



Short communication

Field experiments and simulation to evaluate rice cultivar adaptation to elevated carbon dioxide and temperature in sub-tropical India

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ABSTRACT

Location specific adaptation option is required to minimize adverse impact of climate change on rice production. In the present investigation, we calibrated genotype coefficients of four cultivars in the CERES-Rice model for simulation of rice yield under elevated CO₂ environment and evaluation of the cultivar adaptation in subtropical India. The four cultivars (IR 36, Swarna, Swarn sub1, and Badshahog) were grown in open field and in Open Top Chamber (OTC) of ambient CO₂ (≈390 ppm) and elevated CO₂ environment (25% higher than the ambient) during wet season (June–November) of the years 2011 and 2012 at Kharagpur, India. The genotype coefficients; P1 (basic vegetative phase), P2R (photoperiod sensitivity) and P5 (grain filling phase) were higher, but G1 (potential spikelet number) was lower under the elevated CO₂ environment as compared to their open field value in all the four cultivars. Use of the calibrated model of elevated CO₂ environment simulated the changes in grain yield of –13%, –17%, –4%, and +7% for the cultivars IR 36, Swarna, Swarna sub1, and Badshahog, respectively, with increasing CO₂ level of 100 ppm and rising temperature of 1 °C as compared to the ambient CO₂ level and temperature and they were comparable with observed yield changes from the OTC experiment. Potential impacts of climate change were simulated for climate change scenarios developed from HadCM3 global climate model under the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (A2 and B2) for the years 2020, 2050, and 2080. Use of the future climate data simulated a continuous decline in rice grain yield from present years to the years 2020, 2050 and 2080 for the cultivars IR 36 and Swarna in A2 as well as B2 scenario with rising temperature of ≥0.8 °C. Whereas, the cultivar Swarna sub1 was least affected and Badshahog was favoured under elevated CO₂ with rising temperature up to 2 °C in the sub-tropical climate of India.

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1. Introduction

Increase in atmospheric temperature due to increased levels of greenhouse gas, mainly carbon dioxide has direct or indirect effect on food production (Garg et al., 2001; Krupa, 2003; Aggarwal, 2003; Kang et al., 2009). Despite technological advances, such as improved cultivars, genetically modified organisms, and precise irrigation systems, weather is still a key factor influencing agricultural productivity. At the plant level, a higher CO₂ concentration increases photosynthesis, growth, development, and yield of a wide range of cultivated C3 crops (Long et al., 2004, 2006; Ainsworth and Long, 2005; Ainsworth, 2008). Rice being a C3 crop, its biomass increases up to 40%, under elevated CO₂ (Baker et al., 1996; Ziska et al., 1997). In the absence of temperature increase, many studies

have shown increase in the yield of rice with doubling of CO₂ level (Kim et al., 2003; Baker et al., 1992; Liu et al., 2008; Yang et al., 2009; Razzaque et al., 2011; Madan et al., 2012). However, despite these beneficial effects, the combined increase in temperature and variability of rainfall would considerably affect the rice yield. Rice becomes sterile if exposed to temperatures above 35 °C for more than 1 h during flowering and consequently produces no grain. Under climate change scenarios, the rising temperature nullifies the positive effect of increased CO₂ concentration on rice yield as reported by several researchers (Peng et al., 2004; Sheehy et al., 2006; Krishnan et al., 2007; Masutomi et al., 2009; Mohammed and Tarpley, 2009).

Crop production system involving fertilizer management, pest control, genotype, environment, and cultural practices is complex and conducting trials that take all these factors into account becomes increasingly complex and expensive. Suitably validated crop simulation models could be used to test many such combinations in a brief time with limited expense. Such simulations can adequately describe relative trends in yields caused by environmental

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Table 1
Soil properties of the experimental site at Kharagpur, India.

Soil depth (cm)	Clay (%)	Silt (%)	Sand (%)	Organic carbon (%)	pH in water	Total nitrogen (%)
0–5	14.3	26.2	59.5	0.5	6.3	0.05
5–20	14.3	26.2	59.5	0.4	6.3	0.04
20–40	27	20.2	52.8	0.1	6.5	0.01
40–60	28.6	19.2	52.2	0.1	6.7	0.01

variation (Penning de Vries et al., 1989). Models for complex crop system simulations aims to be dynamic rather than static, deterministic rather than stochastic and mechanistic rather than empirical (Wang, 1997). Mechanistic models offer more options to improve the system and to understand processes and their interactions. Many such crop models are available in Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al., 2003), that was developed by the International Benchmark Sites Network for Agrotechnology Transfer (Uehara and Tsuji, 1993) at the University of Hawaii. CERES (Crop Environment Resource Synthesis) model of the DSSAT simulates growth, development, nutrient uptake and yield of cereal crops considering the effect of weather, crop management, crop genetics, and soil water, C and N content.

Using CERES-Rice model, many researchers have reported the climate change impact on rice production (Babel et al., 2011; Kumar et al., 2010; Wikarmpapraharn and Kositsakulcha, 2010; Swain and Thomas, 2010; Gouranga et al., 2009; Yao et al., 2007). However, a well validated location specific management option for climate change adaptation in rice production system is lacking. Location specific cultivar, planting time and nutrient management adaptations needs detailed investigation for reducing the climate change impacts on rice production of tropical and subtropical climate, the major producer and consumer of rice. Varying cultivars of rice will show variable response to elevated CO₂ and rising temperature because of differing capacity in plant assimilation of atmospheric CO₂ via photosynthesis. The simulation of rice yield for climate change scenarios is generally based on calibration of the model parameter of desired cultivar for current weather condition and its subsequent application for climate change scenarios. It is essential to understand the effect of climate change scenarios on growth, phenology and yield of cultivars through controlled environmental experiments under elevated CO₂ level and accordingly estimate the model parameters for their use under climate change scenarios. In the present investigation, we used experimental facility and crop simulation model to calibrate genotype coefficient of CERES-Rice model for four rice cultivars grown under elevated CO₂ environment as in Open Top Chamber and to evaluate the cultivar adaptation to climate change in subtropical India.

2. Materials and methods

Field experiments were carried out in the research farm of Agricultural and Food Engineering Department, Indian Institute of Technology Kharagpur, Kharagpur (22°19' N latitude and 87°19' E longitude) India for calibration and validation of CERES-Rice model for elevated CO₂ environment. Soil of the location is red lateritic with sandy loam in texture, which is taxonomically grouped under the group 'Haplustalf'. The soil properties of the experimental site used for crop simulation are given in Table 1. The climate of Kharagpur is classified as humid and subtropical. It is characterized by hot and humid in summer (April and May), rainy during June–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–October). The average

daily temperature varies between 21 °C in December/January and 32 °C in May/June.

