Impact of climate change on wheat and winter maize over a sub-humid climatic environment

Abdul Vahab Abdul Haris*, Sandeep Biswas, Vandna Chhabra, Rajamanickam Elanchezhian and Bhagwati Prasad Bhatt

ICAR Research Complex for Eastern Region, ICAR Parisar, P.O. B.V. College, Patna 800 014, India

Accumulation of greenhouse gases (GHGs) in the atmosphere has exposed us to the potential warming and its adverse effects on agriculture. The present study deals with the impact of climate change on winter wheat and maize using the Infocrop model. Simulation studies were performed for different time-periods using HADCM3 factors at four centres located in three different agroecological zones, with prevalent management practices. The results showed that under changed climate, wheat yield decreased whereas the yield of winter maize increased due to warmer winters and enhanced CO_2 compared to baseline. Duration of both the crops has decreased owing to the higher temperatures during the growing period. The increase in yield of winter maize points to the suitability of the region for its cultivation in future. Further, increase in maize cultivation in locations with poor wheat yield could well be considered as an adaptation option.

Keywords: Climate change, maize, simulation studies, wheat.

ANTHROPOGENIC activities have caused accumulation of greenhouse gases (GHGs) in the atmosphere, leading to the potential hazards of climate change looming over us. The atmospheric concentration of carbon dioxide (CO_2) has increased from the pre-industrial levels of 280 to 379 ppm in 2005 (ref. 1). High CO_2 and other GHGs tend to warm up the atmosphere, besides affecting other meteorological variables. Agriculture sector, whether in developing or developed countries, depends on climate and climatic resources[2,3], leading to the development of special consideration for this sector to study the impacts of climate change. The Intergovernmental Panel on Climate Change (IPCC) and other researchers have stressed the need to study the impacts on agricultural production at local, regional, national and on global scales to capture the local conditions[4–7]. Projecting future crop yields has significant uncertainty due to changed fertilizer and water application strategies, occurrence of extreme climatic events, changes in pest and disease occurrence[8–11]. Decision support systems (DSS) or crop models provide a way, where the relative effects of these variables on crop growth and yield can be studied in particular combinations on regional basis. Early simulation studies on the impacts of climate change gave prime importance to the expected increase in CO_2 levels only, whereas recent studies have suggested that agricultural production is also affected by weather variables[12–14]. Most crops grown under enriched CO_2 environment showed increased growth and yield[15,16]. Enhanced CO_2 affects the growth and physiology of crops, enhancing photosynthesis and water-use efficiency[17–24]. Elevated CO_2 besides affecting the crop also affects the environment, which in turn may have either beneficial or damaging effect on agricultural production[25–28]. Changes in temperature play a crucial role in determining crop productivity[29]. Small changes in growing season temperature over the years appear to be the key aspect of weather affecting yearly wheat yield fluctuations[30]. Enhancement in wheat yield under enhanced CO_2 and no change in temperature have been reported[31]. Yield of cereals has been reported to decrease for different future scenarios[16,32–34]. Decline in potential yield of wheat and rice is linked to negative trend in solar radiation and an increase in minimum temperature in the Indo-Gangetic Plains of India[35]. FAO and IPCC have estimated a drop in cereal production for India by 125 mt and an overall increase of 2°C in temperature may lead to almost 8% loss in farm level net revenue and around 5% in GDP[36]. Differences in physiology of C3 and C4 plants make C4 plants more efficient photosynthetically than C3, especially when the level of CO_2 is high[37]. Response of C3 and C4 crops to elevated CO_2 levels when exposed frequently to water stress or changes in climatic factors such as temperature or rainfall may provide inconsistent results because of the feedback between hydrology and nutrient relations[38–43].

Bihar (middle Gangetic Plains of India, with dry sub-humid climatic conditions) is a low productivity region in eastern India with high potential for better agricultural production with suitable agronomic interventions. Wheat and maize are the main cereal crops of winter season in Bihar, covering a total area of about 2.28 million ha (m ha), out of which wheat is grown in approximately 2.07 m ha. Wheat stands the second position after rice with 32% of gross cropped area (GCA) in Bihar and maize crop covers 6% of GCA. In 2006, wheat and maize had a total production of 4.1 and 0.5 million tonnes respectively (source: State Agriculture Department, Bihar).

---

*For correspondence. (e-mail: abdulharis123@rediffmail.com)

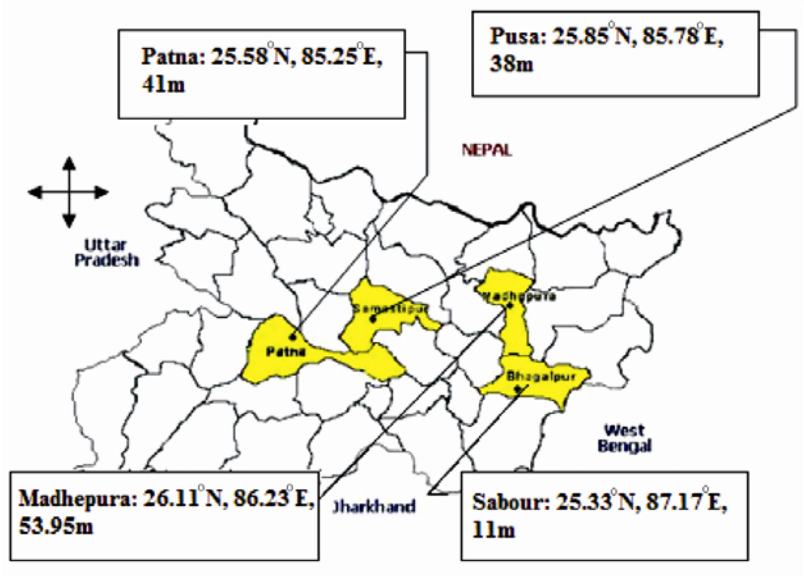

Figure 1. Geographical location of the study area.

