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Simulating the impact of climate change on rice yield using DSSAT model

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Abstract
Rice (*Oryza sativa* L.) is the second most important food grain after wheat in World. A decline in productivity of rice in recent years has been ascribed to decrease in soil organic carbon and reserve of nutrients, non-uniform distribution of rainfall, and increase in temperature and carbon dioxide because of climate change. To assess the impact of climate change on rice yield, crop simulation DSSAT model CERES – rice was calibrated and well evaluated for short and medium duration varieties through field experimental data at Prayagraj, India. Using past 8 years (2012 – 2019) weather data, the CERES-Rice model predicted higher yield variability of the medium duration variety (130 days) “NDR – 359” as compared to the short duration (90 days) variety “NDR – 97” under irrigated condition of Prayagraj, India. However NDR – 359 simulated the higher mean yield. With increase in atmospheric CO_2 level by 150 ppm, the grain yield of NDR – 359 and NDR – 97 was increased by 7.16% and 5.86% respectively under irrigated condition. Increase in average air temperature by 3ºC resulted a decline in yield of short duration variety but an increase in yield of the medium duration variety. The medium duration variety showed better adaptability to climate change than the short duration varieties under optimum input management condition.

Keywords: DSSAT CERES-rice model, climate change, rice yield, simulation

Introduction

Rice (*Oryza sativa L.)* is a grain plant belonging to the family Poaceae and genus *Oryza* with chromosome no. = 24. Rice is one of the most important food grains produced and consumed all over the world. It is a subsistence crop for most farmers. Rice is the longest continuously grown cereal crop in the world and according to the International Rice Research Institute (IRRI) it is “one of the most important developments in history”. Rice (*Oryza sativa L.*) is one of the most important staple food crop of India for more than 2/3rd of its population. The slogan “Rice is life” can be considered appropriate for our country as this crop plays a vital role in our national food security and is a means of livelihood for millions of rural households. Rice is one of the world’s largest cereal crop providing the caloric need for millions of people. India produces 99.15 million tons of rice (Anonymous, 2009) while China is first in rice production in the world (Anonymous, 2007). However, at the current rate of population growth, rice production has to enhance to about 120 million tons by 2020 (Survey of Indian Agriculture, 2005).

Since the beginning of the 1980s a threat to agriculture has attracted much attention is climate change due to global warming. Many climatologists predict significant global warming in the coming decades due to increasing concentration of CO2 and other greenhouse gases in the atmosphere. The CO2 concentration has been projected to increase to 670 to 760 µ mol mol-1 by the year 2075 due mainly to continued burning of fossil fuel (Rotty and Marland, 1986). The increasing concentration of CO_2 may have significant effect on rice productivity due to increase in both the average surface temperature and the amount of CO_2 available for photosynthesis (Aggarwal, 2003) [1]. In the absence of temperature increase, many studies have shown that the net effect of doubling of CO2 was increase in the yield of rice (Kim *et al*., 2003; Baker *et al*., 1992; Baker *et al*, 2000) [2, 9, 3]. Baker *et al*. (1992) [2] stated that potentially large negative effects on rice yield are possible with increase in atmospheric CO2, if air temperatures also rise.

It is felt that global warming will affect agricultural production directly because of alterations in temperature and rainfall, and indirectly through changes in soil quality, pests, and diseases. In particular, the agricultural production is expected to decline in tropical and sub-tropical countries (developing world), whereas some parts of world, especially the places in northern latitude above about 55 may be benefited from the climate change (Parry *et al*., 2004; Stern, 2006; Hadley-Centre, 2006) [5]. The continued impact of elevated CO2, rising temperature and varying rainfall on crop behaviour is very complex. It is important to understand this phenomenon of climate change on crop production and to develop adaptation strategies for sustainability in food production, using a suitable validated crop simulation models. The simulation output can adequately describe relative trends in yields caused by environment variation (Penning de Vries *et al*., 1989) [17].

Many crop simulations models have been evaluated and used to assist the decision making process in agriculture (Muchow and Belamy, 1991; MacRobert and Savage, 1998) [14, 13]. Decision Support System for Agro technology Transfer (DSSAT), which is a combination of several dynamic crop simulation models, can predict accurately the growth, development and yield of crops with the help of soil, daily weather and management inputs, to aid farmers in developing long-term strategies (Tsuji *et al*., 1994). The DSSAT has unique feature of using historical or future weather data to predict the yields under different management options. CERES (Crop Environment Resource Synthesis) Rice model available in DSSAT simulate crop growth, development and yield taking into account the effects of weather, genetics, and soil and management parameters. The model can be used to evaluate uncertainties and risk associated with rice production system. The present rice production in India concerns with the climatic risk due to global warming. Because of this, an estimation of likely impact is vital in planning strategies to meet the increased rice demand of ever growing population pressures.