2.1. Experimental setup

The experiment for calibration and validation of CERES-Rice model under elevated CO₂ environment was conducted during wet season (June–November) of the years 2011 and 2012 in Open Top Chambers (OTCs). Open Top Chambers, made up of polycarbonate sheets are the most widely used and precise experimental method for exposing field grown plants to elevated CO₂ and other atmospheric gases. Four popular rice cultivars selected for the experiment were IR 36, Swarna, Swarna sub1 and Badshahbhog. The cultivars IR 36 of medium duration (110–120 d) type and Swarna of long duration (140–150 d) type are commonly grown in the region. The cultivar Swarna sub1 (140–150 d), similar in nature to Swarna is a recent introduction in the region as an emerging cultivar, which has high tolerance to flood/submergence condition. The cultivar Badshahbhog (150–160 d), an aromatic rice with lower yielding potential as compared to rest cultivars, is grown to a limited extent. Differences in physiological characteristics of these cultivars are given in Table 2. These four cultivars were grown with two replications in open field and in two OTCs as one ambient and the other elevated CO₂ environment. The field area (4 m × 4 m) of the OTC was divided into eight equal plots of size 1.8 m × 1 m, where each rice cultivar was grown. The plots were separated by inserting aluminium sheets up to 75 cm inside the soil and 25 cm above the soil to restrict water and nutrient movement between the plots. Rice seedlings of 25 days old were transplanted on 27th July in 2011 and on 15th July in 2012 with 2–3 seedlings per hill in a spacing of 20 cm × 15 cm. All the cultivars were grown with their recommended nutrient (NPK) management through chemical fertilizer (CF) in open field and OTCs. The CF dose as N:P₂O₅:K₂O were 100:50:60 kg ha⁻¹ for IR 36/Badshahbhog and 120:50:60 kg ha⁻¹ for Swarna/Swarna sub1. The required amount of CF as N, P and K were supplied through urea containing 46% N, single super phosphate (16% P₂O₅) and muriate of potash (60% K₂O), respectively. Full dose of P and K were applied as basal at 1 day before transplanting of rice and were well incorporated in the soil. Nitrogen was applied in four equal splits at basal, active tillering, panicle initiation and flowering stage of the cultivars. Standing water height of minimum 1 cm was maintained in the field from transplanting to dough stage of the crop.

2.2. Plant sampling

Plant samples were collected from transplanting to harvest at 20 days interval. For this purpose, non-destructive observations on tiller numbers of 20 hills of a plot, leaving two border rows, were recorded, and the average number of tillers of representative hill was established (Thyagarajan et al., 1995). From these 20 hills, one hill with average tiller number was considered as sample hill. After collection, the above ground plant samples were cleaned and washed in water to remove surface contamination and separated into stems (leaf sheath + stem), leaves and panicles. Thereafter, the plant parts were kept in paper packets which in turn placed in an oven for drying. All these plant samples were oven dried at 70 °C till

Table 2
Differences in plant characteristics of the rice cultivars used in the experiment.

Cultivars	Season of use	Maturity duration (days)	Height (cm)	Lodging ability (0–1 scale)	Tillering ability	Leaf length (cm)	Leaf colour	Grain type	Single grain weight (g)	Grains per panicle	Yielding potential (tha ⁻¹)
IR 36	Dry/wet	115–120	87 ± 2.2	0.05	High	46 ± 2.3	Green	Long slender	0.022	114 ± 2.0	6
Swarna	Wet	135–140	101 ± 2.0	0.05	High	43 ± 2.0	Dark green	Medium slender	0.020	149 ± 4.0	8
Swarna sub1	Wet	135–140	101 ± 2.0	0.05	High	43 ± 2.0	Dark green	Medium slender	0.020	148 ± 6.0	8
Badshahog	Wet	150–155	160 ± 2.0	0.07	Low	50 ± 2.0	Light green	Short	0.010	175 ± 3.0	4

constant weights were obtained. Dry biomass of leaves, stems and panicles were noted. The sum of the weights of these plant parts was taken as the shoot biomass production. The observation on growth: leaf weight, stem weight, panicle weight, shoot biomass, and plant height; phenology: appearance of flowering and maturity, and yield parameters: panicle number per m², spikelet number per panicle, grain number per panicle, single grain weight, grain and straw yield, and harvest index were recorded.

2.3. Instrumentation

Carbon dioxide monitors, temperature and relative humidity sensors were used to record CO₂ concentration, temperature and relative humidity in open field and OTC. Release of CO₂ to the OTC is controlled by computer based SCADA (supervisory control and data acquisition) software. The software SCADA regulates the flow of CO₂ according to the set value in the OTC. Data loggers are used to record the mean CO₂ concentration as process value of all chambers at 1-min interval. When the process value is lower than set value, command passes from system software to SMPS (switching-mode power supply) for opening of relay module to regulate the opening of solenoid valve for releasing CO₂ into the OTC. When process value reaches the set value, there is normal closing of relay module and solenoid valve to stop the release of CO₂. The CO₂ content of open field was ≈390 ppm. Accordingly, the CO₂ content of the OTC of elevated CO₂ was maintained at 25% higher than open field, i.e. ≈490 ppm through the computer-based real time data acquisition and control system.

2.4. CERES model

CERES is a process-based, dynamic and mechanistic model that can simulate the growth and development of cereal crops under varying weather, soil and management levels. 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 model simulates total biomass of the crop as the product of the growth duration and average growth rate. The simulation of yields at the process level involves the prediction of these two important processes. The yield of the crop is the fraction of total biomass partitioned to grain. Crop growth rate is simulated by employing a carbon balance approach in a source–sink system (Ritchie et al., 1998) and crop duration through thermal time concept (Jones et al., 2003).

2.5. Model calibration and validation

Calibration is adjustment of the system parameters so that simulated results reach a predetermined level, usually that of an observation. Genotype coefficients of the rice cultivars IR 36, Swarna, Swarna sub1 and Badshahog were calibrated and validated for open field as well as elevated CO₂ environment using the experimental data on phenology, biomass, and grain yield for the year 2011 and 2012, respectively, at Kharagpur, India. Statistical methods are selected to compare the results from simulation and observation. Model performance evaluation is presented by the root mean square error (RMSE), root mean square error normalized (RMSE_n) and *D*-index (Willmott, 1982; Willmott et al., 1985).

$$RMSE = \left\{ \frac{\sum_{i=1}^n (S_i - Ob_i)^2}{n} \right\}^{0.5}$$

$$RMSE_n = 100 \frac{\left\{ \sum_{i=1}^n (S_i - Ob_i)^2 / n \right\}^{0.5}}{Ob_{avg}}$$

$$D = 1 - \frac{\sum_{i=1}^n (S_i - Ob_i)^2}{\sum_{i=1}^n (|S_i - \overline{Ob}_{avg}| + |Ob_i - \overline{Ob}_{avg}|)^2}$$

where S_i and Ob_i are the model simulated and experimental observation points, respectively. Ob_{avg} is average of experimental observations and n is the number of observations.

The genotype coefficients used for growth and developments of rice cultivars are: P1 (basic vegetative phase), it is the time period expressed as growing degree days ($^{\circ}\text{C}$ -days) above a base temperature of 9°C ; P2O (Critical photoperiod or the longest day length) in hours at which the development occurs at a maximum rate; P2R (photoperiod sensitivity), extent to which the phasic development leading to panicle initiation is delayed is expressed in $^{\circ}\text{C}$ -days; P5 (grain filling phase), time period in $^{\circ}\text{C}$ -days from beginning of grain filling to physiological maturity with a base temperature of 9°C ; G1, potential spikelet number per panicle; G2, single grain weight; G3, tillering coefficients relative to IR64 cultivars; and G4, temperature tolerance coefficient (Buddhaboon et al., 2004). The P coefficients enable the model to predict events such as flowering and maturity and the G coefficients to predict the potential grain yield of a specific cultivar. For calibration and validation of the genotype coefficients of the four cultivars under open field environment, we used daily weather data (maximum and minimum temperature, rainfall, and solar radiation) and CO_2 level of 390 ppm of the open field. For calibration and validation of the genotype coefficient under elevated CO_2 environment, we used the daily weather data of the elevated CO_2 environment inside OTC and CO_2 level of 25% higher than the open field, i.e. ≈ 490 ppm.