Maize cultivation in Bihar is done throughout the year owing to its adaptability to a range of temperatures. The present study deals with the impact assessment of climate change on the winter season crops for Bihar. Timely assessment of the effects of climate change on agriculture might help adopt suitable farming techniques to maximize agricultural production in this low-productivity, high-potential region. The study provides insights into possible changes in the cropping pattern and adaptation options for future.

Material and methods

Study area

Bihar lies in the alluvial plains of India. The state is situated between 24°N and 27°N, 83°E and 88°E with a height of 52.73 m amsl, having a total geographical area of 9.36 m ha with cultivable land of 0.58 lakh ha and a normal rainfall of 1176.4 mm. It is divided into three agro-ecological zones: zone I (north west alluvial plains), zone II (north east alluvial plains) and zone III (south Bihar alluvial plains). Zone III is further subdivided into categories A and B. GCA is maximum (30.07 lakh ha) for zone I and minimum (6.21 lakh ha) for zone IIIB and irrigated area ranges from 3.68 to 18.41 lakh ha. Zone II receives highest annual rainfall (1387 mm) and is coldest among the three zones (average temperature: 21.3°C). Zone III receives least rainfall (1104 mm) and is the warmest (average temperature: 22.45°C). Average minimum temperature (7.7°C) is least for zone I[44]. For this study four stations were selected (Figure 1), representing different zones (Pusa, zone I; Madhepura, zone II; Sabour, zone IIIA and Patna, zone IIIB).

Experimental data

Daily data for air temperature and rainfall from four representative centres were collected for the period 1961–1990 (except for Sabour 1972–1990). Missing values of solar radiation, vapour pressure and wind speed were worked out by the methods laid down in a FAO paper[45]. Meteorological, crop and soil data used for the simulation studies were collected from Rajendra Agricultural University (RAU), Pusa; Bihar Agriculture College, Sabour; Krishi Vigyan Kendra, Madhepura; ICAR-Research Complex for Eastern Region, Patna and RAU Rice Research Station, Patna.

IPCC describes future scenarios for the period 2010–2039, 2040–2069 and 2070–2099 referred to as 2020s, 2050s and 2080s respectively. The General Circulation Model (GCM) used in this study is the output of UK Hadley Center for Climate Prediction and Research model, ver. 3 (HADCM3) for the A2 scenarios. (The A2 scenario describes a heterogeneous world with a focus on self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population.) The 30 year averaged monthly changes obtained from Data Distribution Centers (DDC) of IPCC were incorporated into individual years according to eqs (1) and (2) given below. The outputs of minimum and maximum temperature and rainfall were used to generate future scenarios and solar radiation was then calculated from the temperature values.

Expected changes in temperature = Baseline temperature + Expected change in temperature obtained from HADCM3 outputs. (1)

Expected changes in precipitation = Baseline daily rainfall × (1+ % change in rainfall). (2)

Table 1. Generic coefficients used for the simulation

Parameters and practices used for simulation	Maize var. Ganga11	Wheat var. HD2733	Wheat var. HUW468	Wheat var. RW346
Thermal time (°C days)				
Sowing to germination	85	70	84	70
Germination to 50% flowering	1050	850	1025	875
50% flowering to physiological maturity	480	450	487	380
Radiation use efficiency (g/MJ/day)	3.26	2.8	2.8	2.8
Specific leaf area (dm^2/mg)	0.0015	0.0022	0.002	0.00199
Potential storage organ weight (mg/grain)	165	37.8	37.7	37.7
Date of sowing	18 November 2000	19 November 2000	20 November 2000	20 November 2003
Seed rate (kg/ha)	20	100	100	100

Table 2. Validation results for wheat and maize crops

Crop	Coefficient of efficiency (%)	RMSE (kg/ha)	MAE (kg/ha)	R^2
Wheat (RW-346)	69	72.8	43	0.79
Wheat (HUW-468)	84	166.4	137	0.97
Wheat (HD-2733)	86	106.7	73	0.91
Winter maize (Ganga-11)	70	293.5	238	0.91

RMSE, Root mean square error; MAE, Mean absolute error.

Crop model used

The generic crop model InfoCrop ver. beta developed at IARI, Pusa[46] was used. Infocrop is a DSS, designed to simulate the effects of weather, soil, agronomic management (including planting, nitrogen, residues and irrigation) and major pests on crop growth and yield. The model is designed to use a minimum set of soil (soil type, pH, organic matter, bulk density, etc.), weather, genetic and management information (sowing date, sowing depth, transplanting date, irrigation, fertilizer, etc.). It integrates on a daily basis and therefore requires daily weather data (maximum temperature, minimum temperature, rainfall, solar radiation, vapour pressure and wind speed). The model calculates the crop development phases and morphological development as a function of temperature, day length and genetic characteristics.

