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Simulating the Impact of Climate Change on Rice Yield Using CERES-Rice 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 because of climate change. To assess the impact of climate change on rice yield, crop simulation model CERES-rice was calibrated and well evaluated for medium and long duration varieties through field experimental data at Kharagpur, India. Using past 27 years (1974-2000) weather data, the CERES-Rice model predicted higher yield variability of the long duration (140 days) variety 'Swarna' as compared to the medium duration (120 days) verities (IR 36 and Lalat) under rainfed condition of Kharagpur, India. However the highest mean yield was simulated for the variety Swarna. With increase in atmospheric CO_2 level by 100 ppm, the grain yield of rice was increased up to 6% under optimum supply of water and nutrients. Increase in average air temperature by 20^{o} C resulted a decline in yield of both the medium duration varieties but an increase in yield of the long duration variety. The long duration variety showed better adaptability to climate change than the medium duration varieties under optimum input management condition.

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

1. Introduction

Food security and environmental sustainability are the major focuses of global agriculture. Rice is the second most important food grain after wheat in the World. The food security of India principally depends on production of rice (*Oryza sativa* L.), which is grown in an area of 42 millions hectares and contributes 43% of total food grain production. With the advent of high yielding varieties and use of high potency chemical fertilizers, especially nitrogen, the yield of rice increased dramatically in late sixties and early seventies bringing the green revolution in India. However, in recent years the production of rice in response to the increasing application rates of input resources is experiencing a declining trend (Pathak et al., 2003). This decline in productivity of rice has been ascribed to the decrease in soil organic carbon and reserve of nutrients, nonuniform distribution of rainfall, and increase in temperature and changes in soil environment (Ladha et al., 2003).

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 CO_2 and other green house gases in the atmosphere. The CO_2 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 concentrations 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). In the absence of temperature increase, many studies have shown that the net effect of doubling of CO_2 was increase in the yield of rice (Kim et al., 2003; Baker et al., 1992; Baker et al, 2000). Baker et al. (1992) stated that potentially large negative effects on rice yield are possible with increase in atmospheric CO_2, if air temperatures also rise. Changes in rainfall patterns can have both negative and positive effects on agricultural production. In semiarid environments, higher rainfall will increase production whereas less rain will further limit crop production. However, in high rainfall zones, more rain can also increase soil water logging and nutrient leaching which can reduce crop growth.

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). The continued impact of elevated CO_2, rising temperature and varying rainfall on crop behavior is very complex. It is important to understand this phenomenon of climate change on crop production and to develop adaptation strategies for sus-

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tainability 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).

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). Most of these models are empirical and mechanistic in function. 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, 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

2.1. Field Experiment

A field experiment was conducted during wet season (June ~ December) of 2006 at the Research Farm of the Agricultural and Food Engineering Department, Indian Institute of Technology, Kharagpur (22º19' N and 87º19' E), India to calibrate and evaluate the crop simulation model CERES-Rice. For this purpose, three popular high yielding rice varieties namely; IR36, Lalat, and Swarna were selected. The varieties IR36 and Lalat are of medium duration (110 ~ 120 days) type and the variety Swarna is of long duration (140 ~ 150 days) type. These three rice varieties were grown with four N application levels (0, 50, 100, 150 kg/ha). Varieties were allocated to main plot and N levels to sub-plot of a split-plot design. Total number of treatments were twelve (3 × 4) and each treatment was replicated thrice. Total number of plots were 12 × 3 = 36. Each plots had the dimension of 6 m × 5 m.

Full dose of P_2O_5 and K_2O at 50 kg/ha each was applied as basal at the time of transplanting. Nitrogen was applied in four equal splits at basal, active tillering, panicle initiation and flowering stages to the individual plots as per the treatment schedule of fertilizer application. Rice seedlings of 25 days old were transplanted on 25 July 2006 in each plot with 3 to 4 seedlings per hills with a spacing of 20 cm × 20 cm. Irrigation and plant protection measures were followed uniformly in all the plots as per the requirement.