2.6. Evaluation of cultivar adaptation

Through the OTC experiment, the percentage change in grain yield under elevated CO_2 (+100 ppm) as compared to ambient CO_2 (≈ 390 ppm) was calculated for all the four cultivars. The recorded average air temperature inside OTC of elevated CO_2 was approximately 1°C higher than the OTC of ambient CO_2 during the crop growing season. The percentage change in grain yield of the cultivars with the increasing CO_2 level (+100 ppm) and the rising temperature ($+1^{\circ}\text{C}$) from the OTC experiment was compared with simulation yield from the CERES-Rice model for the two years (2011 and 2012) at the same location 'Kharagpur'. For simulation under open field and elevated CO_2 environment, we used the calibrated genotype coefficients of respective environment in the model. The simulated yield under elevated CO_2 environment represent the yield under chamber environment which will be different from the yield could have been simulated in open air with CO_2 enrichment. Hence the chamber effects of different cultivars were considered to assess the change in simulated yield under elevated CO_2 and temperature as compared to the open field environment. The factor for the chamber effect was determined from the yield of open field environment and ambient OTC environment through averaging the two seasons experimental observation.

For the yield simulation under climate change scenarios, fixed rise in CO_2 and temperature above the current weather were created and developed scenario as output of global climate model (GCM), HadCM3 was also used. The fixed weather scenarios were combination of three levels of rise in CO_2 concentration (ppm): 100, 200, 300 and three levels of rise in average air temperature ($^{\circ}\text{C}$): 1, 2, and 3. These nine-treatment combinations [$3(\text{CO}_2 \text{ level}) \times 3(\text{temperature level}) = 9$] were incorporated in environmental modification component of crop management file in the CERES model. We used these changed weather scenario, soil

Table 3 Simulated and observed phenology and growth of rice cultivars (IR 36, Swarna, Swarna sub1 and Badshahbhog) grown under open field environment during wet season of the year 2011 (calibration of CERES-Rice).

Crop parameters	IR 36		Swarna		Swarna sub1		Badshahbhog	
	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed
Anthesis day (DAT)	55	49	75	74	77	76	92	95
Physiological maturity day (DAT)	79	79	107	105	112	111	123	123
Grain yield at maturity (kg ha^{-1})	4071	4438 (± 341)	6307	6153 (± 513)	5804	5410 (± 272)	3791	3617 (± 307)
Shoot weight at maturity (kg ha^{-1})	8598	8930 (± 1446)	11,925	11,309 (± 1311)	12,427	11,570 (± 1396)	12,779	12,486 (± 1206)

DAT: days after transplanting, values within open parenthesis are standard deviations.

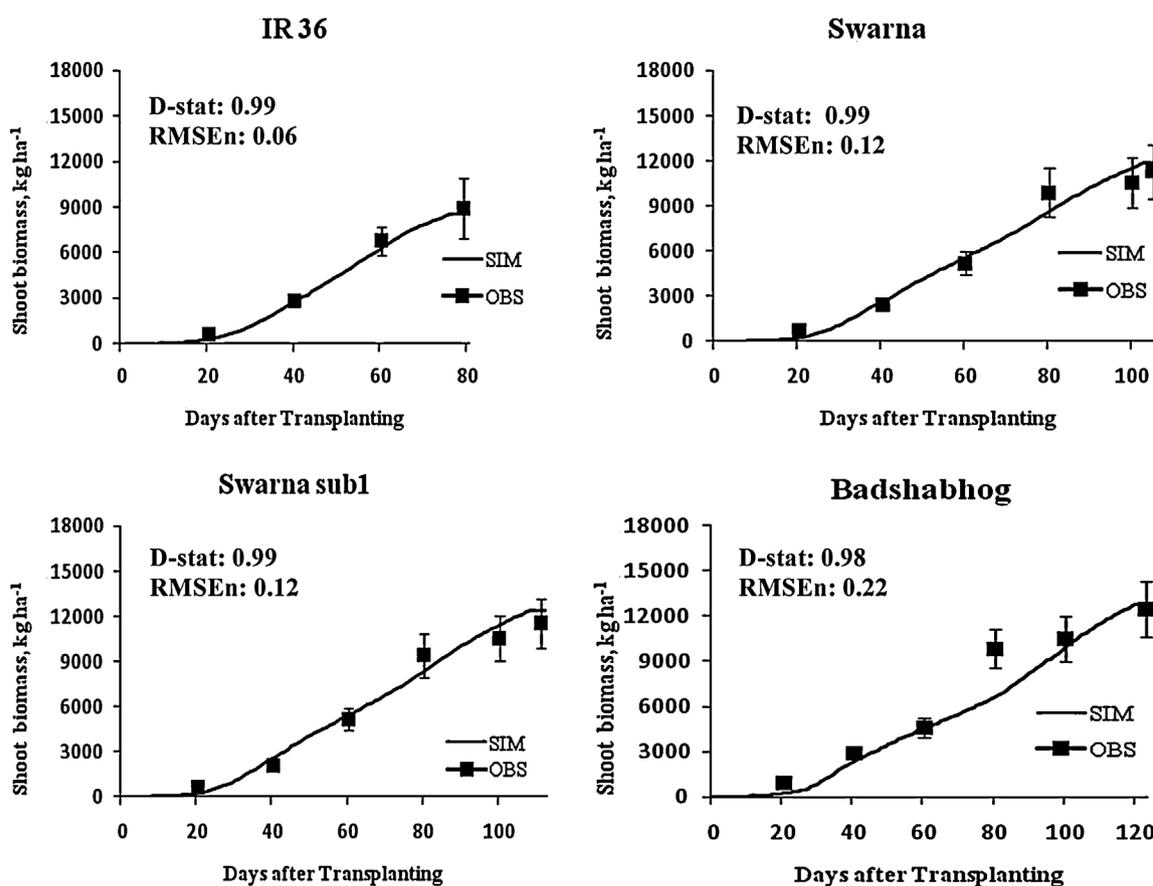


Fig. 1. Observed (OBS) and simulated (SIM) time series shoot biomass in days after transplanting of rice cultivars (IR 36, Swarna, Swarna sub1, and Badshabhog) grown in open field during wet season of year 2011 at Kharagpur, India (calibration of CERES-Rice).

properties of the location, calibrated genotype parameters of the cultivars under elevated CO_2 environment, and existing crop management practices for the grain yield simulation. The percentage change in the simulated grain yield was calculated for the rising CO_2 and temperature scenarios as compared the yield of the cultivars under current weather. For the developed scenarios, weather of HadCM3 global climate model under the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios of A2 and B2 for the years 2020 (2010–2039), 2050 (2040–2069) and 2080 (2070–2099) of the location 'Kharagpur' were used. The A2 scenarios are characterized by a heterogeneous world of independently operating, self-reliant nations, continuously increasing population and regionally oriented economic development. The B2 scenarios describe a world with intermediate population and economic growth, emphasizing local solution to economic, social and environmental sustainability (IPCC, 2007). The projected CO_2 concentrations for both the scenarios were 420, 480 and 540 ppm for the years 2020, 2050 and 2080, respectively. The corresponding rise in air temperature under the elevated CO_2 environment were 0.8, 2.19, and 3.97°C for A2 scenario and 0.8, 1.68, and 2.87°C for B2 scenario during the years 2020, 2050, and 2080, respectively, as compared to the base line weather (1961–1990).