Calibration, validation and simulation for selected locations

The model had been calibrated by comparing the simulated yield with the observed yield for three years. Calibration in the case of maize for var. Ganga11 for Pusa and for three different varieties of wheat, viz. HUW468, HD2733 and RW346 for three different locations, viz. Pusa, Patna and Sabour respectively, was done according to crop yield data availability. Crop specific thermal time is calculated according to eq. (3)[47]. Generic coefficients arrived after calibration are presented in Table 1. The results of validation are presented in Table 2. The coefficient of efficiency is calculated according to eq. (4) below[48].

$$\text{Thermal time} = \sum_{i=1}^{n}\left(\frac{T_{\max}+T_{\min}}{2} - \text{Base temperature}\right), \quad (3)$$

where $T_{\max}$ is the maximum temperature, $T_{\min}$ the minimum temperature and base temperature is the crop and stage-specific base temperature.

$$E = 1.0 - \left(\frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2}\right), \quad (4)$$

where O is the observed yield, P the yield predicted by the model and N the number of observations.

After calibration, the model was run for the baseline and scenarios based on the practices used for validation purposes. Figure 2 depicts the overall methodology in the form of a flow diagram.

Variables considered in the study include: (i) climate (temperature, rainfall, solar radiation and vapour pressure); (ii) soil variables; (iii) CO_2 fertilization effect; (iv) irrigation and (v) fertilizer. We did not study the following: (i) pests and diseases; (ii) water availability for irrigation; (iii) socio-economic factors and (iv) possible improvement of crop varieties in future.

Sensitivity analysis

The widely accepted approach to analyse possible effects of different climatic parameters on crop growth and yield is by specifying the incremental changes to climatic parameters and applying these changes uniformly to baseline/normal climate[49]. Sensitivity analysis was performed for all the three varieties of wheat and winter maize to know the role of projected changes of mean, maximum and minimum temperature in various combinations at current and projected levels of CO_2 on potential yield. The study was done by increasing the maximum, minimum and both maximum and minimum temperatures (mean) from 1°C to 4°C. Potential yields of wheat and winter maize were

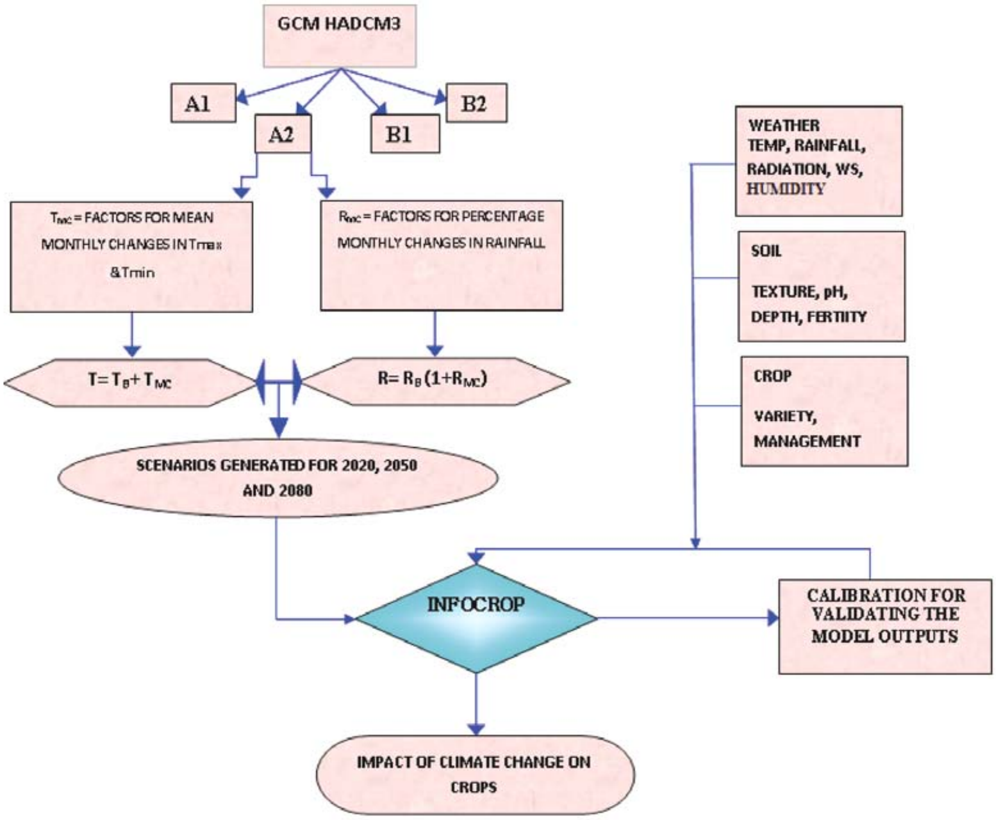

Figure 2. Flow diagram depicting the methodology used.

first simulated at 370 ppm of CO_2 (current level) for the baseline period (1961–1990). Further the maximum, minimum and daily mean temperatures were increased gradually from 1°C to 4°C, as incremental variable scenarios have the capacity of capturing a wide range of possible changes in the near future. In the next cycle CO_2 level was increased to 682 ppm along with changes in temperature as before.

Results and discussion

Variability of climatic parameters of selected stations during winter season

Analysis of weather data showed inter-annual variation in weather variables. Rainfall ranged between 7 and 221.6 mm, 5.8 and 124.1 mm, 33.2 and 276.5 mm and 11.8 and 216 mm for Pusa, Patna, Madhepura and Sabour respectively. Rainfall had a decreasing trend in zones I and II by 0.46 and 0.42 mm/yr respectively, and an increase by 0.97 and 0.38 mm/yr for zones IIIA and IIIB respectively.