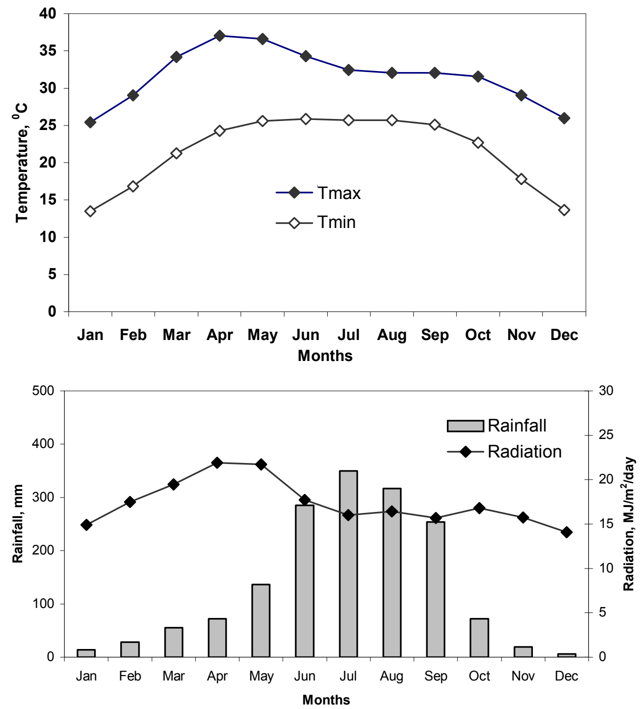

Figure 1. Average daily maximum temperature (Tmax), minimum temperature (Tmin), and solar radiation and monthly rainfall of Kharagpur, India.

2.2. Weather and Soil

The climate of Kharagpur, India is classified as warm and humid. It is characterized by hot and humid in summer (April and May), rainy during June to September, moderately hot and dry in autumn (October and November), cool and dry in winter (December and January) and moderate spring in February and March. The site receives an average annual rainfall of 1400 mm with an occurrence of 70 ~ 75% of the total rainfall in the monsoon months (June to October). The average maximum temperature ranges from 25.4 ºC in December/January to 37.1 ºC in April/May. The average minimum temperature ranges from 13.5 ºC in December/January to 25.9 ºC in June. The average temperature, rainfall and solar radiation for Kharagpur, India is shown in Figure 1.

The soil of this region is of red and lateritic type with sandy loam in texture, which is taxonomically grouped under the great group 'Haplustalf'. The pH of the soil is about 6.2 and organic carbon content is about 0.4%. The pH was determined by glass electrode pH meter (Jackson, 1967) and organic carbon through Walkley-Black method (Jackson, 1973). The soil is low in available N and K content and medium in available P. The methods used for soil nutrient analysis were Alkaline $KMnO_4$ (Subbaiah and Asija, 1956) for N, NH_4-F extraction (Jackson, 1973) for P, and NH_4-OAc extraction (Jackson, 1973) for K determination.

2.3. Plant Sampling and Observations

Plant samples were collected at different crop growth stages from all treatments till harvesting. For this purpose, non-destructive observations on tiller numbers of 10 hills in each side (total 20 hills) of a plot, leaving two border rows, were recorded, and the average number of tillers of a representative hill was established (Thyagarajan et al., 1995). From these 20 hills, five representative hills are considered as sample hills. After collection, the plant samples were cleaned and washed in distilled water to remove surface contamination and separated into stems (leaf sheath + stem), leaves, and panicles. Thereafter the plant parts were kept for sun drying as well as oven drying at 80 ºC till constant biomass. Dry biomass of leaves, stems, and panicles were noted down for statistical analysis. The dried plant parts were powdered in a porcelain basin to homogenate for analyzing N content using the micro-Kjeldahl distillation method (Yoshida et al., 1976).

Yield attributes collected are panicles/m^2, filled grains/panicle and thousand-grain weight. The crop was harvested at grain moisture content of 18 ~ 20%. In each plot, a m^2 area where plant sampling was not done earlier, was selected for grain and straw yield determination. The grain yield was converted to 0% moisture content.

2.4. 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). Daily crop growth rate is calculated as:

$$PCARB = \frac{RUE \cdot PAR}{PLTPOP}\left(1 - e^{(-k \cdot LAI)}\right) \cdot CO_2 \quad (1)$$

where:

PCARB – Potential growth rate, g/plant;

RUE – Radiation use efficiency, g dry matter/MJ·PAR;

PAR – Photosynthetically active radiation, MJ·m^{-2};

PLTPOP – Plant population, plant·m^{-2};

K – Light extinction factor;

LAI – Green leaf area index;

CO_2 – CO_2 modification factor.