3. Results

3.1. Model calibration and validation for open field environment

The simulated time series shoot biomasses were within standard deviation of their observed values throughout the growing season for all the cultivars (Fig. 1). Between the simulated and observed time series shoot biomass, the RMSE_n values were less

than 0.22 and the d-stat values were >0.98 for all the cultivars. The data in Table 3 stated that the simulated physiological maturity day was same as observed for the cultivars IR 36 and Badshabhog, and was 1 and 2 days difference in Swarna sub1 and Swarna, respectively. The simulated shoot weight and grain yield at maturity of all the cultivars were within the standard deviations of their measured values. The calibrated genotype coefficients for all the cultivars are given in Table 4. The genotype coefficients were validated using experimental results of the open field environment of the year 2012. Between the simulated and observed time series shoot biomass, the RMSE_n values were less than 0.19 and the d-stat values were 0.99 for all the cultivars (Fig. 2). Further, the simulated time series biomass values were within standard deviation of their observed values in all the cultivars. Between simulation and experimental observation, the appearance of flowering differed by 2–4 days among the cultivars and the maturity by 1–4 days in all cultivars, except Swarna (Table 5). The variation between simulated and observed shoot weight of the cultivars were in the range 5–12%. The simulated grain yield varied up to 9% of observed yield for all the cultivars except Badshabhog. However, the simulated grain yield of Badshabhog was within standard deviation of the observed yield.

3.2. Model calibration and validation for elevated CO_2 environment

The open field calibrated model was used for simulating physiological maturity days, shoot weight at maturity, and grain yield of the four cultivars grown under elevated CO_2 environment in OTC during the year 2011. From the data in Table 6, it is understood that the simulated physiological maturity days of all the cultivars were considerably earlier to their observed values: 6 days in IR

Table 4
Calibrated genotype coefficients of the cultivars IR 36, Swarna, Swarna sub1 and Badshabhog in CERES-Rice model for open field environment.

Coefficients	IR 36	Swarna	Swarna sub1	Badshabhog
P1 (°C-days)	470	620	640	750
P2R (°C-days)	50	180	180	300
P5 (°C-days)	350	490	520	420
P20 (h)	11.7	11.8	11.6	11.6
G1 (no.)	65	70	67	62
G2 (g)	0.02	0.02	0.02	0.01
G3	1	1	1	1
G4	1	1	1	1

P1: basic vegetative phase, P20: critical photoperiod, P2R: photoperiod sensitivity, P5: grain filling phase, G1: potential spikelet number per panicle, G2: single grain weight, G3: tillering, and G4: temperature tolerance coefficients.

36, 9 days in Swarna sub 1 and 11 days in Swarna/Badshabhog. Similarly the simulated grain yield of all the cultivars, except Badshabhog varied widely from their observed values. Only the simulated shoot biomass values at maturity of all the cultivars were within standard deviation of their observations. There exists a large variation between simulated and observed values for physiological maturity and grain yield of the cultivars under elevated CO₂ environment, while simulating with use of the calibrated model of ambient CO₂ as in open field. This result suggests that there is a necessity for calibration and validation of the model under elevated CO₂ environment as in OTC for its application under climate change scenarios because of increasing CO₂ level.

We calibrated and validated the genotype coefficients of CERES-Rice model for elevated CO₂ environment using the OTC experimental data of the year 2011 and 2012, respectively. In calibration, the time series shoot biomass values were within standard deviation of measured values throughout the growing season for all the cultivars (Fig. 3), except Badshabhog, which differed at one observation point only. The RMSE_n between the simulated and observed time series shoot biomass were <0.20 for the cultivars IR

36, Swarna and Swarna sub1, and 0.28 for Badshabhog. The d-stat values were >0.96 for all the four cultivars. The difference between observed and simulated physiological maturity was <3 days among the cultivars and the simulated grain yield and shoot biomass were within standard deviation of their observed values (Table 7). The calibrated genotype coefficients for all the cultivars are given in Table 8. The genotype coefficients of the model were validated using experimental results of the OTC under elevated CO₂ environment of the year 2012. Between the simulated and observed time series shoot biomass, the RMSE_n values were <0.14 and the d-stat values were 0.99 for all the cultivars and the simulated time series biomass values were within standard deviation of their observed values (Fig. 4). From the experimental observation, the appearance of simulated anthesis day differed by less than 3 days in all the cultivars and simulated maturity day by less than 3 days among all the cultivars, except Badshabhog, where the difference was 6 days (Table 9). The simulated grain yield of the cultivars Swarna and Swarna sub1 matched well with their observed yield. The yield was marginally under simulated for IR 36 and over simulated for Badshabhog. However, the simulated shoot biomass at maturity

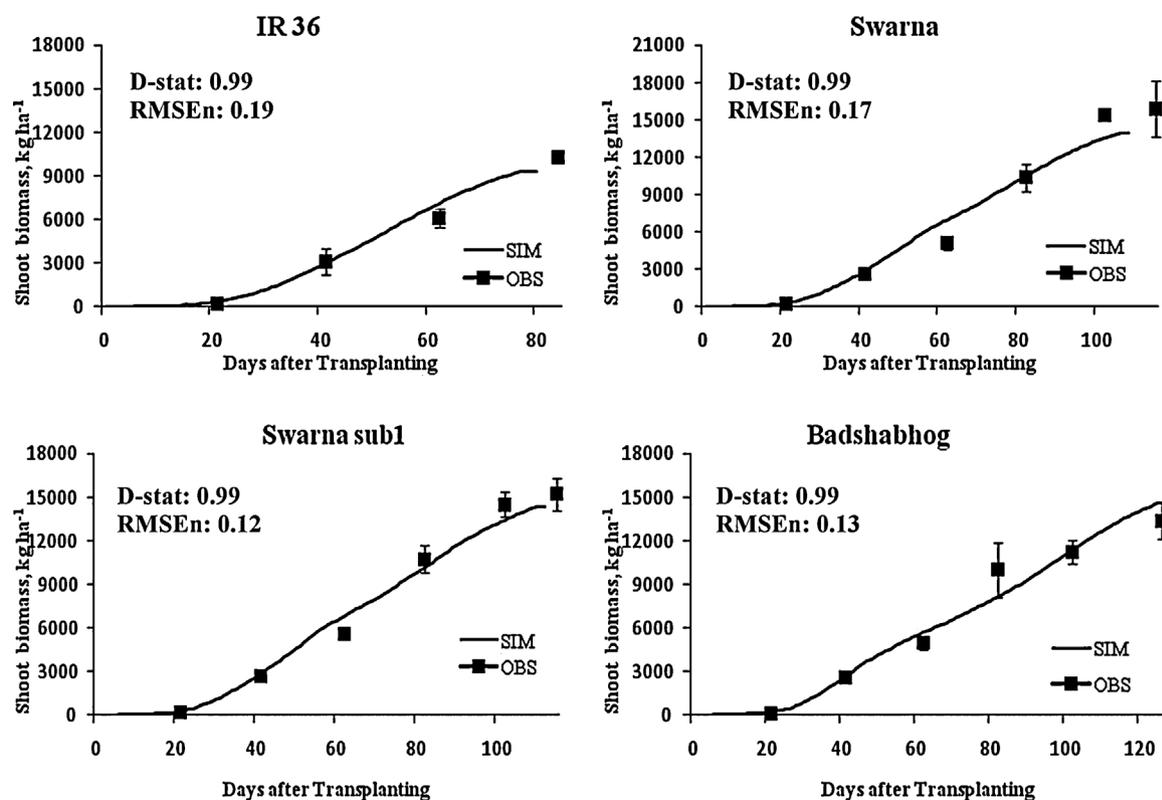


Fig. 2. Observed (OBS) and simulated (SIM) time series shoot biomass in days after transplanting of rice cultivars (IR 36, Swarna, Swarna sub1, and Badshabhog) grown in open field during wet season of year 2012 at Kharagpur, India (validation of CERES-Rice).

Table 5

Simulated and observed phenology and growth of rice cultivars (IR 36, Swarna, Swarna sub1 and Badshahhog) grown under open field environment during wet season of the year 2012 (validation of CERES-Rice).