The range of minimum and maximum temperature was highest for zone I and lowest for zone IIIB. The lowest minimum temperature was found in zone II (10.17°C). Minimum temperature increased significantly at rates of 0.03 and 0.04°C/year for zones I and IIIA respectively, whereas for zone II significant decrease in minimum temperature was observed at the rate of 0.09°C/year. No significant change in maximum temperature was observed in any of the four zones. The results point towards gradual warming up of winter nights with time. Changes in minimum temperature have a profound effect on crop productivity and increase in minimum temperature leads to increased respiration rate and its decrease increases the crop duration and yield[50].

Sensitivity analysis

Yield of wheat decreased from the current levels on increasing the mean, maximum and minimum temperatures at 370 ppm CO_2. On increasing CO_2 concentration from 370 to 682 ppm, the potential yield increased from baseline potential yield which decreased on increasing the temperature (Figure 3).

Sensitivity analysis for winter maize revealed that on increasing minimum temperature during the growing period, average potential yield also increased. An increase of 3°C in minimum temperature resulted in an enhancement of almost 2% from the baseline average potential yield. When CO_2 level was increased to 682 ppm, the yield also increased concurrently – least with increase of

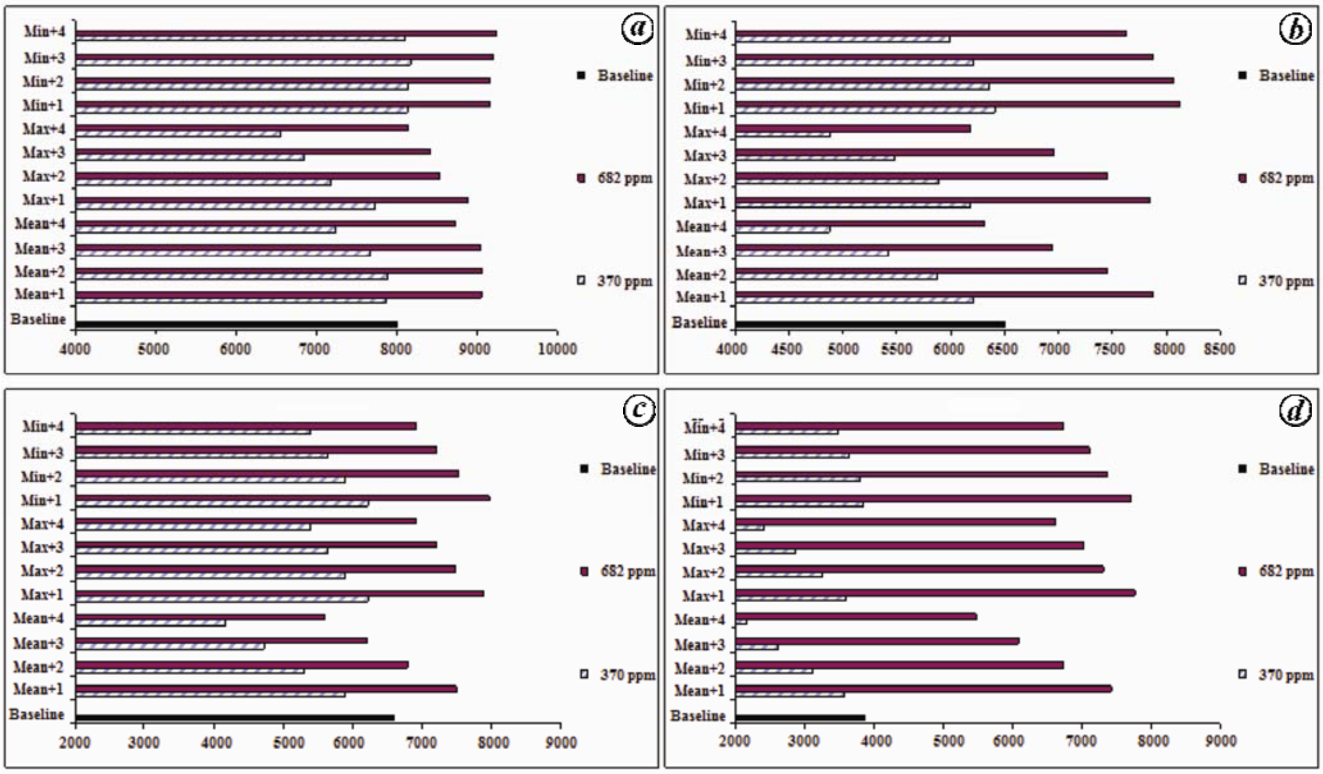

Figure 3. Sensitivity analysis of (***a***) winter maize, and wheat at (***b***) Pusa, (***c***) Patna and (***d***) Sabour by varying the temperature from 1°C to 4°C for 370 and 682 ppm CO_2 compared with the baseline.

4°C in mean temperature (2%) and most with an increase of 4°C in minimum temperature (15%). Sensitivity analysis for wheat at different locations and cultivars indicates a decline in yield with increasing temperature, irrespective of location, cultivar and soil type. Wheat is a major winter crop in this region and with the winters getting warmer the pressure of maintaining food security would be high with decreasing wheat production potential.

Impacts of climate change on wheat and winter maize

Impact of climate change on wheat and winter maize was simulated using factors for HADCM3 A2 scenario and concomitant CO_2 increase.

Scenario of increase in atmospheric CO_2 concentration: With the current cultivars, cultivation and management practices, the impacts of climate change on three varieties of wheat, namely HD 2733, HUW 468 and RW 346 and one variety of maize, i.e. Ganga-11 under A2 scenario were studied at the selected centres (Table 3). All the results are compared with the yields between A2 climate change scenario time slices, i.e. 2020, 2050 and 2080 and baseline (1961–1990).

