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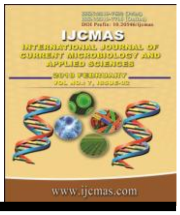

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Imitation of Climate Change Impacts on Growth and Yield of Wheat Crop in Eastern India

Uma Shankar Gupta, Shatruhan Jaiswal* and P.B.S. Bhadoria

Agricultural Engineering, Faculty of Agriculture Abhilashi University Chailchowk Chachyot, Dist. - Mandi – 175028, India

**Corresponding author*

ABSTRACT

India is second most populous country after China which houses 15% of global population (census 2011) within 2.42% of geographical land area of world. The ever growing population and improving economic condition pressurize to produce and supply higher quantity of food grains. However, the country's agriculture production is not increasing but somewhere stagnated, this increasing demand for food grain production. Agriculture sector therefore needs much attention to decrease this gap between increasing demand and production. Wheat, the staple cereal crop in world, is grown in 220.38 million hectare contributing 27.21% of total cereal grain production. In India, wheat is grown in an area of about 29.06 million hectares with a production of 86.87 million ton (FAO, 2011). The yield of wheat increased after sixties and early seventies bringing the green revolution in India. In recent years, production of wheat crop in response to the increasing application rates of the input resources is experiencing a declining trend. The decline in yield is mainly due to shortening of growth period, decrease in photosynthesis ability and increase in respiration demanding more irrigation water supply. Crop simulation models can provide an alternative, less time-consuming and inexpensive means of determining the optimum management option (Nitrogen and irrigation requirements) under varied soil and climatic conditions. Crop growth modeling has emerged as a powerful tool for optimizing crop yield and identifying critical factors, contributing to yield under varying climate change. In this context, dynamic mechanistic models CERES (Crop Environment Resource Synthesis)-Wheat available in Decision Support System for Agrotechnology Transfer (DSSAT) can be used for predicting growth and yield of wheat (*Triticum aestivum L.*) under different nitrogen and water management conditions. Our present study focuses the performance evaluation of CERES wheat model and use of the model for analysis of climate change impact on wheat yield. Keeping these in view the present study was formulated with the objectives of Calibration and validation of CERES-wheat model.

Keywords

Wheat, Temperature, CO_2 and CERES model

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Introduction

The probable reasons for stagnation production are decline soil fertility and climate change. Global warming and associated climate change will affect agricultural crop yield because of alterations in temperature and rainfall cycle and through changes in soil quality, pests and diseases. The decline in yield is mainly due to shortening of growth period, decrease in photosynthesis ability and increase in respiration demanding more irrigation water supply. Climate change because of increasing concentration of atmosphere CO_2 may bring benefits to some parts of the world, especially in developed countries, but it is a threat to food security in the developing countries. This is due to the generally predicted deleterious impacts on agriculture, particulars in tropical and sub-tropical countries (Parry *et al.,* 2004). Crop simulation models can provide an alternative, less time-consuming and inexpensive means of determining the optimum management option (Nitrogen and irrigation requirements) under varied soil and climatic conditions. Crop growth modeling has emerged as a powerful tool for optimizing crop yield and identifying critical factors, contributing to yield under varying climate change. In this context, dynamic mechanistic models CERES (Crop Environment Resource Synthesis)-Wheat available in Decision Support System for Agrotechnology Transfer (DSSAT) can be used for predicting growth and yield of wheat (*Triticum aestivum L.*) under different nitrogen and water management conditions. DSSAT is one of the potential modeling tools that can simulate appropriately the growth, development and yield of crops, using soil, weather and management as input data to the model. Suitably validated crop simulation models could be used to test many such combinations in a brief time and such simulations can adequately describe relative trends in yields caused by environmental variation (Penning de Vries *et al.,* 1989). To assess the vulnerability of agriculture to climate change, it is necessary to consider the role of adaptation, as appropriate adaptation can greatly reduce the magnitude of impacts of climate change. Analysis of climate change impacts on wheat production and evaluation and adaptation is lacking in eastern India. Xiao *et al.,* (2005) conducted a field experiment on rain-fed spring wheat (*Triticum aestivum*) at the Haiyuan Experimental Station (36°34'N, 105°39'E), in China, during 2001–2003. According to the experimental design, the CO_2 concentration increased by 90 μmol/mol (from 360 to 450 μmol/mol), while the mean daily temperature, during the whole growth stage, increased 0.8 °C (from 14.3 to 15.1 °C) and 1.8 °C (from 14.3 to 16.1 °C). The results showed that the combination of a 450 μmol/mol CO_2 concentration and a 0.8 °C temperature increase stimulated rain-fed spring wheat yield by~ 5.3%. The combination of a 450 μmol/mol CO_2 concentration and a 1.8 °C temperature increase, however, reduced wheat yield by~ 5.7%. This combined effect on wheat yield presents the result of global climate changes over the next 30 years in semiarid regions of China. As an agronomic practice, supplemental irrigation of 30 mm may compensate for any loss of yield caused by climatic changes in the future. Furthermore, 60 and 90 mm supplemental irrigation improved wheat yield 3.8 and 10.1%, respectively.

