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Research Paper

Yield Prediction, Sensitivity Analysis and Calibration of DSSAT Crop Model for Different Cultivars, Establishment Methods and Nitrogen Levels in Rice (*Oryza sativa* L.) Under Normal and Varied Temperatures

Masina Sairam[1*], Lalichetti Sagar[1], M. Devender Reddy[1], T.L. Neelima[2] and V. Ramulu[2]

[1]Department of Agronomy, M.S. Swaminathan School of Agriculture, Centurion University of Technology and Management, Paralakhemundi, Odisha, India
[2]Water Technology Center, Prof. Jayashankar Telangana Agricultural University, Rajendranagar, Hyderabad, Telangana, India

*Corresponding author: sairam.masina@cutm.ac.in (**ORCID ID:** 0000-0002-1031-2919)

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ABSTRACT

Rice is one of the important cereal crops grown throughout the world. There are various factors like climate, soil, variety and management are influencing the growth and yields of rice. Selection of best performing cultivar, proper irrigation scheduling and nutrient management techniques can play a key role in improving the productivity of rice. To evaluate these constraints the data was taken from an experiment conducted for two years during *kharif* 2009 and 2010 at Water Technology Centre, College Farm, Rajendranagar, Hyderabad and was used to calibrate and evaluate the DSSAT model for rice. In the experiment, there were three cultivars (Tellahamsa, IR 64 and MTU 1010), two crop establishment methods (Aerobic rice and transplanted rice) and five nitrogen levels (100,150, 200, 250 and 300 kg ha^{-1}) which were laid in split –split plot design. The inputs like soil data, weather data, crop data, genetic coefficients, irrigation scheduling and harvesting dates were given to the model for calibration and validation. The observed and model predicted yields were evaluated and the outcome revealed that the predicted values were statistically similar to the observed values with a mean RMSEn of 2.26 and 22.2 for crop establishment methods, 2.02 and 18.87 for cultivars and 4.43 and 16.01 for Nitrogen levels during the years of study. The sensitivity analysis when performed with 1^{o}C increase and decrease in temperature significantly affected the rice yield. The decrease in daily maximum and minimum temperatures of the region has increased the yield. However, the increase in temperature forecast a drastic reduction in the grain yield of rice.

HIGHLIGHTS

- DSSAT crop model can understand the crop management activities better by interrelating weather, soil and crop data to evaluate the yield and resource use efficiency.
- Sensitivity analysis can predict the effect of climate change and temperature on rice crop growth and productivity

Keywords: DSSAT crop model, Nitrogen levels, Irrigation, Grain yield, Sensitivity analysis

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Irrigation is one of the major constraints in extending the rice production in many countries including India (Sikka *et al.* 2022). In majority of rice growing areas, it is cultivated by different methods in India as well as in Asia. Rice is grown under submergence and there is a greater requirement of irrigation water for its better growth and productivity. Rice yields are highly susceptible to improper water management and the yield reduction can be more than 40-60% with irregular irrigation practices (Wassmann *et al.* 2009). Improved methods of rice establishment such as aerobic rice cultivation can enhance the water use efficiency and grain yields. Along with proper irrigation management and scheduling, nitrogen fertilization plays an important role in improving rice productivity (Kadiyala *et al.* 2012). The recommended dose of nitrogen can sometimes lead to under or over fertilization in the fields (Zilio *et al.* 2023). Timely and optimal nitrogen management can improve the productivity of the crop and thereby increasing the nitrogen use efficiency (Ram *et al.* 2020). In India, many high yielding varieties were developed which respond to nutrient application. Selection of variety is one of the most important aspects for achieving the target yield suitable for a particular location (Zhou *et al.* 2023).