Detailed description of the model can be found in Hunt and Boote (1998). 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.

2.5. Calibration and Evaluation of Model

The CERES-Rice model was calibrated first to fit the model in the specific soil and environmental conditions. Genetic coefficients for the rice cultivars IR36, Lalat and Swarna were calibrated using experimental data on biomass, grain yield, plant N content etc at optimum N application level. The genetic parameters were set following least root mean square error (RMSE) between observed and simulated values through fitting coefficient procedure (Hunt and Boote, 1998). RMSE was estimated by the following equation:

$$RMSE = \sqrt{\sum_{i=1}^{n}(S_i - O_i)^2/n} \quad (2)$$

where S_i is i^{th} predicted value; O_i is i^{th} observed value and n is number of observation.

The calibrated model was used to simulate grain yield of all varieties at rest N application levels. The simulated and observed grain yields were compared statistically for model validation.

2.6. Yield Simulation

The model was used to simulate grain yield of the varieties at their optimum N requirement for Kharagpur region using historical daily weather data (rainfall, maximum and minimum temperature, and solar radiation) of past 27 years (1974 ~ 2000) of the location. As past weather data represents the true climate change, so the variation in simulated yield in the past years is expected to be due to climate change. The grain yield was also simulated for fixed climate change scenarios by raising atmospheric CO_2 level and air temperature in the model inputs. The scenarios were combination of three levels of rise in CO_2 concentration (ppm): 0, 50, and 100 and three levels of rise in average air temperature (ºC): 0, 1, and 2. Nine-treatment combinations [3 (CO_2 level) $\times$ 3 (temperature level) = 9] were taken, which includes one normal (normal CO_2 level and normal temperature) and eight changed climate scenarios. These 9 climate scenarios were imposed over historical years weather data for the grain yield simulation of medium and long duration rice varieties.

2.7. Statistical Analysis

The analysis of variance for the data recorded and estimated in the field experiments was performed using the software package 'MSTATC'. The difference between treatment means was tested by critical difference value at 5 percent level of significance (Gomez and Gomez, 1984).

3. Results and Discussions

3.1. Experimental Grain Yield

The results from field experiment indicated an increase in grain yield with increasing N application levels up to 100 kg N/ha for both the medium duration varieties IR36 and Lalat (Table 1). The maximum grain yield of 4220 and 4572 kg/ha was noted for variety IR36 and Lalat, respectively at 100 kg N/ha. Further increasing the N application level up to 150 kg/ha resulted a significant decrease in grain yield for both the varieties. Whereas, for long duration variety Swarna, the grain yield increased all the way up to 150 kg N/ha application. The variety Swarna recorded the highest grain yield of 6425 kg/ha at 150 kg N/ha application, which was significantly higher than that obtained at 100 kg N/ha application. The increased in grain yield was due to increase in grain N use efficiency, grain number per panicle and panicles per m^2 area. Increasing yield with increasing N application level was also reported by several researchers (Wilkinson et al., 2000; Patil et al., 2001). The optimum N application level for both the medium duration varieties was 100 kg N/ha and for the long duration variety was 150 kg N/ha.

Table 1. Effect of Varying N Application Levels on Grain Yield (kg/ha) of Rice Varieties

Variety	N0	N1	N2	N3	Mean
IR-36	2910	4107	4220	3443	3670
Lalat	3000	4185	4572	3680	3859
Swarna	3603	4791	5781	6425	5425
Mean	3171	4361	4857	4516	
	V	N	VxN		
CD (P = 0.05)	437	298	516		

* N0, N1, N2 and N3 represent application of N at 0, 50, 100 and 150 kg/ha ; CD – Critical Difference.

Table 2. Genetic CoefficientsCcalibrated for Varieties IR 36, Lalat and Swarna in CERES-Rice Model

Coefficient	IR 36	Lalat	Swarna
P1	560	400	740
P2O	11.7	11.7	11.2
P2R	95	170	200
P5	385	403	395
G1	60	58	60
G2	0.023	0.023	0.025
G3	1.00	1.00	1.00
G4	1.00	1.00	1.00

* P1 – Time required for basic vegetative phase of the crop, expressed in Growing Degrees Days (GDD); P2O - Critical photoperid (h); P2R - Photoperiod sensitivity (GDD); P5 – Time period from beginning of grain filling stage to maturity (GDD); G1 - Potential spikelet number coefficient (number); G2 - Single grain weight (g) under ideal growing conditions; G3 - Tillering coefficient (scalar value); G4 - Temperature tolerance coefficient (scalar value).