Simulated yield of wheat (HUW 468) decreased from the baseline in 2050 and 2080 to 3.6% and 14.1% respectively, for Pusa. At Madhepura, decline in yield from the baseline was by 5% during 2020 and 13% and 21% for 2050 and 2080 respectively. Patna and Sabour showed decrease in simulated yield around 40% for 2080s (Table 3). With increased CO_2 (decrease in crop duration), total dry matter (TDM) and days to anthesis for all stations from the baseline to 2080 was observed. Crop duration showed maximum decline at Madhepura by 26 days. Number of grains increased marginally for Pusa and Patna during 2020; otherwise a decrease was noted for other time periods from the baseline (Table 4). Zones I and II showed lesser decline in the number of grains and more or less constant weight of grains than zone III. However, zone III showed decrease in both number and weight of grains during different time-periods, thus indicating suitability of North Bihar (zones I and II) for wheat cultivation.

Simulated yield of winter maize showed an increase from the baseline. This increase was in the range 8.4–18.2%, 14.1–25.4% and 23.6–76.7% for 2020, 2050 and 2080 respectively. Maximum increase was observed in Sabour for all the three time-periods (Table 3). Maize with increased CO_2 and consequent rise in temperature showed a decrease in duration and days to anthesis from the baseline. TDM, grain weight and grain number showed an increase from the baseline to 2080. The decrease in duration is probably well compensated by increased growth rate with better temperature regimes resulting in

Table 3. Impact of climate change on percentage change in yield of winter maize and wheat

	Winter maize			Wheat		
	2020	2050	2080	2020	2050	2080
Pusa						
Elevated CO_2	10.7	18.7	37.4	2.7	–3.6	–14.1
Constant CO_2	7.2	13.1	7.8	0.3	–9.6	–23.3
Madhepura						
Elevated CO_2	8.8	16.9	23.6	–5.0	–13.0	–21.0
Constant CO_2	8.1	11.1	5.3	–7.0	–20.0	–31.0
Patna						
Elevated CO_2	8.4	14.1	28.5	–3.9	–18.9	–39.5
Constant CO_2	8.4	14	13.2	–8.1	–26.7	–49.9
Sabour						
Elevated CO_2	18.2	25.4	76.7	–11.1	–22.3	–38.4
Constant CO_2	16	19.4	35.9	–12.1	–24.7	–42.9

Table 4. Simulated impact of climate change on growth parameters of wheat

	Duration (days)	Maximum CGR (kg/ha/day)	Maximum LAI (kg/ha/day)	TDM (kg/ha)	No. of grains/ha	Weight of grains (g/1000 grains)
Pusa						
Baseline	123	257	3.66	13,796	114,699,833	37.306
2020	117	249	3.54	13,197	116,578,283	37.471
2050	108	246	3.34	12,106	107,897,132	37.7
2080	100	273	3.05	11,238	96,575,358	37.7
Madhepura						
Baseline	111	284	3.58	13,510	136,776,467	35
2020	100	293	3.49	12,394	120,584,333	38
2050	91	290	3.39	11,178	107,761,030	38
2080	85	272	3.16	10,455	98,064,733	38
Patna						
Baseline	97	134	2.88	5,399	37,508,229	36
2020	92	130	2.93	5,186	42,182,533	38
2050	87	128	2.71	4,526	37,961,153	34
2080	79	122	2.26	3,893	29,137,213	30
Sabour						
Baseline	107	229	3.41	10,883	108,409,826	33
2020	100	209	3.30	9,742	92,359,979	34.6
2050	92	197	3.08	8,570	84,163,695	31.2
2080	86	188	2.83	7,642	71,424,974	29.8

CGR, Crop growth rate; LAI, leaf area index; TDM, Total dry matter.

increased number of grains and grain weight leading to overall increase in biomass (Table 5). Increase in grain number and TDM is an indicator of increased net photosynthesis, as the net rate of photosynthesis is more in full sunlight and also photo-respiratory losses are almost negligible in case of C4 plants compared to C3 plants[51].

Scenario without change in CO_2 concentration: Simulated growth parameters showed decreasing trend for wheat crop when observed with enhanced CO_2 (Table 3). Reduction in simulated yield of wheat without change in CO_2 was higher compared to simulation with elevated CO_2 for all stations and scenarios. For 2020, difference in reduction percentage between simulated yield with and without elevated CO_2 was less compared to 2050s and 2080s, considering that increase in CO_2 had a beneficial effect on the yield for the 2080 scenario.

For maize, the number of grains increased from the baseline to 2080 (Table 5). Increase in yield was observed with or without elevated CO_2 but it was more pronounced with CO_2 enhancement. Yield for 2020 and 2050 time-periods remained close, but the difference between the increase percentages for 2080 showed a marked difference, with and without CO_2 enhancement.