The occurrence of rainfall, humidity and temperature can influence the irrigation scheduling of a crop (Wang *et al.* 2022). Temperature plays a major role in determining the crop genetic coefficient. The parameters like, soil texture and nutrient status are having a remarkable effect on nitrogen requirement. In this regard, a CERES rice model based on DSSAT 4.6 can be an alternative to agronomic experiments. This model can understand the crop management activities better by interrelating weather, soil and crop data to evaluate the crop phenology, growth stages and yield and there by efficiently handling the resource use efficiency (Jones *et al.* 2003). CERES rice model is a decision support tool for agricultural technology transfer (Kadiyala *et al.* 2015), which is used by many developed and developing countries to evaluate the model developed predictions for successful raising of a crop with more emphasis on maximizing the yields and minimizing the resource use (Goswami and Dutta, 2020).

Considering the above facts, the present study was taken up with the data having two rice establishment practices, three cultivars and five levels of nitrogen application to validate the CERES rice model for yield simulations. Further, the model calibration performance was tested for rice crop performance with increased and decreased temperatures.

MATERIALS AND METHODS

Experimental site

A field experiment was carried out for two successive years during *kharif* 2009 and 2010 at Water Technology Centre, College Farm, Rajendranagar, Hyderabad, India. The data generated was used to calibrate and evaluate the CERES rice model. The site was located in Deccan interior region of Telangana, India with an altitude of 543 MSL and the soil of the experimental site is sandy loam in nature with slightly basic pH of 7.8. The details of the soil profile is presented in Table 1. The climatic conditions of the area is semi-arid in nature with an annual rainfall of 860 mm. The daily weather data from June to December (cropping period) for the years 2009 and 2010 for maximum and minimum temperature, rainfall and solar radiation of Rajendranagar, Hyderabad was provided for the system (Figs. 1 and 2).

Treatment details

Rice crop was cultivated for two years (2009 and 2010) during the *kharif* season (June to November). The data considered for this study consists of 30 treatment combinations laid under split-split plot design. The treatments are namely, two rice establishment methods (aerobic rice (AR) and Transplanted rice (TR)) in main plot, three cultivars (Tellahamsa, IR64 and MTU1010) in subplot and five levels of nitrogen (100, 150, 200, 250 and 300) in sub-sub plot. The aerobic rice was line sown in the field at a distance of 20 cm between rows and the transplanted rice was sown in the nursery and later the seedlings were transplanted in main field at a spacing of 20 cm row to row and 15 cm plant to plant. The sowing of AR was done on 27th June during 2009 and 2nd July during 2010 and the transplanting was done on 9th August during 2009 and 25th August during 2010 (Table 2). The nutrients were applied as per the treatments. Nitrogen was applied in three splits whereas an equal amount of phosphorous (60kg ha^{-1}) and potassium (60kg

Table 1: Physical and chemical properties of experimental soil used for DSSAT validation

Depth (cm)	Bulk density (g cm^{-3})	Soil organic carbon (%)	Clay (%)	Silt (%)	Sand (%)	pH	CEC (cmol kg^{-1})
0-15	1.28	0.56	36.4	15.0	48.6	7.8	24.6
15-30	1.35	0.44	34.2	11.7	54.1	8.1	19.0
30-45	1.44	0.42	33.6	9.3	57.1	8.3	14.2
45-60	1.52	0.21	28.3	9.1	62.6	8.3	10.7

Table 2: Experiment details provided to run DSSAT model

Parameters	Aerobic	Transplanted
Date of planting	27th June for 2009 and 2nd July for 2010	9th August for 2009 and 25th August for 2010
Method of planting	Line sowing	Transplanting
Planting distribution	Hills	Hills
Plant population at seeding stage (plants m^{-2})	44	33
Row spacing, cm	20	20
Seeding/Planting depth, cm	3	5
Seeding material	Dry direct seed sowing	33 days old seedlings