Ziska (2008) examined two contrasting spring wheat cultivars, Marquis and Oxen, over a 3-year period under field conditions at two different planting densities. Marquis was introduced into North America in 1903, and is taller, with greater tiller plasticity (i.e. greater variation in tiller production), smaller seed and lower harvest index relative to modern wheat cultivars. Oxen, a modern cultivar released in 1996, produces fewer tillers, and has larger seed with a higher harvest index relative to Marquis. Under ambient CO_2 conditions, Oxen produced more seed than Marquis for all 3 years. However, at a CO_2 concentration 250 μmol/mol above ambient (a concentration anticipated in the next 50-100 years), no differences were observed in seed yield between the two cultivars, and vegetative above ground biomass (e.g. tillers) was significantly higher for Marquis relative to Oxen in 2006 and 2007. Significant CO_2 by cultivar interaction was observed as a result of greater tiller production and an increased percentage of tillers bearing panicles for the Marquis relative to the Oxen cultivar at elevated carbon dioxide. This greater increase in tiller bearing panicles also resulted in a significant increase in harvest index for the Marquis cultivar as CO_2 increased. While preliminary, these results intimate that newer cultivars are not intrinsically more CO_2 responsive; rather, that yield sensitivity may be dependent on the availability of reproductive sinks to assimilate additional carbon. Erda *et al.,* (2005) evaluated the climate change impacts on crop yield and quality with CO_2 fertilization in China using PRECIS model. Their results showed that depending on the level of future emission, the average annual temperature expected increase by the end of 21st century may be between 3°C to 4°C. Also the modeling results elaborated that the climate change without carbon dioxide fertilization may reduce the rice, maize and wheat yields by up to 37% in the next 20-80 years. Palosuo *et al.,* (2011) used eight different crop growth models (APES, CROPSYST, DSSAT, DAISY, FASSET, HERMES, STICS and WOFOST) for winter wheat crop in 49 growing seasons at eight different sites of Europe to study how different process-based crop model perform at the field scale when provided with a limited set of information for model calibration and simulation. In their study, they concluded that the wide range of grain yield estimates provided by the models for all sites and years reflects substantial uncertainties in model estimates achieved with only minimum calibration. Mean predictions from the eight models, on the other hand, were in good agreement with measured data. Mutlu Ozdoğan (2011) investigated the impacts of elevated atmospheric CO_2 concentrations and associated changes in climate on winter wheat yields in northwestern Turkey. They suggested prioritization of adaptation strategies in the region, including development of local cultivars of drought and heat-resistant crop varieties, earlier planting to avoid heat stress during summer, development and adoption of slower-maturing varieties to increase the grain filling period, and further investments to boost agricultural productivity.

Materials and Methods

Study site

The present study has been 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. The climate of Kharagpur is classified as sub humid, sub-tropical with 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 daily mean temperature of the study area ranges from a minimum of 12 °C in January to a maximum of 37 °C in April with average annual rainfall of 1400 mm. The variation in average daily maximum and minimum temperatures, solar radiation and rainfall for the study area during 1971 - 2012 is shown in Figure 1.

CERES-Wheat model

CERES-Wheat, growth and yield simulation model of wheat crop that have been incorporated in DSSAT (Hoogenboom *et al.,* 1994). The CERES model simulates crop growth, development and yield taking into account the effects of weather, genetics, soil (water, carbon and nitrogen), planting, and irrigation and nitrogen fertilizer management. It includes XBuild used to create and modifies experiment files, weatherman for weather data, Gbuild for graphing output, ATCreat for observed data and SBuild for soil database.

