\sum_{i=1}^{n}(Si - Oi)^2}{\sum_{i=1}^{n}((|Si - \bar{O}|) + (|Oi - \bar{O}|))2}$$

where, S*i* refers to simulated value under every treatment combination, O*i* is the observed value, $\bar{O}$ denotes average of observed values.

Yield gap analysis

Yield was simulated by using crop simulation model and yield loss (yield gap) was calculated as:

$$\textbf{Yield gap} = \left(\frac{Ysim - Yobs}{Ysim}\right) * 100$$

where, Ysim is the simulated yield through model under optimal condition ($I_1N_1D_1$), Yobs is the observed yield under different treatment combination.

Results and Discussion

Model calibration and validation

The genetic coefficients of the wheat cultivar (PBW-502) obtained after accomplishment of calibration process tabulated in Table 2. The calibration result of CSM-CROPSIM-CERES-wheat model was assessed under different treatment combinations in the present study using the days from planting to emergence, planting to anthesis, planting to physiological maturity, maximum leaf area and yield. Results revealed that the days taken from planting to emergence ranged between 7 to 12d and 4 to 7d for observed and simulated values, respectively. Model underestimated the emergence period under every treatment combination.

For planting to anthesis period, simulated period ranges from 96 to 80d while observed anthesis period was from 93 to 81d. The estimated days to attain physiological maturity were 113 to 127d which was higher than the observed data for physiological maturity (108 to 127 d). Leaf area index (maximum) ranged between 1.4 to 5.1 and 1.5 to 5.1 for simulated and observed data, respectively.

Table.1 Irrigation and nitrogen treatments used for calibration of the CSM-CROPSIM-CERES-Wheat model. Details include amount of water and nitrogen applied (mm)

Irrigation Levels (Fixed irrigation amount at each stage = 60 mm)	
I_1	Four irrigations at CRI, late jointing, flowering and milking
I_2	Three irrigations at CRI, late jointing and milking
I_3	Two irrigations at CRI and late jointing
Nitrogen levels (Recommended dose = 150:60:40)	
N_1	150 kg N/ha
N_2	112.5 kg N/ha
N_3	75 kg N/ha

CERES-Wheat model. Details include amount of water and nitrogen applied (mm)

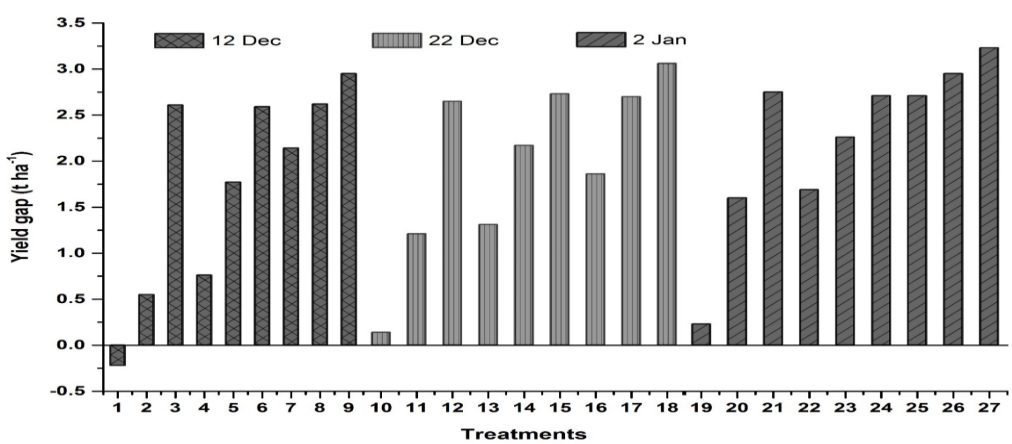
Table.2 Genetic coefficients of wheat cultivar (PBW-502) obtained through calibration of CSM-CROPSIM –CERES-Wheat model

Code	Parameters	Genetic coefficient	Unit
P1V	Days at optimum vernalization temperature required to compete vernalization	0.5	d
PID	Percentage reduction in development rate in a photoperiod 10 hr shorter than the threshold relative to that at the threshold	88	%
P5	Grain filling (excluding lag) phase duration	620	^{0}C d
G1	Kernel number per unit canopy weight at anthesis	40	nr/g
G2	Standard kernel size under optimum conditions	45	mg
G3	Standard, non-stressed dry weight (total, including grain) of a single tiller at maturity	4.0	g
PHINT	Phyllochron interval (GDD)	95	^{0}C d