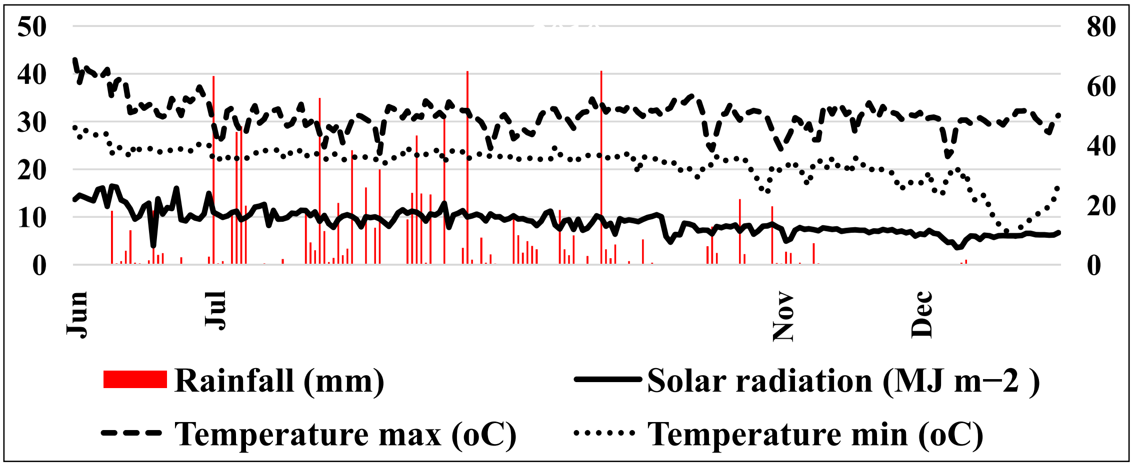

Fig. 1: Meteorological data of the cropping period for the year 2009

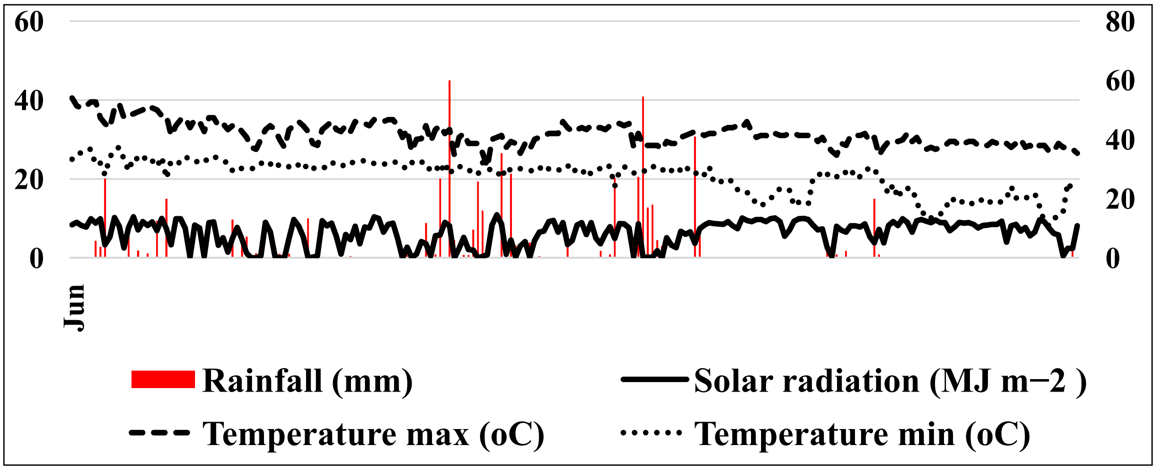

Fig. 2: Meteorological data of the cropping period for the year 2010

ha^{-1}) was applied as basal dose before sowing / transplanting. In AR rice, irrigation was scheduled when the moisture content of top 30 cm of the soil layer reached 60%, and in TR, irrigation was scheduled to maintain continuous ponding (Table 3).

Weather and crop coefficient measurement

Weather data such as maximum and minimum temperature, rainfall and solar radiation was considered for DSSAT model application. The weather data for the years 2009 and 2010 were collected from the meteorological observatory at Agricultural Research Institute (ARI), Rajendranagar, Hyderabad. The daily sunshine hours were converted into solar radiation (MJ m^{-2} day^{-1}) by using DSSAT weatherman tool for weather analysis.