The objectives of the present investigation were (1) to simulate the impact of climate change on rice yields and (2) to evaluate varietal adaptation to climate change scenarios.

2. Materials and methods

The study was carried out in the Department of Agrometeorology, Sam Higginbottom University of Agriculture, Technology and Sciences, Naini, Prayagraj. Prayagraj is taken as the representative experimental site for this study. It is situated at an elevation of 94 m (295 ft.) above mean sea level at 25º 43' N latitude and 81º 84' E longitude. Prayagraj has a humid sub-tropical climate.

2.1. Weather data

Allahabad (Prayagraj) has a humid subtropical climate common to cities in the plains of North India, designated *Cwa* in the Köppen climate classification. The climate of Allahabad district is characterized by a long and hot summer, a fairly pleasant monsoon and cold seasons. The winter usually extends from mid-November to February and is followed by the summer which continues till about the middle of June.

The weather data (daily basis) on maximum and minimum temperatures, rainfall and solar radiation of ten years (2012 – 2019) for centre Prayagraj was obtained from Department of Environmental science and NRM, College of Forestry, Sam Higginbottom University of Agriculture, Technology and Sciences. The complete weather data sets without any discrepancies are needed for crop simulation models to calculate dry matter accumulation and to determine the physiological development of the crop. Solar radiation was calculated by the model based on Hargreaves method, which is reported to be best suited for Indian conditions.

From about the middle of November, the temperatures begin to fall rapidly and in January (the coldest month) the mean daily maximum is 23.7°C (74.7°F). May usually being the hottest month of the year with the mean daily maximum temperature at 41.8°C (107.2°F) and the mean daily minimum at 26.8°C (80.2°F). The city receives 2916 hours of sunshine per year, maximum sunlight in May. The climate is marked by high relative humidity i.e. 70 to 80 percent during monsoon and progressive decrease in humidity (during the summers humidity is very low i.e. 15 to 20 percent only).

2.2. Soil data

Layer wise (0 – 120 cm) data of soil physical and chemical properties which includes Bulk density, Hydraulic conductivity, as organic carbon, clay contents, silt contents, soil pH organic carbon content, clay and silt content etc. of Prayagraj district was collected from India Meteorological Department, New Delhi.

2.3. Cultivar data

These coefficients are crucial because they strongly influence the simulation of growth and development of the crop. The CERES-Rice model uses eight genetic coefficients viz., P1, P2O, P2R, P5, G1, G2, G3 and G4. The eight coefficients for three cultivars (NDR – 359 and NDR – 97) are collected from IMD, New Delhi then again they are calibrated for Prayagraj condition via trial and error method. The genetic coefficients for the two varieties are shown in table 2 below in result and discussion and description of genetic coefficients are as follows:

Table 1: Description of genetic coefficient

GC	Description
P1	Juvenile phase coefficient
P2O	Critical photoperiod
P2R	Photoperodism coefficient
P5	Grain filling duration coefficient
G1	Spikelet number coefficient
G2	Single grain weight
G3	Tillering coefficient
G4	Temperature tolerance coefficient

2.4. Crop management and experimental data

The eight years (2012 – 2019) experimental data conducted at the College of Forestry farm, Sam Higginbottom University of Agriculture, Technology and Sciences, Prayagraj, UP, India was used for the calibration and validation of model.

This experiment was carried out to assess the yield of two cultivar of rice var. NDR – 359 and NDR – 97 for eight years under Prayagraj condition. Experiment includes 2 cultivars which the experiments were conducted based on split plot design. Planting dates were 1st week of July for every cultivar. Grain yield was provided for the model as observed data for the calibration and validation of model.

2.5. CERES – Rice model

The windows-based CERES-Rice model (DSSAT version 4.0) released during the year 2004 by International Consortium for Agricultural Systems Application; University of Hawaii, USA was used for this study. The various processes simulated by this model are phenological

development of the crop; growth of leaves, stems and roots; biomass accumulation and partitioning among leaves, stem, panicle, grains and roots; soil water balance and water use by the crop; and soil nitrogen transformations and uptake by the crop. The phenological stages simulated by the model are sowing or transplanting, germination, emergence, juvenile phase, panicle initiation, heading, beginning of grain filling, end of grain filling, and physiological maturity. The model simulates total biomass of the crop is the product of the growth duration and the average growth rate. The simulation of yields at the process level involves the prediction of these two important processes. The economic yield of the crop is the fraction of total biomass partitioned to grain.
Crop growth is simulated by employing a carbon balance approach in a source-sink system (Ritchie *et al*., 1998).
Detailed description of the model can be found in Hunt and Boote (1998) [6]. The model is based on understanding of plants, soil, weather and management interaction to predict growth and yield. Yield limiting factors like water and nutrient stresses (Nitrogen and phosphorus) are considered by the model. The pest problems, weeds, and diseases, as the yield reducing factors are also covered by the model.