The CERES-Wheat model simulates phenological development of the crop; growth of grains, leaves, stems, and roots; biomass accumulation based on light interception and environmental stresses; soil water balance; and soil N transformations and uptake by the crop.

Input parameters

Input requirements for CERES-Wheat include site characteristics weather and soil conditions, plant characteristics, and crop management (Hunt *et al.,* 2001).

Site

Latitude, longitude, elevation, slope, water table depth.

Weather

Daily solar radiation, maximum and minimum air temperature, and precipitation. Solar radiation can be approximated from other observations, such as the number of sunshine hours, which is sometimes more readily available.

Soil

Physical properties

Depths of layers, percentages of sand, silt, and clay, and bulk density at various depths, moisture content at lower limit (LL, 15 bars), drained upper limit (DUL, 1/3 bar), and at saturation (SAT) for various depths (if they are not available, they could be estimated from percentages of sand, silt, and clay and bulk density).

Chemical properties

pH, organic carbon, total nitrogen, Cation Exchange Capacity.

Crop management

Plant population, planting depth, and date of planting, irrigation and fertilizer scheduling, tillage operations and residue management etc.

Genetic coefficients

Coefficients related to photoperiod sensitivity, duration of grain filling, conversion of mass to grain number, grain filling rates, vernalization requirements, stem size, and cold hardiness.

Growth and yield simulation

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:

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

Where,

PCARB = Potential growth rate, g/plant

RUE = Radiation use efficiency, (gm dry matter/MJ PAR)

PAR = Photosynthetically active radiation (MJ/m^2)

PLTPOP = Plant population, plants/m^2

K = Light extinction factor

LAI = Green leaf area index

CO_2 = Carbon dioxide concentration (ppm)

The stages of development are determined by the accumulation of thermal time (Growing degree days). Thermal time is computed with the following equation:

$$GD_{day} = T_{avg} - T_{GDdaybase}$$

$$CGD_{day} = CGD_{day-1} + GD_{day}$$

$$T_{avg} = \left\{ \begin{array}{ll} T_{GDdaybase} & \text{if } T_{avg} < T_{GDdaybase} \\ T_{cutoff} & \text{if } T_{avg} > T_{cutoff} \\ (T_{max} + T_{min})/2 & \text{Otherwise} \end{array} \right\}$$

Where,

GD day (°C-days) is today's thermal time.

CGD day (°C-days) is today's accumulated thermal time since planting.

TGD day base and T cutoff are crop input parameters that define the range of temperatures for viable development.

Tmin (°C) is the daily minimum air temperature.

Tmax (°C) is the daily maximum air temperature.

Model calibration and validation

Model calibration or parameterization is the adjustment of parameters so that simulated values compare well with observed values. Statistical methods are selected to compare the results from simulation and observation during model validation. Model validation is presented by the Root Mean Square Error (RMSE), Root Mean Square Error normalized (RMSEn) and D-index.

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

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

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

Where S_i and Ob_i are the model simulated and experimental measured points, respectively. $\overline{Ob}_{\ avg}$ is average of observed values from one treatment or multiple treatments and n is the observed data points from number of treatments.

Results and Discussion

Calibration and validation of CERES-wheat

Calibration

Model calibration is the adjustment of model parameter so that simulated output compare well with observed ones.

Genetic coefficients of the model CERES-Wheat were calibrated for the cultivar 'Sonalika' using experimental data on crop phenology, leaf area index (LAI), biomass and yield of the crop for the year 2010-11 at Kharagpur, eastern India. Sowing time and fertilizer dose of the wheat crop for the location is given in Table 1. A basal dose of 50% of total Nitrogen and 100% of total recommended phosphorous (50 kg/ha of P_2O_5) and potassium (60 kg/ha of K_2O) were applied at sowing.

The remaining N was applied in two equal splits at 25 and 45 days after sowing. Calibrated genotype coefficients for wheat cultivar Sonalika are given in Table 2.

The variation between the observed and simulated values for the anthesis and maturity days was 0 and 3 days, respectively 2010-11. Table 3 Simulated and observed crop parameters of wheat for the year 2010-2011 (calibration) (Fig. 2–4).