Maize planted in winter season in Bihar encounters low temperatures during December and January, thus experiencing a phase where plant growth remains retarded. Cultivation of maize requires temperatures in the range 10–30°C for its growth[52–54] and plentiful supply of water. Growth and yield of maize is limited by cold sensitivity as manifested by retardation of growth at low temperature as well as by leaf necrosis and plant death at temperatures below 10°C (ref. 55). Increase in yield of winter maize could thus be attributed to favourable

Table 5. Simulated impact of climate change on growth parameters of maize

	Duration (days)	Post-anthesis duration	Maximum CGR (kg/ha/day)	Maximum LAI (kg/ha/day)	TDM (kg/ha)	Grain weight (g/100 grains)	No. of grains (grains/ha)
Pusa							
Baseline	157	26	216	2.58	13,544	114.3	34,108,353
2020	152	26	223	2.62	13,582	115.6	36,404,873
2050	143	25	244	2.58	13,475	114.3	38,772,077
2080	135	26	284	2.52	14,262	122.8	39,685,550
Madhepura							
Baseline	159	28	238	2.77	15,555	120.1	39,556,007
2020	154	27	249	2.80	15,639	121.7	41,386,080
2050	145	27	291	2.81	15,608	121.2	43,266,460
2080	135	27	340	2.53	16,392	124.3	44,248,780
Patna							
Baseline	150	22	351	4.79	16,556	90.8	43,590,337
2020	146	22	347	4.75	16,785	94.7	45,289,700
2050	138	22	411	4.65	16,383	93.9	46,697,863
2080	128	23	524	4.54	17,365	100.2	49,212,777
Sabour							
Baseline	150	21	195	2.56	11,468	82.34	29,869,011
2020	145	21	201	2.66	11,720	84.63	31,259,789
2050	137	22	237	2.65	11,604	86.25	35,699,926
2080	130	23	246	2.56	12,597	101.5	37,796,805

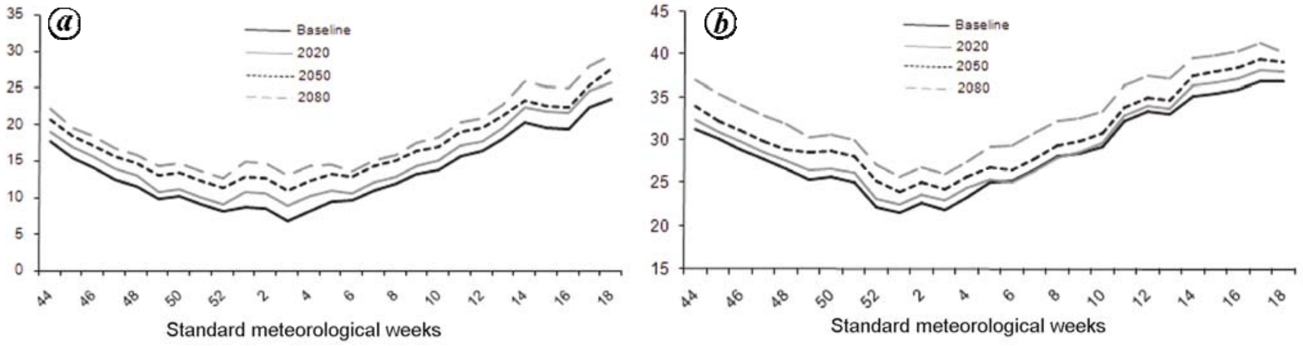

Figure 4. Weekly mean (***a***) minimum and (***b***) maximum temperature for the baseline, 2020, 2050 and 2080 during winter season.

temperature encountered during December–January (Figure 4), thus resulting in better crop performance during future time-periods.

Simulation studies performed without increasing CO_2 also showed increases in yield from the baseline for all the time-periods, indicating that increase is not just dependent on elevated CO_2 but also on higher winter temperatures. Increased CO_2 concentration is making the condition more congenial for crop development. Thus, the increase in yield of winter maize may be attributed to an increase in source, i.e. net photosynthesis.

Conclusion

Though the results showed spatial variations in the yield of maize and wheat, the increase in winter maize yield and decline in wheat yield were the general features observed for future scenarios. The modelling study reported here provides information about the impact of climate change over locations representing different agro-ecological zones of Bihar. The study indicates losses in the yield of wheat with subsequent rise in temperature. Enhanced CO_2 was also unable to counter balance the decline in wheat yield. However, the percentage decline was less in zones I and II compared to zone III (Table 4). Moreover, there can be a decline in wheat grain quality when grown in higher atmospheric concentration of CO_2 (ref. 56). The increase in yield of winter maize indicated favourable changes in climate for its growth and suitability of the region for its cultivation. The results point towards possible decline of rice–wheat cropping sequence, which is predominant in the region. Weather conditions under future scenarios being favourable for winter maize, may result in gradual replacement of wheat by winter maize crop in regions unfavourable to wheat cultivation in Bihar. Adaptation options, such as intensification of maize cultivation in locations of low wheat productivity and adopting new agronomic practices and delineating favourable areas for wheat production, need to be looked into for sustainability of food security in this region.