Crop parameters	IR 36		Swarna		Swarna sub1		Badshahhog	
	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed
Anthesis day (DAT)	56	52	76	80	78	80	95	93
Physiological maturity day (DAT)	80	84	108	115	112	115	127	126
Grain yield at maturity (kg ha ⁻¹)	4420	4850(±495)	7296	6762(±118)	6451	6700(±191)	4312	3723(±596)
Shoot weight at maturity (kg ha ⁻¹)	9346	10,280(±481)	14,006	15,914(±2207)	14,371	15,230(±1101)	14,621	13,390(±1259)

DAT: days after transplanting, values within open parenthesis are standard deviations.

Table 6Simulated and observed phenology and growth of rice cultivars (IR 36, Swarna, Swarna sub1 and Badshahhog) grown under elevated CO₂ environment during wet season of the year 2011(using open field calibrated genotype parameters).

Crop parameters	IR 36		Swarna		Swarna sub1		Badshahhog	
	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed
Physiological maturity day (DAT)	75	81	99	110	105	114	115	126
Grain yield at maturity (kg ha ⁻¹)	3197	2200(±353)	5486	3396(±454)	5168	3039(±427)	3253	3366(±461)
Shoot weight at maturity (kg ha ⁻¹)	6662	8335(±1810)	9920	10,602(±2221)	10,587	11,417(±1981)	10,751	12,309(±2073)

DAT: days after transplanting, values within open parenthesis are standard deviations.

Table 7
Simulated and observed phenology and growth of rice cultivars (IR 36, Swarna, Swarna sub1 and Badshabhog) grown under elevated CO₂ environment during wet season of the year 2011 (calibration of CERES-Rice).

Crop parameters	IR 36		Swarna		Swarna sub1		Badshabhog	
	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed
Anthesis day (DAT)	54	50	74	71	76	71	91	94
Physiological maturity day (DAT)	81	81	108	110	111	114	124	126
Grain yield at maturity (kg ha ⁻¹)	2223	2200 (±353)	3316	3396 (±454)	3371	3039 (±427)	3066	3366 (±461)
Shoot weight at maturity (kg ha ⁻¹)	7748	8335 (±1810)	10,898	10,602 (±2221)	11,158	11,417 (±1981)	11,818	12,309 (±2073)

DAT: days after transplanting, values within open parenthesis are standard deviations.

was within standard deviation of observed value for all the cultivars.

3.3. Cultivar adaptation under elevated CO₂ and rising temperature environment

The change in simulated grain yield of the cultivars under varying levels of elevated CO₂ and rising temperature as compared to ambient environment is shown in Fig. 5. With increasing CO₂ level of ≈100 ppm and rising temperature of ≈1 °C above ambient, the change in experimental grain yield were −17.2%, −11.1%, −8.8%, and +8.9% for IR 36, Swarna, Swarna sub1, and Badshabhog, respectively as observed from the OTC experiment and the corresponding changes in simulated grain yield were −13.3%, −17.4%, −3.6%, and +7.2%, respectively, as averaged over the two years (2011 and 2012). Under similar CO₂ level (+100 ppm), a rise in temperature of 2 °C and 3 °C simulated a corresponding change in grain yield of −25.3 and −37.6% in the cultivar IR 36; −22.8 and −38.7% in Swarna; −9.6 and −27.5% in Swarna sub1; and +1.7 and −3.3% in Badshabhog (Fig. 5). With further increase in CO₂ level (+200 and +300 ppm), there was low reduction in simulated grain yield in all the cultivars.

Use of future weather of the GCM simulated a continuous decline in grain yield from present year to the years 2020, 2050 and 2080 for the cultivars IR 36 and Swarna with rising temperature of ≥0.8 °C (Fig. 6). The cultivar Swarna sub1 had stable performance up to 2050 and thereafter the yield declined in both A2 and B2 scenarios. Whereas, the yield of Badshabhog was increased up to 2080 in B2 scenario and 2050 in A2 scenario. The grain yield under A2 scenario was lower than B2 scenario for all the cultivars in the years 2050 and 2080.

4. Discussion

4.1. Model parameterization in open field and elevated CO₂ environment

The calibrated basic vegetative phase coefficient (P1) for different cultivars, i.e. IR 36, Swarna, Swarna sub1 and Badshabhog in OTC of elevated CO₂ environment were 480, 680, 710 and 800 °C-days, respectively, which were higher than their corresponding open field values (470, 620, 640 and 750 °C-days, respectively). The P1 value for Swarna, Swarna sub1 and Badshabhog was considerably higher in elevated CO₂ than in open field, because of longer crop duration (+3 to +5 days) in the elevated CO₂ environment. Our finding was in corroboration with Madan et al. (2012), who reported delay in flowering and maturity under elevated CO₂ environment. Similarly, the photoperiod sensitivity (P2R) values in elevated CO₂ environment were 70, 200, 190 and 350 °C-days for the cultivars IR 36, Swarna, Swarna sub1 and Badshabhog, respectively, which was higher than their open field values (50, 180, 180 and 300 °C-days, respectively). The higher P1 and P2R values under elevated CO₂ environment as compared to open field indicate that the crop accumulated more growing degree-days in the vegetative phase with increasing CO₂ level, which is discernable from higher increase in shoot biomass under elevated CO₂ at the initial stage of crop growth as compared to later stages from our experiment. The increase in shoot biomass with increasing CO₂ at 20 and 80 DAT were 36 and 1% in IR 36, 37 and 16% in Swarna sub1/Swarna, and 95 and 9% in Badshabhog, respectively, as averaged over the two years. Jitla et al. (1997) also reported higher increase in rice shoot growth due to CO₂ enrichment during early growth period than later growth period. Kim et al. (2003) stated that the positive effect of elevated CO₂ on above-ground biomass of rice decreased from tillering towards maturity. The observed higher response to CO₂ early in the growing season might be due to more effective N uptake with greater root