Calibration and validation of CERES-Wheat

Crop parameter	Simulated	Observed	Variation
Anthesis day(DAS)	65	65	0 days
Maturity day (DAS)	102	105	-3 days
Product weight (kg dm/ha)	3971	4075	-3 %
Product number (no/m^2)	13692	14090	-3%
Product harvest index	0.37	0.35	6%
Maximum leaf area index	3.8	3.2	19%
Canopy (tops) weight (kg dm/ha)	10694	11659	-8%
Vegetative weight (kg dm/ha)	6723	7584	-11%
Above-ground N (kg/ha)	120.0	124.4	-4%
Product N(kg/ha)	97.7	91.4	7%

Table.1 Simulated and observed crop parameters of wheat for the year 2011-2012 (validation)

Crop parameter	Simulated	Observed	Variation
Anthesis day (DAS)	67	65	3 days
Maturity day (DAS)	103	105	-2 days
Product weight (kg dm/ha)	3853	3627	6%
Product number (no/m^2)	13287	13794	-4%
Product harvest index	0.40	0.32	25%
Maximum leaf area index	3.4	2.8	21%
Canopy (tops) weight (kg dm/ha)	9625	11227	-14%
Vegetative weight (kg dm/ha)	5772	7600	-24%
Above-ground N (kg/ha)	103.6	110.3	-6%
Product N (kg/ha)	82.4	75.9	9%

Table.2 Effect of different sowing dates and nitrogen fertilizer application rate on wheat grain yield (kg/ha)

Sowing dates	N fertilizer (kg/ha)					Mean
	0	60	120	180	240	
15-Oct	2189	2567	2832	2987	3069	2729
30-Oct	2486	2883	3099	3236	3329	3006
15-Nov	2849	3373	3649	3787	3863	3504
30-Nov	3036	3588	3886	4042	4132	3737
15-Dec	2996	3575	3873	4028	4117	3718
30-Dec	2791	3391	3717	3893	3989	3556
15-Jan	2223	2803	3128	3284	3369	2962
Mean	2653	3168	3455	3608	3696	

Table.3 Effect of different sowing dates of nitrogen fertilizer application rate on wheat tops weight (kg/ha)

Sowing dates	N fertilizer levels (kg/ha)					Mean
	0	60	120	180	240	
15-Oct	6635	7902	8585	8963	9159	8249
30-Oct	7098	8875	9448	9759	9959	9028
15-Nov	7405	9743	10638	10940	11083	9962
30-Nov	7514	9862	10863	11251	11422	10182
15-Dec	7452	9489	10381	10723	10888	9787
30-Dec	6512	8319	9123	9486	9668	8622
15-Jan	5325	6761	7468	7779	7936	7054
Mean	6849	8707	9501	9843	10016	

Table.4 Effect of different sowing dates and nitrogen fertilizer application rate on wheat water use efficiency (kg/ha-cm) of wheat crop

Sowing dates	N fertilizer levels (kg/ha)					Mean
	0	60	120	180	240	
15-Oct	92	105	113	118	121	110
30-Oct	95	107	114	118	121	111
15-Nov	103	116	123	127	130	120
30-Nov	102	117	124	128	132	121
15-Dec	95	109	116	120	123	113
30-Dec	87	101	109	114	116	105
15-Jan	68	83	91	95	97	86
Mean	92	105	113	117	120	