---

1. IPCC, Summary for policymakers. In *Climate Change 2007: The Physical Science Basis*, Contribution of Working Group (WG) I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds Solomon, S. *et al.*), Cambridge University Press, Cambridge, UK, 2007.
2. Downing, T. E., (ed.), *Climate Change and World Food Security*, NATO ASI Series, Series 1: Global Environmental Change, Springer, Berlin, 1996, p. 662.
3. Watson, R., Zinyorwera, M. and Moss, R. (eds), *Climate Change 1995 – Impacts, Adaptation and Mitigation of Climate Change*, Contribution of WG II to the Second Assessment Report of the IPCC, Cambridge University Press, Cambridge, UK, 1996.
4. Freckleton, R. P., Watkinson, A. R., Webb, D. J. and Thomas, T. H., Yield of sugarbeet in relation to weather and nutrients. *Agric. For. Meteorol.*, 1999, **93**, 39–51.
5. Gadgil, S., Rao, P. R. S. and Sridhar, S., Modeling impact of climatic variability on rainfed groundnut. *Curr. Sci.*, 1999, **76**, 557–569.
6. Kaufmann, R. K. and Snell, S. E., A biophysical model of corn yield: integrating climatic and social determinants. *Am. J. Agron. Econ.*, 1997, **79**, 178–190.
7. Tan, G. X. and Shibasaki, R., Global estimation of crop productivity and the impacts of global warming by GIS and EPIC integration. *Ecol. Model.*, 2006, **168**, 357–370.
8. Cannon, R. J. C., The implications of predicted climate change for insect pests in the UK, with emphasis on non-indigenous species. *Global Change Biol.*, 2003, **4**, 785–790.
9. Engvild, K. C., A review of the risks of sudden global cooling and its effects on agriculture. *Agric. For. Meteorol.*, 2003, **115**, 127–137.
10. Ewert, F. *et al.*, Effects of elevated CO_2 and drought on wheat: testing crop simulation models for different experimental and climatic conditions. *Agric. Ecosyst. Environ.*, 2002, **93**, 249–266.
11. Fuhrer, J., Agroecosystem responses to combinations of elevated CO_2, ozone, and global climate change. *Agric. Ecosyst. Environ.*, 2003, **97**, 1–20.
12. Curry, R. B., Peart, R. M., Jones, J. W., Boote, K. J. and Allen Jr, L. H., Response of crop yield to predicted changes in climate and atmospheric CO_2 using simulation. *Trans. ASAE*, 1990, **33**, 981–990.
13. Curtis, P. S. and Wang, X., A meta-analysis of elevated CO_2 effects on woody plant mass, form, and physiology. *Oecologia*, 1998, **113**, 299–313.
14. Hansen, J. *et al.*, Climate forcings in the Goddard Institute for Space Studies SI2000 simulations. *J. Geophys. Res. D*, 2002, **18**, 4347.
15. Allen Jr, L. H. *et al.* (eds), *Advances in Carbon Dioxide Research*, ASA Special Publication No. 61, Madison, WI, USA, 1997, p. 228.
16. Parry, M. L., Rosenzweig, C., Iglesias, A., Livermore, M. and Fischer, G., Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environ. Change*, 2004, **14**, 53–67.
17. De Costa, W. A. J. M., Weerahoon, W. M. W., Herath, H. M. L. K. and Abeywardena, M. I., Response of growth and yield of rice to elevated atmospheric carbon dioxide in the sub humid zone of Sri Lanka. *J. Agron. Crop Sci.*, 2003, **189**, 83–95.
18. Ewert, F., Modelling plant responses to elevated CO_2: how important is leaf area index. *Ann. Bot.*, 2004, **93**, 619–627.
19. Grant, R. F., Wall, G. W., Kimball, B. A. and Frumau, K. F. A., Crop water relations under different CO_2 and irrigation: testing of ecosystem with the free air CO_2 enrichment (FACE) experiment. *Agric. For. Meteorol.*, 1999, **95**, 27–51.
20. Norby, R. J., Kobayashi, K. and Kimball, B. A., Commentary: rising CO_2-future ecosystems. *New Phytol.*, 2001, **150**, 215–221.
21. Rosenberg, N. J., Kimball, B. A., Martin, P. and Cooper, C. F., From climate and CO_2 enrichment to evapotranspiration. In *Climate Change and US Water Resources* (ed. Waggonen, P. E.), John Wiley, New York, 1990, pp. 151–175.
22. Triggs, J. M. *et al.*, Free-air CO_2 enrichment effects on the energy balance and evapotranspiration of sorghum. *Agric. For. Meteorol.*, 2004, **124**, 63–79.
23. Tubiello, F. N. and Ewert, F., Simulating the effects of elevated CO_2 on crops: approaches and applications for climate change. *Eur. J. Agron.*, 2002, **18**, 57–74.
24. Widodo, W., Vu, J. C. V., Boote, K. J., Baker, J. T. and Allen Jr, L. H., Elevated growth CO_2 delays drought stress and accelerates recovery of rice leaf photosynthesis. *Environ. Exp. Bot.*, 2003, **49**, 259–272.
25. Lemon, E. R., *CO_2 and Plants: The Response of Plants to Rising Levels of Atmospheric Carbon Dioxide*, West View Press, Boulder, CO, USA, 1983.
26. Morison, J. I. L., Intercellular CO_2 concentration and stomatal response to CO_2. In *Stomatal Function* (eds Zeiger, E., Cowan, I. R. and Farquhar, G. D.), Stanford University Press, USA, 1987, pp. 229–251.
27. Peiris, D. R., Crawford, J. W., Grashoff, C., Jefferies, R. A., Porter, J. R. and Marshall, B., A simulation study of crop growth and development under climate change. *Agric. For. Meteorol.*, 1996, **79**, 271–287.
28. Rosenzweig, C. and Hillel, D., *Climate Change and Global Harvest*, Oxford University Press, Oxford, UK, 1998, pp. 135–154.
29. Fiscus, E. L., Reid, C. D., Miller, J. E. and Heagle, A. S., Elevated CO_2 reduces O_3 flux and O_3-induced yield losses in soybeans: possible implications for elevated CO_2 studies. *J. Exp. Bot.*, 1997, **48**, 307–313.
30. Mall, R. K. and Singh, K. K., Climate variability and wheat yield progress in Punjab using the CERES wheat and WTGROWS models. *Vayumandal*, 2000, **30**, 35–41.
31. Aggarwal, P. K. and Sinha, S. K., Effect of probable increase in carbon dioxide and temperature on productivity of wheat in India. *J. Agric. Meteorol.*, 1993, **48**, 811–814.
32. Peng, S. *et al.*, Rice yelds decline with higher night temperature from global warming. *Agric. Sci.*, 2004, **101**, 9971–9975.
33. Rao, G. D. and Sinha, S. K., Impact of climate change on simulated wheat production in India. In *Implication of Climate Change for International Agriculture: Crop Modeling Study* (eds Rosenzweig, C. and Iglesias, I.), USEPA 230-B-94-003, USEPA, Washington DC, USA, 1994.
34. Sinha, S. K. and Swaminathan, M. S., Deforestation, climate change and sustainable nutrients security. *Climate Change*, 1991, **16**, 33–45.
35. Pathak, H. *et al.*, Climatic potential and on farm yield trends of rice and wheat in the Indo-Gangetic Plains. *Field Crops Res.*, 2003, **80**, 223–234.
36. Gahukar, R. T., Food security: the challenges of climate change and bioenergy. *Curr. Sci.*, 2009, **96**, 26–28.
37. Ku, M. B. S. *et al.*, High-level expression of maize phosphoenolpyruvate carboxylase in transgenic rice plants. *Nature Biotechnol.*, 1999, **17**, 76–80.
38. Deepak, S. S. and Aggarwal, M., Influence of elevated CO_2 on the sensitivity of two soybean cultivars to sulphur dioxide. *Environ. Exp. Bot.*, 2001, **46**, 81–91.
39. Drake, B. G., Gonjales-Meler, M. A. and Long, S. P., More efficient plants: A consequence of rising atmospheric CO_2. *Annu. Rev. Plant Physiol., Plant Mol. Biol.*, 1997, **48**, 607–637.
40. Ham, J. M., Owensby, C. E., Coyne, P. I. and Bremer, D. J., Fluxes of CO_2 and water vapor from a prairie ecosystem exposed