Table.3 RMSE, coefficient of determination and d-index (Wilmott's index of agreement) obtained for phenological stages, maximum LAI and yield

Variable	RMSE	RMSE (%)	R^2	d-index
Days from planting to emergence	3.97	44.87	0.62	0.33
Days from planting to anthesis	2.31	2.64	0.84	0.95
Days from planting to physiological maturity	3.82	3.25	0.94	0.92
Maximum leaf area index	0.55	20.58	0.72	0.85
Grain yield (t ha^{-1})	3.19	11.61	0.90	0.97

Fig.1 Yield gap analysis (t ha^{-1}) depicted in the form of bars. Different patterned bars represent crop sown under different dates. 1-9 treatment combinations represent treatments I_1N_1, I_1N_2, I_1N3, I_2N_1, I_2N_2, I_2N_3, I_3N_1, I_3N_2 and I_3N_3 in the same sequence under first date of sowing (12th December, 2017). Similarly, treatment combinations 10-18 and 19-27 represents same sequenced irrigation and nitrogen levels under different dates of sowing



Finally, the model predicted the final yield (product weight) which ranged between 1.42 to 4.73 t $ha^{-1}$and 1.5 to 4.95 t ha^{-1} for observed and simulated data, respectively. We can govern that model adjustments considered satisfactory based on the RMSE values (Table 3). For the days from planting to anthesis, calculated RMSE value was 2.31. Scientists dealing with wheat simulations determined RMSE to be 3.0 (Bannayan *et al.*, 2003) and 6.6 (Rezzoug *et al.*, 2008) for anthesis. Values for maturity in the present study calculated as 3.82; ranges of 10.0 (Bannayan *et al.*, 2003), 7.1 (Rezzoug *et al.*, 2008) and 1.4-12.2 (Maldonado-Ibarra, 2015) were reported. In the same way, RMSE values for maximum LAI and grain yield were calculated as 0.55 (20.58%) and 3.19 (11.61%), respectively. Pal *et al.*, (2015) estimated RMSE (%) values upto 5.8 and 11.0 for PBW-343 and WH-542, respectively. Nain *et al.*, (2002) also stated that model could simulate the crop yields even when RMSE vary upto 20%.

When evaluating R^2 (degree of association) between observed and simulated values for selected variables (Table 3), phenological characters has a very strong adjustment and exhibits high R^2 and low RMSE (%). Fair adjustment was seen for grain yield (t ha^{-1}) having R^2 value as 0.90. Measured R^2 values for maximum leaf area index well corroborates with the result reported by Pal et al (2015). Validation results were found satisfactory with RMSE value of 8.86%, 8.07%, 18.30% and 5.35% for anthesis, physiologoical maturity, maximum leaf area index and grain yield, respectively.

Yield gap analysis

Degree of stress was assessed in terms of yield losses (Fig. 1) which were computed by taking difference between simulated yield under non-limiting conditions (taken as reference level) and observed yield under different treatment combinations. Model underestimated the yield under optimal condition ($1=I_1N_1D_1$) by 4.65%. Further increase in yield gap was observed as a consequence of significantly higher limitations induced in the field in the form of receding water and nitrogen levels. Maximum yield gap (3.23 t ha^{-1}) was observed under lowest level of irrigation (2 irrigations) and lowest level of nitrogen (75 kg ha^{-1}), in which yield is reduced by 68.28%.

In conclusion the results of model calibration and validation showed that the simulated growth and development parameters of wheat were in good agreement with the observed data which was recognized with the aid of statistical analysis (RMSE, r^2 and d-index). Usefulness of DSSAT model for assessing yield gap of wheat in Pantnagar region representing foothills of Himalayas, found quite satisfactory. The yield gap calculated as a difference between simulated yield under optimal conditions and observed yields under different stress conditions increases with increase in the stress level. Consequently, maximum yield gap was observed for plots sown very lately (2 Jan 2018) under lowest level of irrigation (2 irrigations) and lowest level of fertilizer (75 kg ha^{-1}). Improving water and nutrient efficiency can act as an effective solution for improving yield over Pantnagar region.

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