CERES-Wheat model

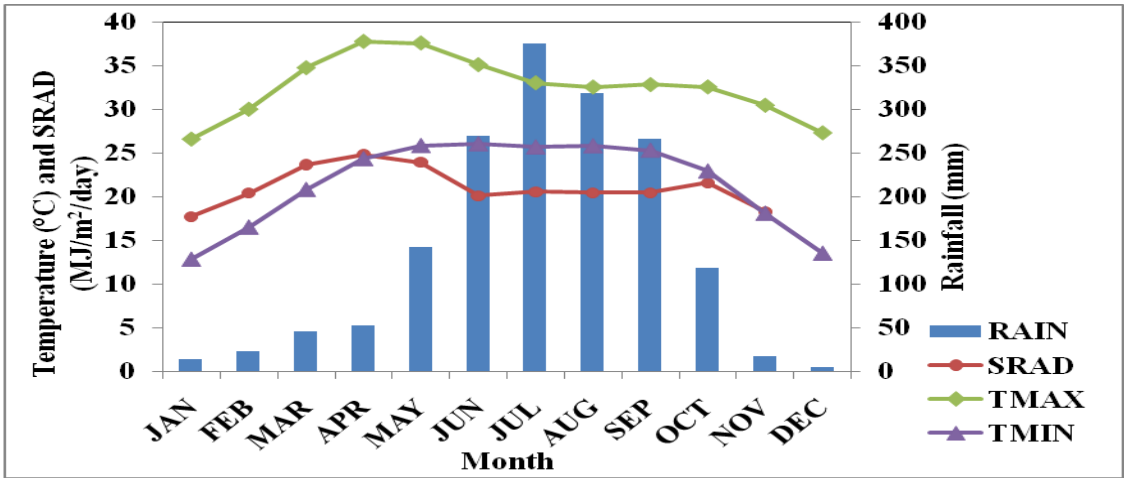


Fig.1 Observed (OBS) and simulated (SIM) time series leaf area index and leaf weight in days after sowing of wheat crop during calibration period (2010-2011)

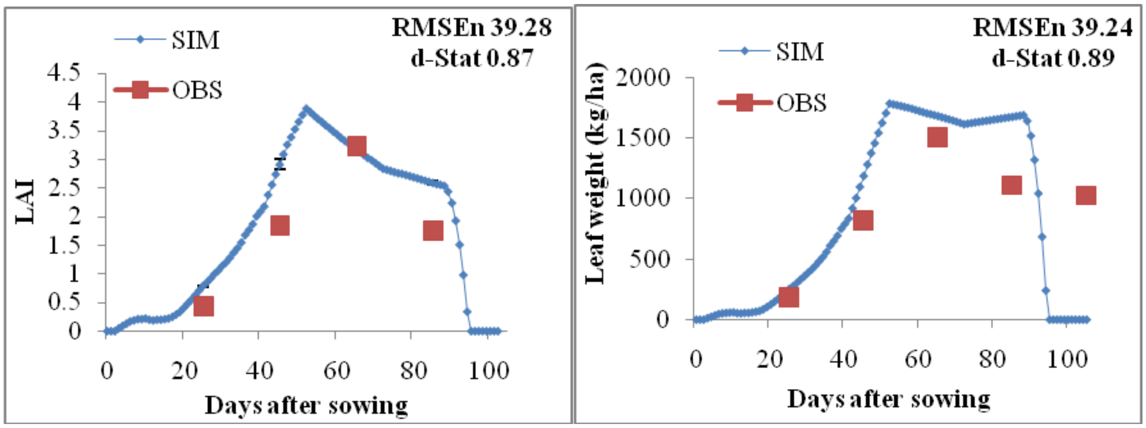


Fig.2 Observed (OBS) and simulated (SIM) time series stem weight and tops weight in days after sowing of wheat crop during calibration period (2010-2011)

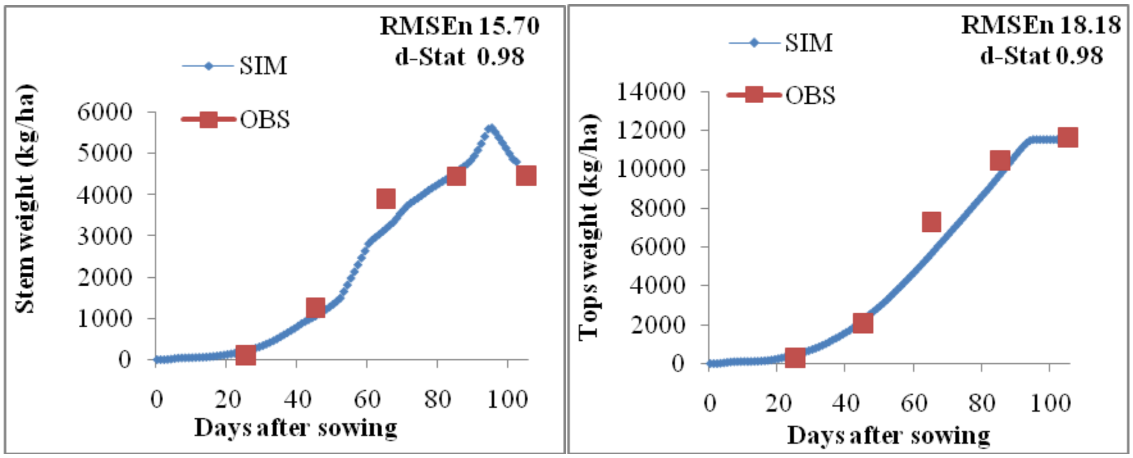


Fig.3 Observed (OBS) and simulated (SIM) time series leaf area index and leaf weight in days after sowing of wheat crop during validation period (2011-2012)