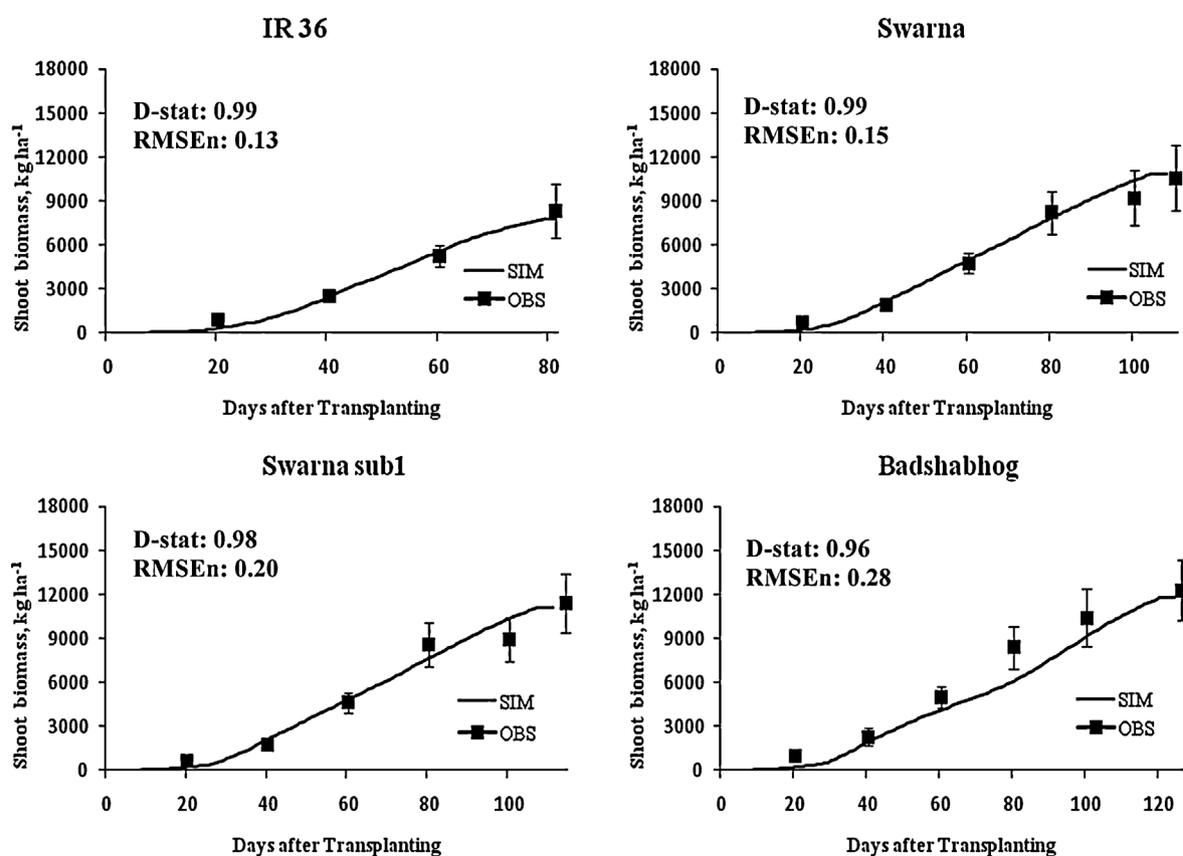


Fig. 3. Observed (OBS) and simulated (SIM) time series shoot biomass in days after transplanting of rice cultivars (IR 36, Swarna, Swarna sub1, and Badshabhog) grown in elevated CO₂ environment inside Open Top Chamber during wet season of year 2011 at Kharagpur, India (calibration of CERES-Rice).

development under elevated CO₂ (Kim et al., 2001). The value of grain filling phase coefficient (P5) of the cultivars was also higher by 60–90 °C-days in elevated CO₂ environment as compared to open field. This finding was in corroboration with the experimental observation where the grain filling duration was higher by 4 days in elevated CO₂ environment as compared to open field for all the cultivars, except Badshabhog. Madan et al. (2012) also noted higher grain filling duration under elevated CO₂ for the cultivar IR64 (+1 d) and N22 (+3 d) as compared with ambient CO₂.

Unlike the phenotype coefficient, the potential spikelet number coefficient (G1) for all the cultivars was lower in elevated CO₂ environment than in open field. However, the single grain weight (G2) value remained unchanged under elevated CO₂ environment; though a marginal decrease was noted in the experiment. During the grain filling period, the average temperature of elevated CO₂ environment was 2 (±0.2) °C higher than in open field (30 °C for IR 36 and 25 °C for rest cultivars) which possibly reduced the filled grain number per panicle by 4% in IR 36, 8% in Swarna, 2% in Swarna sub1, and 5% in Badshabhog. Further, the harvest index of all the

cultivars, except Badshabhog was decreased from 0.48 in open field to 0.33 in elevated CO₂ environment. Lower harvest index at raised temperature under elevated CO₂ environment was due mainly to lower grain yield caused by decreased spikelet fertility. Our result of the temperature sensitivity on filled grain number was in agreement with Kim et al. (1996), Matsui et al. (1997), and Vara Prasad et al. (2006). Short duration exposure of high temperature events (>33 °C) poses a serious threat to rice production (Wassmann et al., 2009). The threat is severe when high temperatures coincide with the grain-filling (Fitzgerald and Resurreccion, 2009), which may be exacerbated by higher canopy temperature associated with stomatal response to elevated CO₂ (Vara Prasad et al., 2006; Long and Ort, 2010).

4.2. Cultivar selection for climate change adaptation

We compared the changes in simulated yield of the four cultivars with their changes in experimental yield under elevated CO₂ (≈+100 ppm) with the rising temperature (≈+1 °C) as compared to

Table 8

Calibrated genotype coefficients of the cultivars IR 36, Swarna, Swarna sub1 and Badshabhog in CERES-Rice model for elevated CO₂ environment.

Coefficients	IR 36	Swarna	Swarna sub1	Badshabhog
P1 (°C-days)	480	680	710	800
P2R (°C-days)	70	200	190	350
P5 (°C-days)	440	570	580	480
P20 (h)	11.7	11.8	11.6	11.6
G1 (no.)	44	44	44	50
G2 (g)	0.02	0.02	0.02	0.01
G3	1	1	1	1
G4	1	1	1	1

P1: basic vegetative phase, P20: critical photoperiod, P2R: photoperiod sensitivity, P5: grain filling phase, G1: potential spikelet number per panicle, G2: single grain weight, G3: tillering, and G4: temperature tolerance coefficients

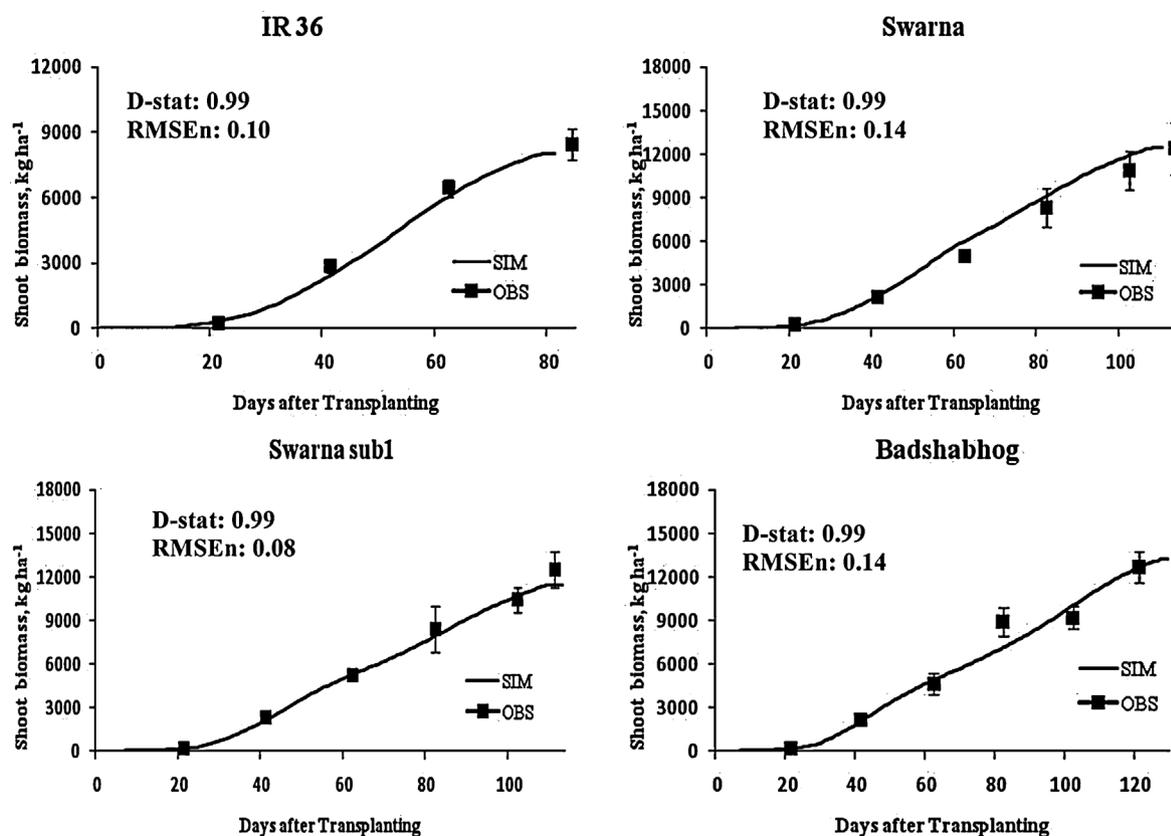


Fig. 4. Observed (OBS) and simulated (SIM) time series shoot biomass in days after transplanting of rice cultivars (IR 36, Swarna, Swarna sub1, and Badshabhog) grown in elevated CO_2 environment inside Open Top Chamber during wet season of year 2012 at Kharagpur, India (validation of CERES-Rice).