The three cultivars which are considered for experiment are medium duration and suitable for *kharif* season. The model calibration was done to estimate the genotype coefficients to confirm an agreement between model predictions and observed values based on the model approach (Pereira *et al.* 2021). The CERES-Rice model was calibrated with the data obtained from 2009 and 2010 field experiment with the treatment receiving 300 kg N ha^{-1} under TR conditions. The genetic coefficient of these three cultivars namely, Tellahamsa (RNR 10754), IR64 and MTU 1010 are calibrated by considering the varietal coefficients which are determined by thermal time from emergence to the end of juvenile stage (P1), Critical photoperiod (P20), rate of photo induction (P2R), optimum photoperiod (P2), thermal time for grain filling (P5), conversion efficiency from sunlight to assimilates (G1), grain size (G2), tillering coefficient (G3) and temperature tolerance coefficient (G4). The details of the genetic coefficient of varieties are presented in Table 4.

Statistical analysis

Model performance evaluation was statistically presented by the absolute Root Mean Square Error (RMSE), normalized root mean square error (RMSEn), coefficient of residual mass (CRM) and Modelling efficiency (ME). The RMSE and RMSEn elucidate the magnitude of the average error but do not provide information about the relative size of the average difference between the observed and predicted. But, CRM indicates the direction of the error magnitude. The root mean square error (RMSE) was calculated using the following equation (Wallach and Goffinet, 1989).

Table 3: Irrigation details of the experiment provided to validate the DSSAT crop model

Treatments	Description	Total number of irrigations		Irrigation amount (mm)	Total amount of irrigation (mm)	
		2009	2010		2009	2010
Aerobic	The water was applied when available soil moisture in top 30 cm reached 60%	11	09	50	550	450
Transplanted	The water was applied at regular intervals to maintain ponding conditions till grain filling stage	22	21	50	1100	1050

Table 4: Genotypic coefficient of cultivars used in experiment

Genetic Coefficients	Tellahamsa	IR64	MTU1010
P1	390	420	450
P20	130	100	175
P2R	350	350	370
P5	11.0	11.4	11.3
G1	75	51	72
G2	0.02	0.02	0.025
G3	1	1	1
G4	1.0	1.0	1.1
PHINT	85	83	83

Root Mean Square Error (RMSE) =

$$\sqrt{\sum_{i=1}^{n}\frac{(Pi-Oi)^2}{n}}$$

The simulation is considered excellent with a RMSEn less than 10 %, good if it is greater than 10% and less than 20%, fair if it is greater than 20% and less than 30%, and poor if it is greater than 30%. The following equation was used to calculate RMSEn (Kumar *et al.* 2017).

Normalized Root Mean Square Error (RMSEn) =

$$\left[\frac{RMSE}{\text{Mean of observed values}}\right]\times 100$$

The Coefficient of Residual Mass (CRM) was also used to measure the tendency of the model to overestimate or underestimate the measured values. A negative CRM indicates overestimation and positive CRM indicated under estimation (Vijayalaxmi *et al.* 2016). The CRM was calculated using the following equation:

Coefficient of Residual Mass (CRM) =

$$\frac{\sum_{i-1}^{n}Oi-\sum_{i-1}^{n}Pi}{\sum_{i-1}^{n}Oi}$$

Modeling efficiency varies between negative infinity to 1.0. A negative modeling efficiency (ME) shows that mean value of the experimental data is higher predictor than the model value whereas a ME of 1.0 signifies a perfect model agreement with observations (Garnier *et al.* 2001).

Modelling efficiency (ME) =

$$\frac{\sum_{i-1}^{n}(Oi-O)-(Pi-Oi)^2}{\sum_{i-1}^{n}(Oi-O)^2}$$

Where *Pi* and *Oi* are the predicted and observed values, *n* is the number of observations and *O* is the mean of the observed values.