2.6. Model calibration
The CERES-Rice model was calibrated first to fit the model in the specific soil and environmental conditions. Genetic coefficients for the rice cultivars NDR – 359 and NDR – 97 were calibrated using experimental data of eight years on grain yield at optimum irrigated condition.

2.7. Model validation
Validation is the comparison of the results of model simulations with observations from crops that were not used for the calibration. A model should be rigorously validated under widely differing environmental conditions to evaluate the performance of major processes in addition to its ability to predict the phenology and yield. Before any model can be used with confidence, adequate validation or assessment of the magnitude of the errors that may result from its use should be performed. Model validation, in its simplest form is a comparison between simulated and observed values.
Several criteria were used to quantify the differences between observed and simulated data. Test criteria have been separated into two groups, called summary measures and difference measures. The summary measures describe the quality of simulation while the difference measures try to locate and quantify errors. The latter include the root mean square error (RMSE) and the normalised root mean square error (NRMSE). NRMSE gives a measure (%) of the relative difference of simulated verses observed data. The simulation is considered excellent with a normalized RMSE less than 10%, good if the normalized RMSE is greater than 10 and less than 20%, fair if the normalized RMSE is greater than 20% and less than 30%, and poor if the normalized RMSE is greater than 30% (Loague and Green, 1991).
They were calculated according to Willmott as follows and were based on the terms (Sim_i – Obs_i).

$$\text{RMSE} = \sqrt{\frac{\sum_{i-1}^{n}(X_{obs_i} - X_{sim_i})^2}{n}}$$

$$\text{nRMSE} = \sqrt{\sum_{i=1}^{n}\frac{(Si-Ob)^2}{n}}\times\frac{100}{M}$$

Varshneya (1999), who gave a simple indication of error in prediction, defined the Percent Error (PE). PE is defined as ratio of RMSE to mean observed value expressed as percentage. Percent Error seems to be accurate when its value is below 15% and was calculated as follows:

$$\text{Error Percent} = \sqrt{\frac{(X_{sim_i} - X_{obs_i})}{X_{sim_i}}}\times 100$$

Note: (i) In RMSE and PE equations, X_{obs} is observed values and X_{sim} is modelled (simulated) values at time/place *i*.
(ii) In NRMSE equation, S_i is simulated value and O_b is observed value.

3. Result and discussion
3.1. Grain yield
Simulated grain yield with observed yield is listed in table 1 for cultivar NDR – 359 and NDR – 97 respectively. The average simulated yield of NDR – 359 is 6258.375 kg and NDR – 97 is 4520.25 kg ha$^{-1.}$ The range of magnitude of deviation between simulated and grain yield varied between -89 kg ha^{-1} to 569 kg ha$^{-1.}$ The values of errors as computed in terms of RMSE is 335.31 and 643.76 for NDR–359 and NDR– 97 respectively, NRMSE is 0.05 and 0.08 for NDR – 359 and NDR – 97 respectively with an average percent error of 2.36 and 4.84 for NDR – 359 and NDR – 97 respectively which indicated that model performed well in all the years in predicting the grain yield of rice for every cultivar.
For medium duration variety (NDR – 359) the variation between mean simulated and mean observed grain yield was 2.73% and 4.82% for the variety NDR – 97. The simulated grain yield of NDR – 359 was closer to observed value.

Table 2: Simulated and Observed yield.

NDR - 359		NDR - 97	
Obs. Yield (Kg/ha)	**Sim. Yield (Kg/ha)**	**Obs. Yield (Kg/ha)**	**Sim. yield (Kg/ha)**
6037	5846	4213	4526
5986	6555	4192	4658
6071	6395	4232	3911
6170	6509	4290	4662
6079	6473	4397	4713
6138	5986	4345	4753
6199	6032	4356	4445
6019	6271	4387	4494
6087.37	6258.37	4302	4520.25

Table 3: Calibrated genetic coefficient for 2 different cultivars of rice at Prayagraj condition.