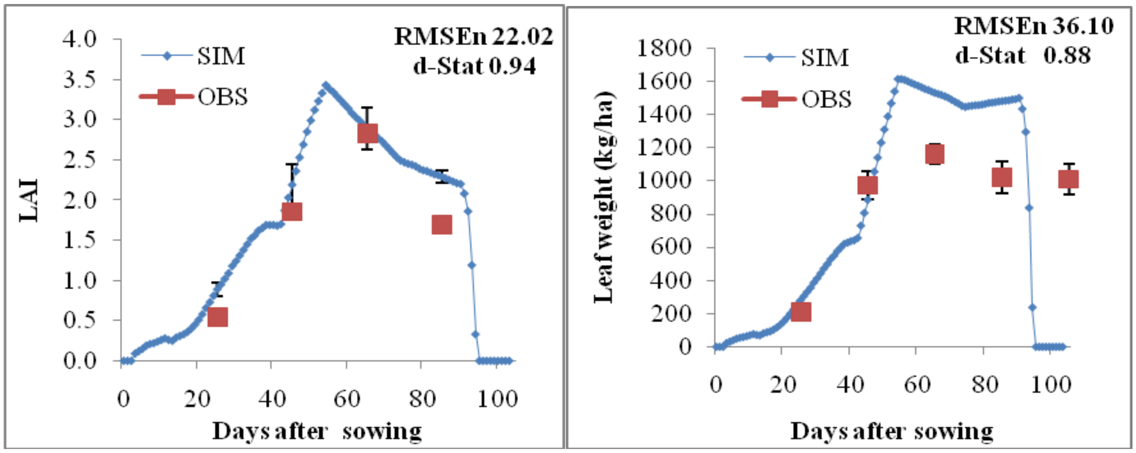


Fig.4 Observed (OBS) and simulated (SIM) series time stem weight and tops weight in days after sowing of wheat crop during validation period (2011-2012)