Model calibration and validation

For calibration of the model, each variety was analyzed separately to find the genetic coefficient of particular variety. Nitrogen at 300 kg ha^{-1} in transplanted conditions was considered for finding the genotypic coefficient to better interrelate simulated and observed data. After calibration of each variety, different treatment combinations are made to run the model. In each set of data, ten combinations of the treatments were run, the treatment combinations include variety, rice establishment method and nitrogen levels. After getting the predicted data of each cultivar combination, the data was compiled and analyzed with observed values. Along with this, the sensitivity analysis was done with increase and decrease in maximum and minimum temperature by 1°C. The weather file was modified by changing the temperatures and the validation of the system was done with new weather data to compare the predictions with changes in temperature.

RESULTS AND DISCUSSION

The data of predicted and observed values for grain yield were validated and statistically analyzed with different indices for rice establishment methods, cultivars and nitrogen levels for the year 2009 and 2010 (Table 5).

In terms of rice establishment methods, the DSSAT model has underestimated the prediction in AR conditions where as the model overestimated the yield under TR condition. In 2009 and 2010, the analysis of predicted and observed values of RMSE were 74.99 and 206.44 respectively. The RMSEn was found to be excellent and fair in both the years with an analyzed value of 2.26 and 22.0. The coefficient of residual mass (CRM) obtained during both the years was 0.29 and 0.38 for 2009 and 2010 respectively. The positive results of CRM reveal that the model was under estimating the yield in terms of rice establishment methods. The values of modelling efficiency (ME) also showed that the experimental values are better than the model simulated values with a mean ME of -0.95 and -0.82 for the year 2009 and 2010, respectively.

The model under estimated the values with respect to cultivars, but the modelling tool showed more efficiency with a mean RMSE of 66.56 and 148.32

Table 5: The predicted and observed grain yield of rice under different methods of establishment, cultivars and nitrogen levels

Treatments	2009		2010	
	Simulated grain yield (kg ha^{-1})	Observed grain yield (kg ha^{-1})	Simulated grain yield (kg ha^{-1})	Observed grain yield (kg ha^{-1})
Rice establishment methods				
Aerobic	3260	3336	2658	3813
Transplanted	3360	3287	3688	3538
RMSE	74.91		206.44	
RMSEn	2.26		22.20	
CRM	0.29		0.38	
ME	-0.95		-0.82	
Cultivars				
Tellahamsa	2602	2612	3066	3214
IR64	3510	3604	3158	3323
MTU 1010	3618	3684	3312	4491
RMSE	66.56		148.32	
RMSEn	2.02		18.87	
CRM	0.48		0.31	
ME	-0.96		-0.74	
Nitrogen levels, kg ha^{-1}				
100	2573	2893	2207	2393
150	3014	3051	2675	3031
200	3295	3238	3325	3626
250	3530	3515	3518	4255
300	3838	3861	4015	5073
RMSE	113.24		127.45	
RMSEn	4.43		16.01	
CRM	0.18		0.34	
ME	-0.99		-0.92	

for the year 2009 and 2010 respectively (Table 5). The RMSEn for cultivars was found to be excellent for the year 2009 with a value of 2.02 and a good prediction (18.87) for 2010. The CRM (0.48 and 0.31) and ME (-0.96 and -0.74) for both the years revealed that the model has under predicted the values when compared with experimental data.

The DSSAT model also made an efficient prediction with respect to nitrogen levels. Similar to the crop establishment methods and cultivars, the system underestimated the yields for nitrogen levels with an RMSE of 113.24 and 127.45 for the years 2009 and 2010 respectively. However, the RMSEn was found to be better in 2009 (4.43) as compared to 2010 (16.01). The CRM (0.18 and 0.34) and ME (-0.99 and -0.92) also supports the study by strongly proving that the system under estimated a little when the analysis was drawn between observed and predicted values. The predicted values shows that the predictions for the year 2009 was more accurate when compared with 2010 this can be due to the increase in observed yield during 2010 than in 2009.