ambient environment in OTC experiment. With this CO_2 and temperature scenario, the trend of the changes in simulated yield was same as of the changes in the experimental yield among the cultivars. Both simulated and experimental rice yields were decreased for the cultivars IR 36 (−17% and −13%), Swarna (−11% and −17%), and Swarna sub1 (−9% and −4%), but increased for the cultivar Badshabhog (+9% and +7%) with increasing CO_2 level by 100 ppm and corresponding rise in temperature of 1°C above ambient CO_2 (≈ 390 ppm) and temperature during the crop growing period. The magnitudes of yield changes of the simulated and experimental value were comparable for all the cultivars, except Swarna sub1 where the simulated yield reduction was higher than observed yield reduction under the elevated CO_2 environment. However, the similar trend of yield changes in simulated value as of the experimental findings for the cultivars under a fixed rise in CO_2 level and temperature favoured application of the CERES-Rice model for simulation of grain yield under varying CO_2 level and temperature for cultivar adaptation.

Increase in CO_2 level at a particular temperature simulated an increase in grain yield, but increase in temperature at a particular CO_2 level simulated a decrease in grain yield. The yield reduction was highly significant when temperature was increased by 3°C irrespective of CO_2 level elevation (+100 to +300 ppm), simulating the reduction of 22–38% in IR 36, 28–39% in Swarna, and 15–28% in Swarna sub1. Whereas under similar rising temperature, the grain yield Badshabhog was increased by 4–10% with increasing CO_2 level (+200 to +300) above ambient value. In contrast, at lower level of CO_2 elevation (+100 ppm), the yield of Badshabhog was decreased marginally at 3°C rising temperature but increased by 2–7% with low temperature increment (up to $+2^\circ\text{C}$). Similarly with use of HadCM3, the yield of IR 36 and Swarna declined significantly during the year 2050 and 2080 in A2 as well as B2 scenarios as

compared to current yield. The yield decrease was lower in B2 scenario (13–18%) as compared to A2 scenario (15–31%) because of lower temperature rise in the former scenario. Whereas, the grain yield of the cultivar Swarna sub1 was marginally affected and of Badshabhog was favoured up to the year 2050 in both the scenarios, where the temperature rise was expected up to $+2^\circ\text{C}$. Many researchers have reported increasing rice yield with increasing CO_2 level (Kim et al., 2003; Baker et al., 1992; Liu et al., 2008; Yang et al., 2009), but decreasing yield with increasing temperature (Peng et al., 2004; Sheehy et al., 2006; Krishnan et al., 2007; Masutomi et al., 2009) under controlled environmental experiment. The experimental findings from the growth chamber studies (Baker et al., 1992) showed a 32% increase in rice grain yield due to increasing CO_2 concentration from 330 to 660 $\text{mmol CO}_2 \text{ mol}^{-1}$ air (ppm). Higher tillering and more grain-bearing panicles under increasing CO_2 concentration was responsible for increased growth and yield of crop. The decreasing rice yield with increasing temperature was mainly due to the rice spikelet sterility at high temperature. The temperature at the time of flowering affects the spikelet fertility and hence the yield (Krishnan and Surya Rao, 2005). Even a small rise in temperature ($+1^\circ\text{C}$) could result in a large yield decrease due to decreasing number of grains being formed (Sheehy et al., 2006). In our chamber experiment, an increasing temperature of 1°C with rising CO_2 level of 100 ppm decreased filled grain number per panicle up to 10% while compared to ambient environment.

The increasing CO_2 level and temperature simulated a lower reduction in grain yield of the cultivar Swarna sub1 as compared to Swarna and IR 36. Whereas, the yield of Badshabhog was favoured with the increasing CO_2 level and the corresponding temperature. Among the cultivars, the expected yielding potential is higher in Swarna/Swarna sub1 (8.0 t ha^{-1}), followed by IR 36 (6.0 t ha^{-1}) and Badshabhog (4.0 t ha^{-1}) at the location. The ambient average

Table 9
Simulated and observed phenology and growth of rice cultivars (IR 36, Swarna, Swarna sub1 and Badshabhog) grown under elevated CO₂ environment during wet season of the year 2012 (validation of CERES-Rice).

Crop parameters	IR 36		Swarna		Swarna sub1		Badshabhog	
	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed
Anthesis day (DAT)	55	52	76	78	78	76	96	94
Physiological maturity day (DAT)	81	84	110	113	113	111	129	123
Grain yield at maturity (kg ha ⁻¹)	2295	3095 (±488)	3712	3949 (±505)	3300	3879 (±407)	3525	2904 (±507)
Shoot weight at maturity (kg ha ⁻¹)	8030	8440 (±713)	12,466	12,426 (±1780)	11,480	12,550 (±1218)	13,221	12,692 (±1072)

DAT: days after transplanting, values within open parenthesis are standard deviations.

temperature for the two years during the grain filling phase was 30 °C for IR 36 and 25 °C for other cultivars, if planted on July 27 as the normal planting period (July 15–30) of the location. The average optimum air temperature for grain filling of rice is 20–29 °C (Satake and Yoshida, 1978). Higher air temperature during the grain filling phase of IR 36 possibly resulted higher spikelet sterility, i.e. lower number filled grains, hence larger yield reduction as compared to other cultivars. Similarly, the large yield reduction in Swarna under elevated CO₂ environment may be due to decrease in filled grain number per panicle, which is lightly substantiated from the OTC experiment. The increasing yield of the cultivar 'Badshabhog' under elevated CO₂ with rising temperature (up to +2 °C) is due to increasing filled grain number per panicle and single grain weight, which is observed in our chamber experiment.

4.3. Implications for recommended rice production systems of the future

Tropical and sub-tropical region of the world are major producer and consumer of rice, where food security is of paramount importance in current as well as future climate. To combat the adverse impact of climate change on food production, localized adaptation technologies in cultivar selection, planting time and water and nutrient management needs special attention for maintenance and improvement of food production and resource use efficiency. The present investigation clearly reflected that cultivar adaptation has the potential to minimize the adverse impact of climate change on rice yield of subtropical India. The cultivar Badshabhog is benefitted through increased grain production under rising temperature and elevated CO₂ environment. The elevated CO₂ encouraged significant improvement in shoot biomass at the initial period of crop growth as compared to the later stages towards maturity in all the cultivars. Among the cultivars, Badshabhog registered highest biomass accumulation at the vegetative phase under the elevated CO₂ environment. The cultivar Badshabhog is characterized as longer leaves (>45 cm) and longer growing duration (>145 d) as compared to rest cultivars, possibly increased solar radiation interception and hence the shoot biomass accumulation at the vegetative stage of the crop growth. Biomass accumulation and translocation to grain portion for grain production depends on available source material and grain size as the sink capacity under a given set of climatic condition. Small grain size (single grain weight = 0.01 g) with high grain bearing panicles (>170 grains per panicle) and larger biomass accumulation of the cultivar Badshabhog, probably favoured better source–sink transfer, which increased grain production under elevated CO₂ and temperature environment as compared to other cultivars. Grain yield of cereal crops are normally source limited. Some researchers (Fischer and HilleRisLambers, 1978; Judi et al., 2006; Koshkin and Tararina, 1989; Ledent and Stoy, 1985) reported reduction of rice grain number with increase in single grain weight under source limitation during grain filling period. Further, under elevated CO₂ environment an imbalance between source and sink may lead to carbohydrate accumulation in leaves at whole plant level resulting decrease expression of photosynthetic genes (Paul and Foyer, 2001). Hence, increased biomass accumulation and a balanced source–sink transfer at plant level are likely to minimize the adverse impact of future climate change on rice production. The cultivar Badshabhog, as a local selection by farmers, is tolerant to abiotic stresses and has shown increased biomass accumulation and grain yield formation under elevated CO₂ and temperature environment. The special characteristics of this cultivar such as long leaves, small grain size and increasing grain number may be considered in breeding technology for development of cultivars that can