3.2. Calibration and Evaluation of Model

The genotype coefficients of CERES-Rice model was calibrated through time series observations collected from the field experiment at optimum N management level. The time series biomass, phenological events, N uptake collected at 100 kg N/ha application for varieties IR36 and Lalat and at 150 kg N/ha application for variety Swarna were used for model calibration. The calibrated genotype coefficients are given in Table 2. The juvenile phase or basic vegetative phase coefficient (P1) was higher in the long duration variety Swarna (740 GDD) as compared to the medium duration varieties IR 36 (560 GDD) and Lalat (400 GDD). Whereas, the time period for grain filling phase was within the range 385 ~ 403 GDD for all the varieties. Grain filling phase remains almost same irrespective of varietal duration, where as basic vegetative phase is longer for long duration varieties. Hence large variation was noted in the coefficient P1, whereas variation in P5 was marginal among the varieties.

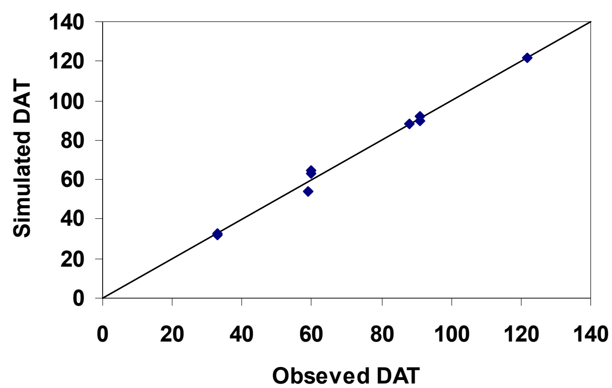

Figure 2. Observed and simulated appearance phenological events from panicle initiation to maturity in days after transplanting (DAT) of rice varieties.

The calibrated model was used for simulating phenological events, grain yield and N uptake at varying N levels as evaluation process.

(a) Phenological events: The model predicted phenological events for all the varieties at varying N level with good accuracy (Figure 2). The difference between observed and simulated days to appearance of panicle initiation, flowering and maturity were within 3 ~ 5 days. Prediction of phenological events is highly important for optimum input management and yield maximization. Flowering is the most critical stage of rice crop and stresses for moisture or nutrients at this stage cause massive reduction in grain yield (Saseendran et. al., 1998).

(b) Yield: For medium duration varieties, the variation between simulated and observed grain yield at 0, 50, 100 and 150 kg N/ha application were 14, 2, 28 and 75%, respectively for the variety IR36 and 25, 11, 0 and 51%, respectively for the variety Lalat (Figure 3). A large variation in yield at 150 kg/ha N in both the varieties is due to increasing simulated grain yield with increasing N application rate beyond 100 kg N/ha (Optimum N rate), which was not true in experimental observation yield. The accuracy of the model prediction is very low at excess N application level (150 kg N/ha), because the adverse effect of excess fertilizer is not taken care by the model. However at optimum N application rate or below that, the simulated grain yields were in closer with observed grain yields for both the varieties. For the long duration variety Swarna, the variation between simulated grain yield and corresponding observed value at 50, 100, and 150 kg N/ ha application were 17, 0.4, and 4%, respectively. The simulated grain yield of Swarna was closer to observed value at all N application rates.

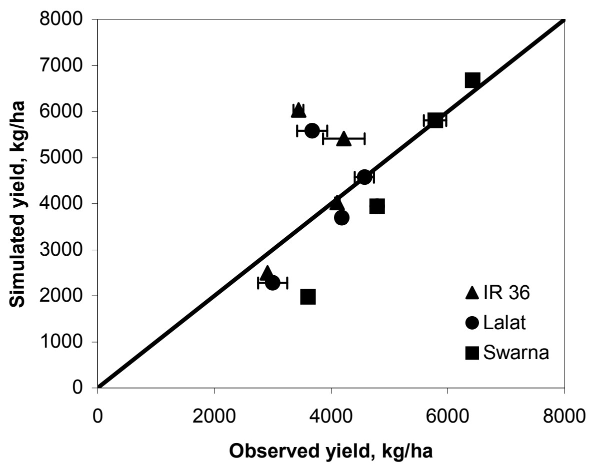

Figure 3. Simulated and observed grain yield of rice varieties IR 36, Lalat and Swarna at varying N application levels.