Cultivar	P1	P2R	P5	P2O	G1	G2	G3	G4
NDR 359	500.0	200.0	450.0	12.5	62.0	0.190	1.00	1.00
NDR 97	300.0	120.0	390.0	11.5	59.0	0.220	1.00	1.00

3.2 Yield simulation for climate change scenario
The model was used to simulate grain yield of varieties at their optimum N application rate using historical weather data and developed climate change scenarios.

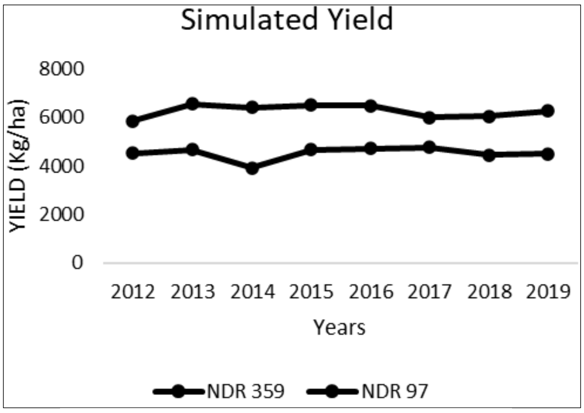

Fig 1: Simulated grain yield of NDR – 359 and NDR – 97 over year 2012 – 2019

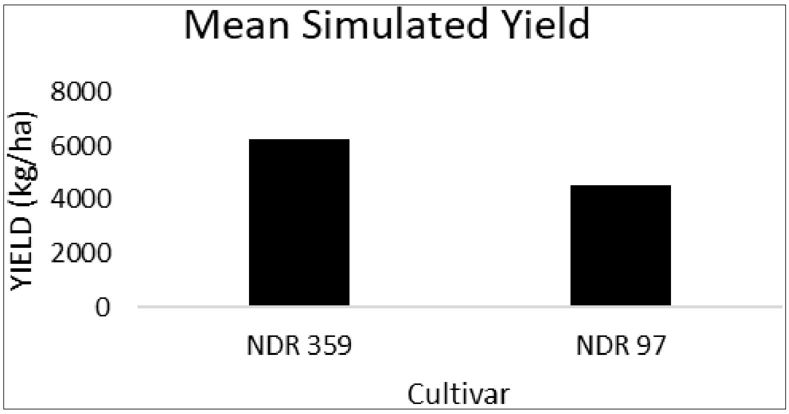

Fig 2: Mean simulated yield of NDR – 359 and NDR – 97

a) **Historical weather data:** The model was applied to simulate grain yield of both varieties at Prayagraj region for irrigated condition using historical weather data of past 8 years (Figures 1 and 2). The grain yield of NDR – 359 ranged from 5846 to 6555 kg/ha with a mean yield 6258.375 kg/ha. The variation in grain yield of NDR – 97 was in the range 3911 ~ 4753 kg/ha and the mean yield was 4520.25 kg/ha. The variations in grain yield across the past years were low for the medium duration varieties and high for the early duration variety. However, the mean simulated grain yield of the medium duration variety was higher than early duration varieties (Figure 2).

b) **Developed climate change scenario:** The grain yield of all varieties was simulated at their optimum N application without any water stress for rising CO2 level and temperature scenarios. Increase in CO2 level increased the grain yield of all the varieties (Figure 6). With increase in CO2 level by 50 to 100 ppm, the yield increased by 1.5 to 3.0% for medium duration varieties IR 36 and Lalat and 3 to 6% for the long duration variety Swarna. Increasing CO2 level increases the photosynthetic activity of the crop and thereby the yield.