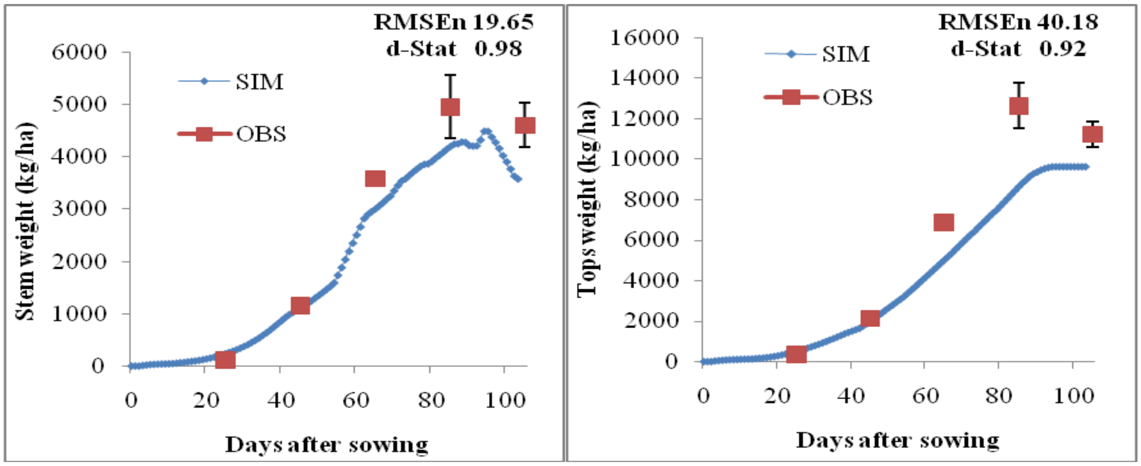


Fig.5a Simulated grain yields in past years (1975-2011) for wheat crop

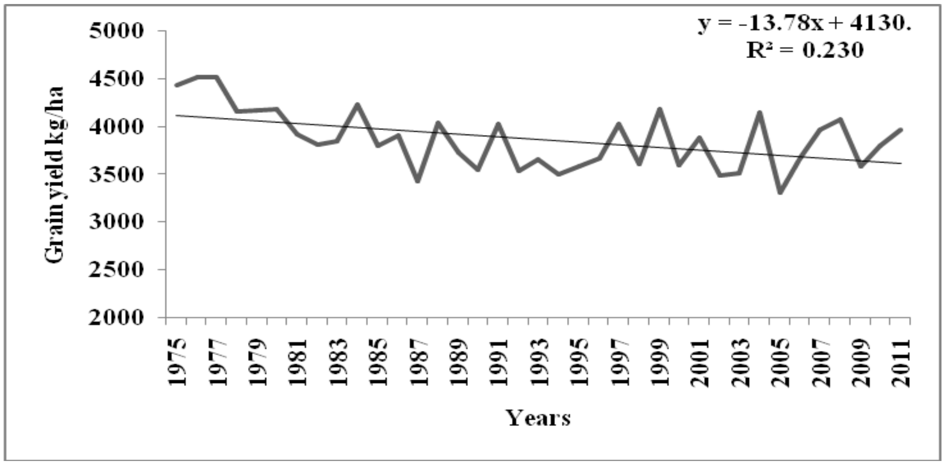


Fig.5b Average daily temperature of past years at Medinipur during 1975-2012

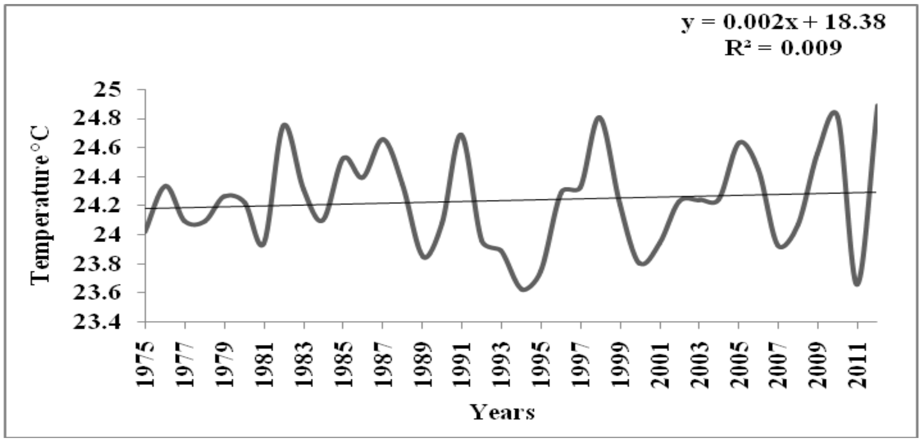


Fig.6 Change in wheat grain yield (%) under different sowing dates and N fertilizer application rate as compared to the reference sowing date (30 November) and N fertilizer rate (120 kg/ha)

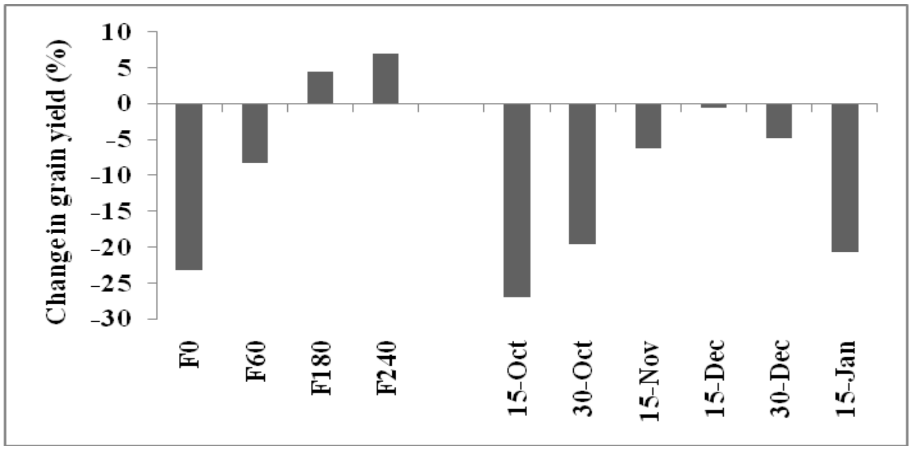
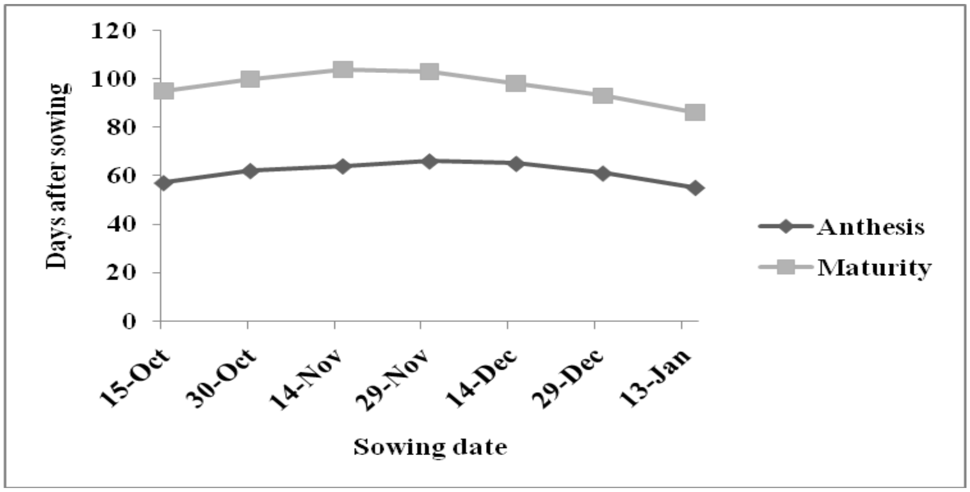