Table 3. Observed and Simulated Grain N Uptake and Tops N Uptake at Maturity of Rice Varieties at Varying N Application Level

Variety	N level, kg/ha	uptake, Grain N kg/ha		Tops N uptake, kg/ha	
		Obs.	Sim.	Obs.	Sim.
IR 36	0	25	28	45	52
	50	42	47	71	75
	100	49	66	89	132
	150	44	74	88	159
Lalat	0	24	26	50	46
	50	38	44	86	82
	100	50	62	101	128
	150	52	70	108	156
Swarna	0	18	31	45	64
	50	53	48	103	94
	100	62	72	106	139
	150	67	85	136	166
r*		0.89		0.85	

* Correlation coefficient.

(c) Nitrogen uptake: Simulated grain N uptake and total N uptake at maturity were in close agreement with observed values at all the N application levels except at the highest level (150 kg N/ha), where simulated value was overestimated for all the varieties (Table 3). However a very good correlation coefficient between simulated and observed grain N uptake (r = 0.89) and tops N uptake (r = 0.85) substantiate well calibration of the model.

3.3. Yield Simulation for Climate Change Scenarios

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.

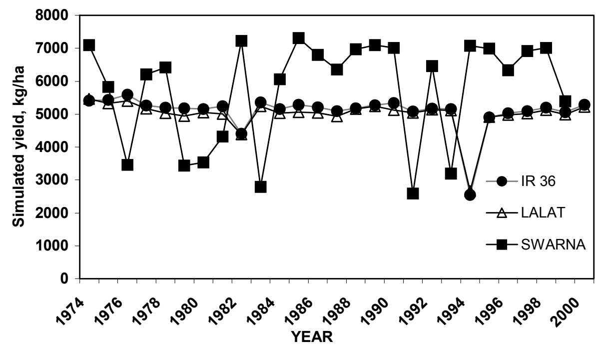

Figure 4. Simulated grain yield of rice varieties IR 36, Lalat and Swarna under rainfed condition in past years (1974-2000) at Kharagpur, India.

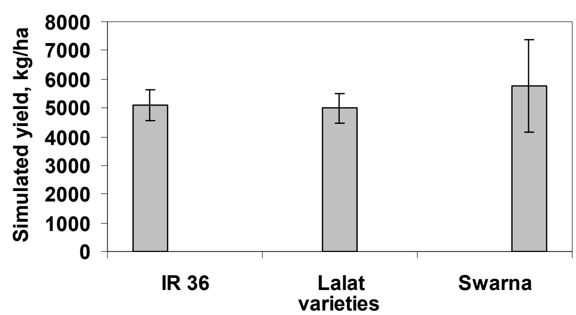

Figure 5. Mean simulated grain yield of rice varieties IR 36, Lalat and Swarna under rainfed condition at Kharagpur, India (The vertical lines indicate standard deviation).

(a) Historical weather data: The model was applied to simulate grain yield of all varieties at Kharagpur region for rain- fed condition using historical weather data of past 27 years (Figures 4 and 5). The grain yield of IR 36 ranged from 2544 to 5589 kg/ha with a mean yield 5085 kg/ha (SD 548 kg/ha). The variation in grain yield of Lalat was in the range 2658 ~ 5460 kg/ha and the mean yield was 4992 kg/ha (SD 505 kg/ha). Grain yield of the long duration variety Swarna varied from 2558 to 7223 kg/ha with the mean yield 5765 kg/ha (SD of 1596 kg/ha). The variations in grain yield across the past years were low for the medium duration varieties and high for the long duration variety. However, the mean simulated grain yield of the long duration variety was higher than medium duration varieties (Figure 5). The large variation in grain yield of the long duration variety in past years is probably due to uneven distribution of rainfall during the crop-growing season. Similar results have also been reported by Swain et al. (2005).