to ambient and elevated atmospheric CO_2. *Agric. For. Meteorol.*, 1995, **77**, 73–93.

41. Idso, K. E. and Idso, S. B., Plant responses to atmospheric CO_2 enrichment in the face of environmental constraints: a review of the past ten years' research. *Agric. For. Meteorol.*, 1994, **69**, 153–203.
42. Samarakoon, A. and Gifford, R. M., Elevated CO_2 effects on water use and growth of maize in wet and drying soil. *Aust. J. Plant Physiol.*, 1996, **23**, 53–62.
43. Rosenberg, N. J., Adaptation of agriculture to climate change. *Climate Change*, 1992, **21**, 385–405.
44. Anon., *Bihar at a Glance*, Ministry of Agriculture, Government of India, 2005.
45. Allen, R. G., Pereira, L. S., Raes, D. and Smith, M., Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, 1998.
46. Aggarwal, P. K., Kalra, N., Chander, S. and Pathak, H., Infocrop: a generic simulation model for annual crops in tropical environments. Indian Agricultural Research Institute, New Delhi, 2004.
47. Mavi, H. S., *Introduction to Agrometeorology*, Oxford & IBH Publishing Co, 1986, pp. 64–65.
48. Hubbard, K. G., Mahmood, R. and Carlson, C., Estimating daily dew point temperature for the Northern Great Plains using maximum and minimum temperature. *Agron. J.*, 2003, **95**, 323–328.
49. Hundal, S. S. and Kaur, P., Climatic variability and its impact on cereal productivity in Indian Punjab. *Curr. Sci.*, 2007, **92**, 506–512.
50. Matthews, R. B. *et al.* (eds), *Modeling the Impact of Climate Change on Rice Production in Asia*, CAB International and International Rice Research Institute, 1995, pp. 3–9.
51. Black, C. C., Ecological implications of dividing plants into groups with distinct photosynthetic production capacity. *Adv. Ecol. Res.*, 1971, **7**, 87–114.
52. Hellmers, H. and Warrington, I., Temperature and plant productivity. In *CRC Handbook of Agricultural Productivity* (ed. Rechcigl, M.), CRC Press, Boca Raton, FL, USA, 1982, vol. 1, pp. 11–21.
53. Miedema, P., Post, J. and Groot, P. J., The effects of low temperature on seedling growth of maize genotypes. *Versl. Landbouwkd. Onderz*. (Agricultural Research Reports), 1987, 1–124.
54. Muldoon, D. K., Wheeler, J. L. and Pearson, C. J., Growth, mineral composition and digestibility of maize, sorghum and barnyard millets at different temperatures. *Aust. J. Agric. Res.*, 1984, **35**, 367–378.
55. Janowiak, F. and Markowski, A., Changes in leaf water relations and injuries in maize seedlings induced by different chilling conditions. *J. Agron. Crop Sci.*, 1994, **172**, 19–28.
56. Erda, L., Wei, X., Hui, J., Yinlong, X., Yue, L., Liping, B. and Liyong, X., Climate change impacts on crop yield and quality with CO_2 fertilization in China. *Philos. Trans. R. Soc. London, Ser. B*, 2005, **360**, 2149–2154.

ACKNOWLEDGEMENTS. This study is funded by ICAR through a network project on climate change. We thank ICAR for funding this work at ICAR-Research Complex for Eastern Region, Patna. We also thank the Vice Chancellor and Director of Research at the Rajendra Agriculture University (RAU) for providing valuable and relevant crop, soil and meteorological data from RAU and its sister concerns.

Received 16 September 2011; revised accepted 4 December 2012