Fig.7 Effect of different sowing date on appearance of anthesis and maturity in days after sowing of wheat crop



Simulation of climate change impacts

The model was applied to simulate the grain yield of wheat crop, using the historical weather data (Figure 5). The simulated grain yield over past years is decreasing trend with progress of year. The influence of different sowing dates (15 October, 30 October, 15 November, 30 November, 15 December, 30 December and 15 January) and N fertilizer doses (0, 60, 120, 180 and 240 kg/ha) was simulated on yield of wheat crop (Table 4). The minimum grain yield of 2729 kg/ha was simulated on 15 October sowing and maximum grain yield of 3737 kg/ha on 30 November sowing. Among the different sowing dates, sowing on 30 November was taken as reference date since maximum yield was simulated on this date. Percentage change in the yield for the dates earlier to 30 November i.e. 15 November, 30 October and 15 November were -6, -20 and -27, respectively. Similarly the percentage change in simulated grain yield for the sowing later to 30 November i.e. 15 December, 30 December and 15 January were -1, -5 and -21, respectively, as shown in Figure 6. Increase N fertilizer level up to 120 and 180 kg/ha simulated on yield improvement 30 and 36% as compared to control (no N application rate). Further N application did not simulated any significant yield improvement. The tops weight and water use efficiency were found maximum sowing on 30 November. Appearance of anthesis and maturity were 66 and 103 days after sowing for 30 November sowing date. Sowing earlier or later to 30 November reduced the maturity duration 8 and 17 days.

The present atmospheric concentration of CO_2 is about 390 ppm by volume, which is expected in the range of 535 to 983 ppm by 2100, about 41 to 158 percent higher than current levels. The present study has been 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. The daily mean temperature of the study area ranges from a minimum of 12 °C in January to a maximum of 37 °C in April with average annual rainfall of 1400 mm. The CERES-Wheat model was used in evaluation of management options to assist decision making procedure in agricultural production system in general and climate change scenarios in particular. The CERES-Wheat model was calibrated and validated for the cultivar ‘Sonalika’ using experimental data on crop phenology, leaf area index (LAI), biomass and yield of the crop for the year 2010-11 and 2011-12, respectively. The CERES-wheat model was used for simulation of different adaptation management includes effect of change in planting date, variation in nitrogen application rate for minimizing the adverse impact of climate change on wheat yield. There was a good agreement between observed and simulated time series leaf area index, leaf weight, stem weight and tops weight of wheat crop with d-Stat value 0.87, 0.89, 0.98 and 0.98, respectively during calibration period (2010-2011).

Similarly for validation period (2011-2012), the d-stat value between the observed and simulated time series leaf area index, leaf weight, stem weight and tops weight of wheat crop were 0.94, 0.88, 0.98 and 0.92, respectively. The variation between the observed and simulated value for grain yield was 6% and for tops weight was 14% during the validation period. The following conclusions are summarized.

The wheat sowing period around 30 November was simulated to be the best for increased production under the current and future climate scenario at Kharagpur, eastern India.

A marginal increase in yield was simulated by shifting the sowing time from 30 Nov to 15 December under future climate scenarios.

The N fertilizer application rate in the range 120 to 180 kg/ha was recommended for the yield maximization.

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