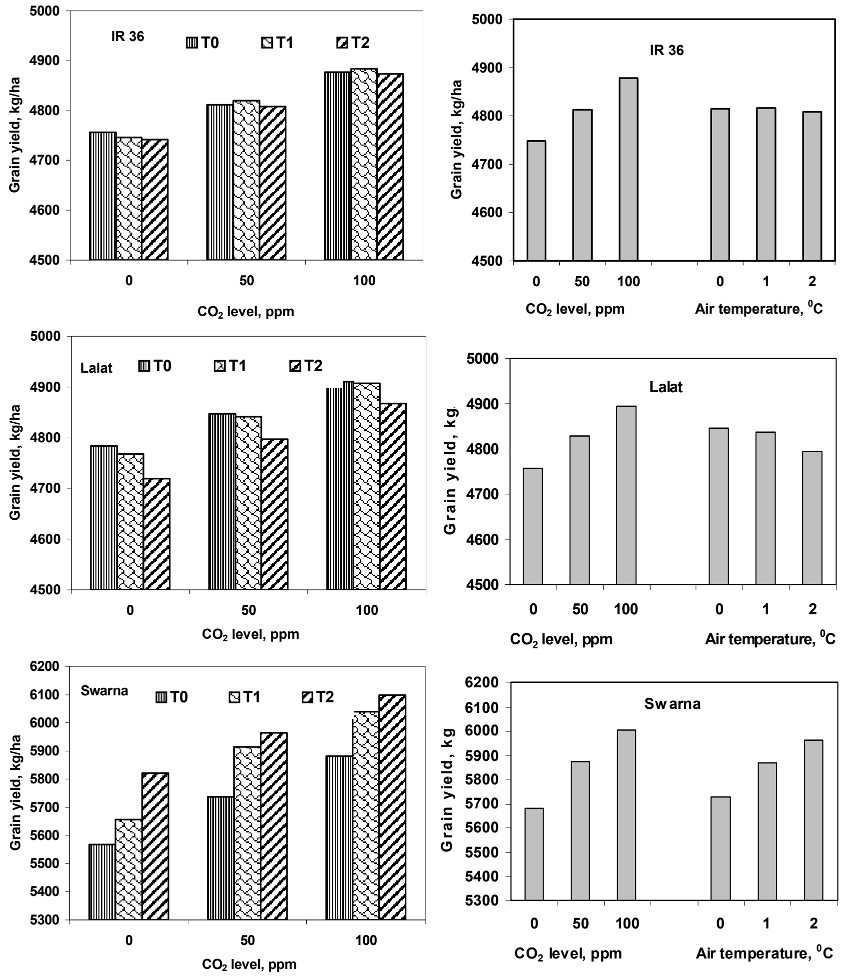

Figure 6. Effect of increasing CO_2 level of 0, 50, and 100 ppm and rise in air temperature by 00 C (T0), 10 C (T1), and 20 C (T2) above ambient in the atmosphere on grain yield of rice varieties IR 36, Lalat and Swarna as simulated at Kharagpur, India.

(b) Developed climate change scenario: The grain yield of all varieties was simulated at their optimum N application without any water stress for rising CO_2 level and temperature scenarios. Increase in CO_2 level increased the grain yield of all the varieties (Figure 6). With increase in CO_2 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 CO_2 level increases the photosynthetic activity of the crop and thereby the yield. Summarizing the data from several experimental studies on different agricultural crops, Kimbal et al. (2002) 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) showed a 32% increase in rice grain yield due to doubling of the CO_2 concentration from 330 to 660 µmol 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. The net assimilation rate and canopy net photosynthesis also increased with increasing CO_2 concentration. In our study the model also simulated a comparative yield increase about 6% with 100 ppm increase in CO_2 level.

Increase in temperature up to 2 ºC, resulted a marginal decrease (< 1%) in grain yield of medium duration varieties. However, the yield of the long duration variety was increased by 4% 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). In our simulation study, the long duration variety Swarna performed better than medium duration varieties with 2 ºC rise in temperature and 100 ppm increase in CO_2 level over ambient value. The variety Swarna adapted better to rising temperature as compared to other varieties.

4. Conclusions

CERES-Rice model was able to simulate phenological events and grain yield with good accuracy under varying management levels. The model provides insights about the response mechanism to different N management and various weather conditions. The simulated grain yield of the long duration variety Swarna was found to be less stable but with a higher mean yield as compared to medium duration varieties IR 36 and Lalat in rainfed condition. However the variety Swrana showed better adaptability to climate change scenarios under optimum input management condition.

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