Sensitivity analysis

The sensitivity analysis of the model showed a significant change in yield predictions due to the increase and decrease in daily maximum and minimum temperatures (Sreenivas *et al.* 2010) (Table 6).

The sensitivity analysis clearly shows the impact of temperature on rice grain yields and the fluctuations in yields with increase and decrease in temperatures (Table 6). The validation clearly shows that the decrease in temperature has increased the grain yield and the increase in temperature has reduced the grain yield. The observations show that 1°C increase in both maximum and minimum temperatures resulted in decrease of the yield

Table 6: Sensitivity analysis of normal predicted data with observed values and change in temperature values

Treatments	Grain yield (kg ha⁻¹)					
	2009			2010		
	Normal Simulation	Decreased temperature (-1°C)	Increased temperature (+1°C)	Normal Simulation	Decreased temperature (-1°C)	Increased temperature (+1°C)
Rice establishment methods						
Aerobic	3260	3944	2753	2658	2586	1813
Transplanted	3360	3861	2967	3688	3833	2785
Cultivars						
Tellahamsa	2702	3643	2634	3066	2979	2117
IR64	3510	4052	2848	3158	3236	2329
MTU 1010	3718	4011	3098	3312	3413	2451
Nitrogen levels						
100	2573	2844	2238	2207	2112	1541
150	3114	3449	2664	2675	2766	2029
200	3395	3976	2931	3325	3351	2461
250	3630	4450	3136	3518	3703	2625
300	3838	4793	3331	4015	4115	2837

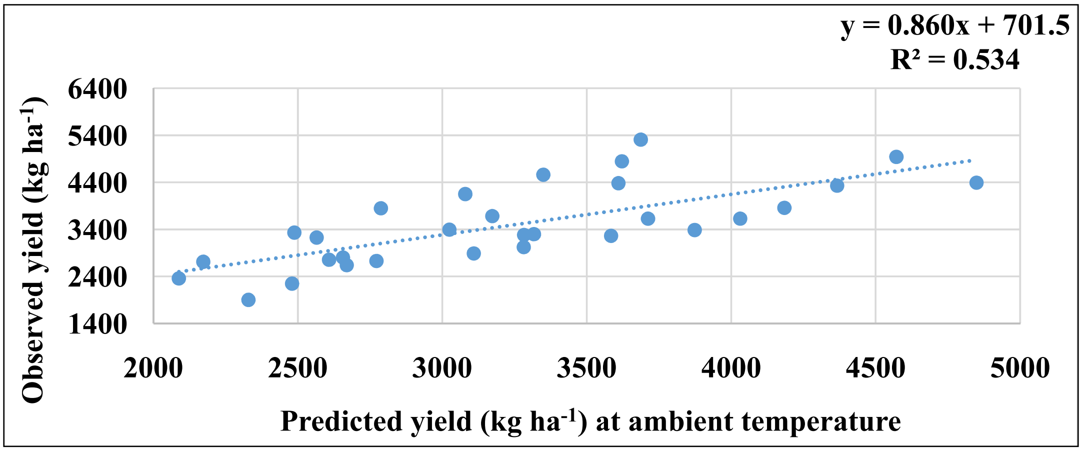

Fig. 3: Regression analysis between two years mean predicted yield and observed yield