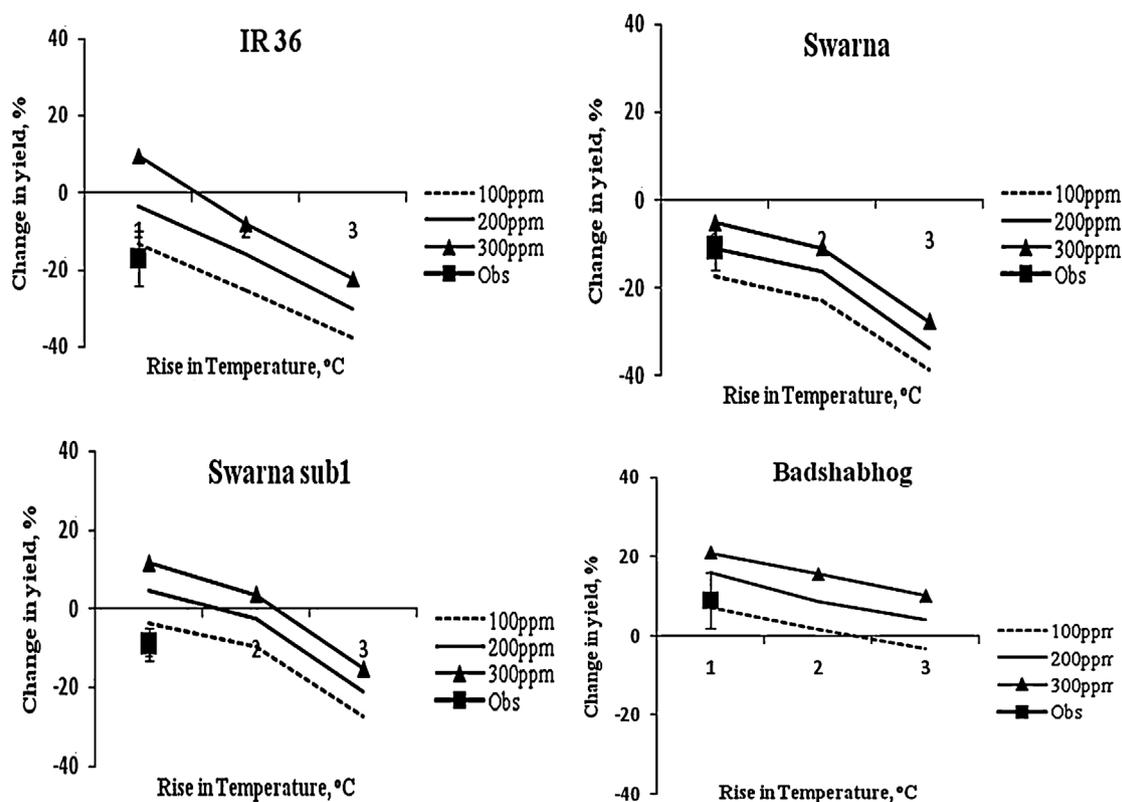


Fig. 5. Change in simulated grain yield of rice cultivars (IR 36, Swarna, Swarna sub1, and Badshahbhog) grown with elevated CO₂ level (+100, +200 and +300 ppm) and rising temperature (+1 °C, +2 °C, and +3 °C) as compared to ambient environment and change in observed (OBS) grain yield at elevated CO₂ level (≈+100 ppm) and rise in temperature (≈+1 °C) at Kharagpur, India (averaged over the years 2011 and 2012).

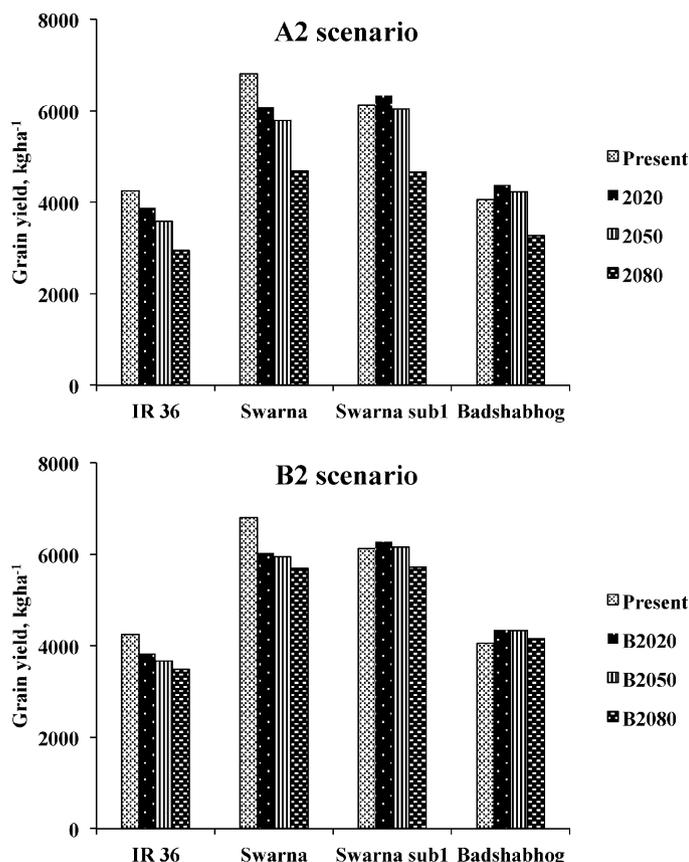


Fig. 6. Effect of Global Climate Model on grain yield of rice cultivars (IR 36, Swarna, Swarna sub1, and Badshahbhog) simulated for the years 2020, 2050 and 2080 under A2 and B2 scenarios at Kharagpur, India.

adapt better to future climate scenarios for ensuring global food security.

5. Conclusions

Genotype coefficients of the CERES-Rice model needs to be calibrated for elevated CO₂ environment for better simulation of rice grain yield under climate change scenarios leading to rise in CO₂ level and temperature. Use of the model parameterized under elevated CO₂ environment was able to simulate the yield trend of cultivars accurately under rising CO₂ level and temperature. While evaluating the response of cultivars with respect to grain yield changes under varying level of CO₂ and temperature rise from simulation and from the observations of two years OTC experiment, it was noted that the cultivars IR 36 and Swarna were worst affected, Swarna sub1 was marginally affected, but Badshahbhog was favoured under elevated CO₂ with rising temperature up to +2 °C. The yielding potential of the long duration cultivars 'Swarna/Swarna sub1' is significantly higher than the medium duration cultivar 'IR 36' as well as the aromatic cultivar 'Badshahbhog' under irrigated/rainfed ecosystem of the subtropical India. In perspective of the future climate change and food demand, the cultivar Swarna sub1 should be preferred for irrigated as well as rainfed lowland ecosystem in the subtropical climate to minimize the adverse impact of climate change on rice production. As the cultivar Badshahbhog shows favourable response to the elevated CO₂ environment, this welcomes breeding technology for genetic manipulation in high yielding cultivars for increasing their adaptability to abiotic stresses. Secondly, the Badshahbhog cultivation may be extended to larger area as the demand for aromatic rice is increasing dramatically in international market.

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