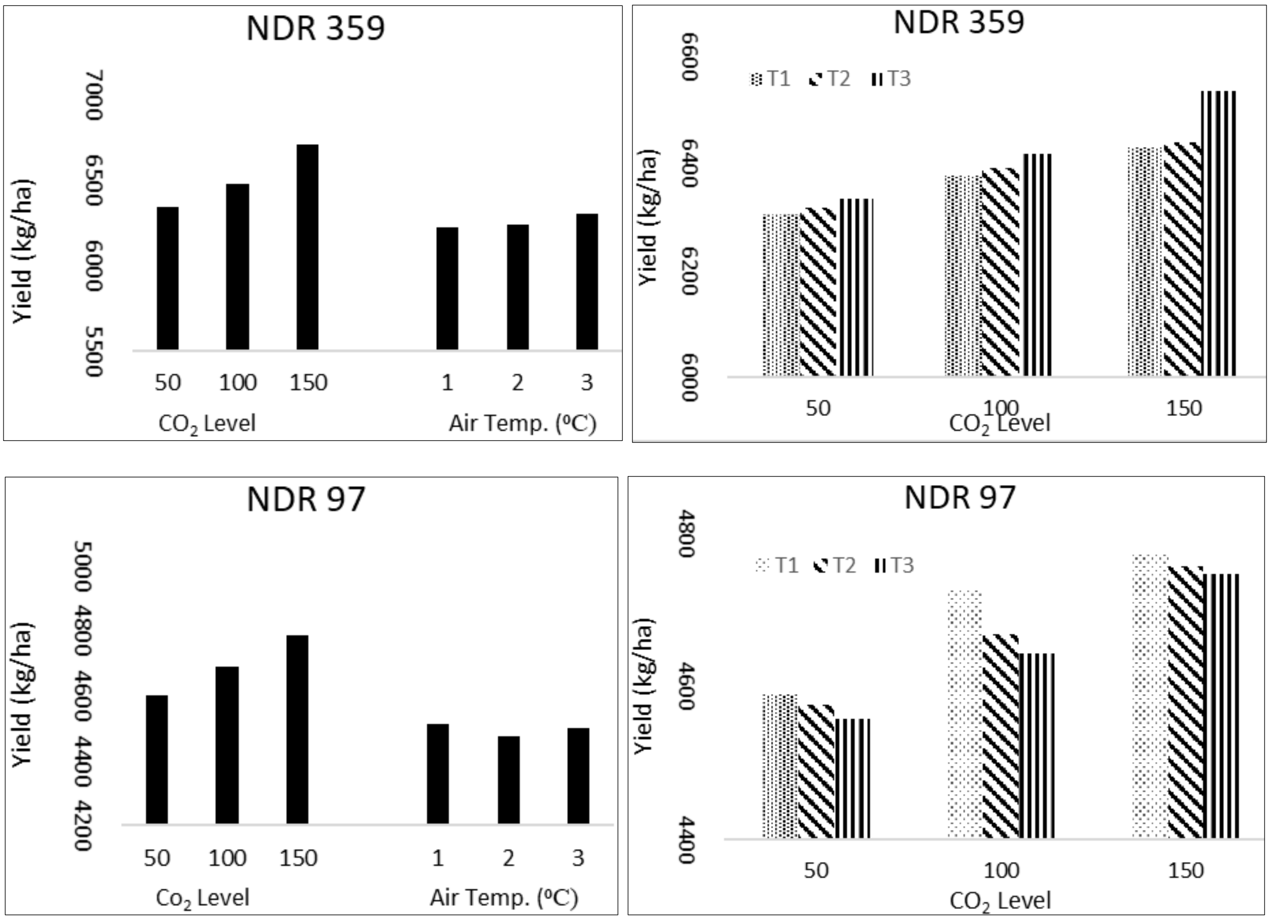

Fig 3: Effect of increasing CO_2 level of 50, 100 and 150 ppm and rise in air temperature by 1ºC (T1), 2º C (T2), and 3ºC (T3) above ambient in the atmosphere on grain yield of rice varieties NDR – 359 and NDR – 97 simulated in Prayagraj region.

Summarizing the data from several experimental studies on different agricultural crops, Kimbal *et al*. (2002) [10] found a 30% increase in growth rate with a doubling of CO_2 levels. Nevertheless, the experimental findings from the growth chamber studies (Baker *et al*., 1992) [2] showed a 32% increase in rice grain yield due to doubling of the CO_2 concentration from 330 to 660 μ mol CO_2 mol^{-1} air (ppm). The increased growth response with increasing CO_2 concentration was attributed to greater tillering and more grain-bearing panicles. In our study the model also simulated a comparative yield increase about 7% with 150 ppm increase in CO_2 level.

Increase in temperature up to 3 ºC, resulted a marginal increase (< 1%) in grain yield of medium duration variety and the yield of the early duration variety was decreases marginally (<1%) with similar increase in temperature. Many researchers have stated increase in yield with elevated CO_2 level and decrease in yield with rise in temperature (Krishnan *et al*., 2007; Saseendran *et al*., 2000; Singh and Ritchie, 1993; Singh and Padilla, 1995) [11]. In our simulation study, the medium duration variety NDR – 359 performed better than early duration variety with 3ºC rise in temperature and 150 ppm increase in CO_2 level over ambient value. The variety NDR – 359 adapted better to rising temperature as compared to other varieties.

4. Conclusion

CERES-Rice model was able to simulate grain yield with good accuracy under varying management levels. The model provides insights about the response mechanism to irrigated condition management and various weather conditions. The simulated grain yield of the medium duration variety NDR – 359 was found to be more stable with a higher mean yield as compared to early duration variety in irrigated condition. However the variety NDR – 359 showed better adaptability to climate change scenarios under optimum input management condition.

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