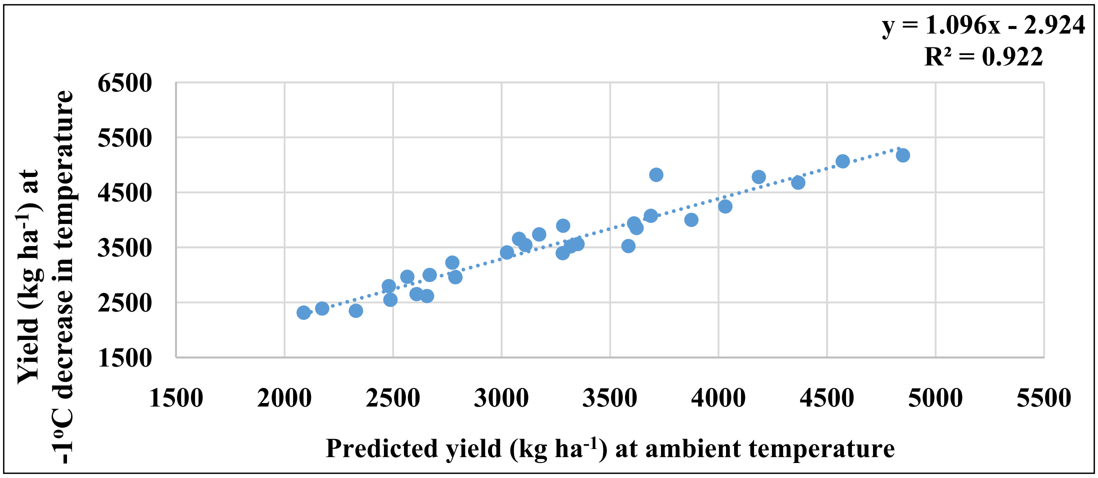

Fig. 4: Regression analysis between two years mean normal predicted yield and yield at decreased temperature

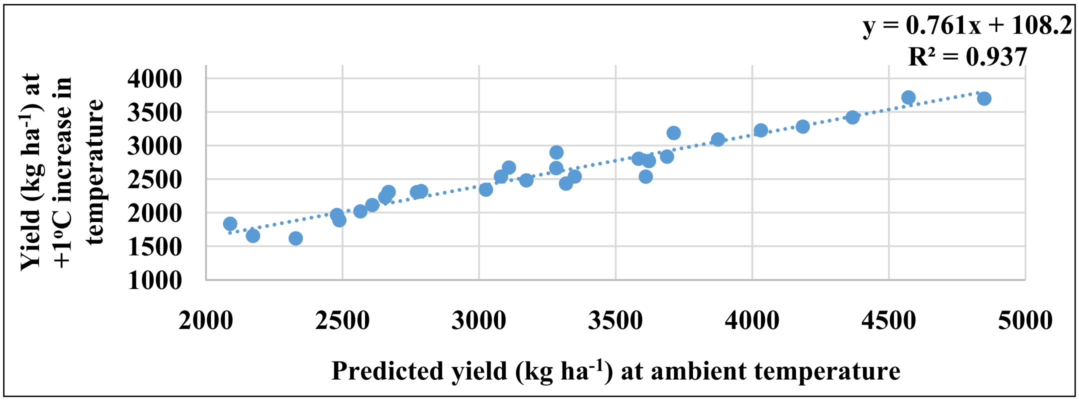

Fig. 5: Regression analysis between two years mean normal predicted yield and yield at increased temperature

which was much lower than the predicted yields at normal temperature. Similarly, the decrease in temperature by 1°C in both maximum and minimum temperatures improved the yield.

The regression analysis carried out between predicted and observed values of two years average shows that the observed data and predicted data are moderately correlated with an R^2 value of 0.534 which shows that the predicted values can be considered with medium agreement with predicted data (Fig. 3).

The regression analysis of the predicted yield with increase or decrease in temperature vs yields obtained at ambient temperature were highly correlated with predicted data at ambient temperature with R^2 value of 0.922 and 0.937 (Figs. 4 and 5). The R^2 value of more than 0.9 shows that there was a strong agreement between normal predicted values with increase or decrease in temperature.

CONCLUSION

The use of CERES rice model based on DSSAT 4.6 was found to be efficient in predicting the yield data of rice for various treatments like rice establishment methods, cultivars and nitrogen levels. The prediction was found to be high to moderately accurate and this modeling tool can be used as research tool to predict different treatment effects on yield of rice under varying agro climatic conditions.

The model is also efficient in predicting the yield variation due to change in temperature conditions, which may help in studying the impact of climatic change on rice growth and productivity.

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