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Elevated temperature and carbon dioxide concentration effects on wheat productivity in Madhya Pradesh: a simulation study

M. MOHANTY[1], NISHANT K. SINHA[1], K.M. HATI[1], K. SAMMI REDDY[2] and R.S. CHAUDHARY[1]

[1] *Division of Soil Physics, ICAR-Indian Institute of Soil Science, Bhopal (MP)-462038*

[2] *Division of Resource Management, ICAR-CRIDA, Hyderabad (AP)- 500 059*

Corresponding author: mmohanty_bpl@yahoo.co.in

ABSTRACT

The Agricultural Production System Simulator (APSIM) Wheat model was used to test the sensitivity of wheat cropping system for the Bhopal region in Madhya Pradesh to changes in temperature (0 to 5°C from the base mean temperature) and atmospheric carbon dioxide concentration (0 to 550 ppm from the base of 350 ppm). The wheat cultivar Sujata was used for this simulation study. It was found that there was a negative relationship between grain yield and temperature while there were positive correlations of grain yield with atmospheric CO_2 concentration for the region under study. However, the rate of decrease in grain yield was more for higher temperatures rise in contrast to lower temperatures, and the rate of increase in grain and biomass yield was more for higher CO_2 concentration compared with the lower levels. On an average, there was 8% decrease in wheat grain and biomass yield per 1 °C increase in temperature. On the contrary, wheat grain yield increased by 33% and biomass yield by 35% with the elevation in CO_2 concentration from 350 to 850 ppm. Increasing the temperature by1 °C and CO_2 concentration to 500 ppm, the yield decline in wheat was lower than individual effect of increased temperature. This study showed that environmental factors have significant effects on wheat grain and biomass yield with changes in atmospheric CO_2 and temperature. These findings provided a sound basis for preliminary coping and prioritizing adaptation options for the future climate change scenarios.

Keywords: Climate change; CO_2; temperature; APSIM; wheat

Wheat is considered as the major crop of Madhya Pradesh and occupies 15% of country's total wheat production area but produces only 10% of the total yield. Climate change presents a significant challenge to agriculture productivity over the globe (van Gool and Vernon, 2005) and hence on wheat production. Research on the effects of temperature rises on the crop growth and yields has achieved some major advances against a background of global climatic change. A number of studies on climate change impact on wheat production around the world have reported varying results. Lobell *et al.,* (2012) stated that with temperature increase, the yield of C_3 crops like wheat would decrease but with elevated CO_2 level photosynthesis would increase and that may compensate the negative effect of temperature. Yield gain moderated with increased CO_2 concentration at an elevated temperature, and in some cases decreased under a reduced rainfall scenario (Luo *et al.,* 2003) in case of rainfed wheat. In India, Attri and Rathore (2003) observed that an increase of 1.0 ^{0}C temperature and a doubling of the atmospheric CO_2 concentration could increase wheat yields by 29 – 37%. However, they found that further increases in temperature (beyond 3 ^{0}C) would negate the beneficial impacts of enhanced CO_2, and wheat yield would decrease by 20%. Otheres have also reported similar results on wheat in India. (Pathak *et al.* 2003; Lal *et al.,* 1998). An ongoing argument exists among plant scientists where one school of thought predicts that the concomitant elevation of atmospheric CO_2 and air temperature will improve crop production and increase food supply for the increasing human population worldwide (Wittwer 1995). But the other school of thought is concerned about the negative impacts of high temperature, which offsets the positive effects of elevated CO_2 on crops in the future and, in turn, may lead to food shortage (Rosenzweig and Hillel, 1998).

Keeping in view the ecological and economic importance of central India in terms of wheat production, the present study was conducted to determine the impact of change in mean temperature and elevated CO_2 concentration on wheat growth and yield under sub-humid dry climatic conditions of Bhopal, Madhya Pradesh, so as to make possible applications of the results to similar regions in central India.

Table 1 : An overview of different emission Scenario as per IPCC IV[th] and V[th] assessment report.

Emission scenarios	Description	CO_2 equivalent by 2100 (ppm)	Projected changes in global mean surface air temperature 2046-2065	2081-2100	SRES equivalent
RCP 8.5	Rising radiative forcing pathway leading to 8.5 W m^{-2} in 2100	1370	2.0(1.4-2.6)	3.7 (2.6-4.8)	A1F1
RCP 6.0	Stabilization without overshoot pathway to 6.0 W m^{-2} at 2100	850	1.3 (0.8-1.8)	2.2 (1.4-3.1)	B2
RCP 4.5	Stabilization without overshoot pathway to 4.5 W m^{-2}	650	1.4 (0.9-2.0)	1.8 (1.1-2.6)	B1
RCP 2.6	Peak in radiative forcing at ~3 W m^{-2} before 2100, afterwards decline	490	1.0 (0.4-1.6)	1.0 (0.3-1.7)	None

RCP: Representative Concentration Pathways, specific emission trajectory suggested by IPCC fifth assessment report.

SRES: Specific Report on Emission Scenarios, as suggested by IPCC fourth assessment report

MATERIALS AND METHODS

A crop growth simulation model 'APSIM' in conjunction with actual and modified long-term historical climate data was used to assess the potential impact of climate change on wheat yield in Bhopal.

In this study the APSIM -Wheat modules was used to simulate the growth and development of wheat crop on a daily time-step. The APSIM model was parameterized and validated for wheat (cv. Sujata) crop for central Indian conditions and the detailed description of the wheat module along with parameterization and validation has been provided by Mohanty *et al*., (2012). The details of other parameters and constants for intilisation of the model can be found at www.apsim.info.

Climate scenarios examined

In this study, a series of simulations were carried out for a period of 30 years (1980-2010) to investigate changes in the simulated yield potential of wheat caused by changes in the temperature and CO_2 concentration for the Bhopal region. The range of temperature and CO_2 concentrations were based on the IPCC assessment report 5 (AR 5, 2013) which is presented in the Table 1. The wheat modules in APSIM are able to respond to temperature and increased CO_2 levels by modifying the transpiration efficiency coefficient and the N concentration optimum for photosynthesis (Ludwig and Asseng, 2006). Based on the climate change projections, we have examined the following scenarios through APSIM simulations:

- Baseline - This scenario looked at simulations derived from the unmodified current climate data of 30 years (1980-2010).
- Increased temperature - This scenario examined the impact of increasing the mean temperature, (1,2,3,4,4.5 and 5°C) keeping all other parameters constant.
- Carbon dioxide fertilization - This scenario examined the impact of increasing the CO_2 level to 850 ppm, from 350 ppm keeping all other parameters constant.
- Carbon dioxide and temperature changes (interactive effect).

It was assumed that these changes in climatic variability could explain the declining or improvement in yield or yield stagnation of wheat crop in Madhya Pradesh.

The wheat cultivar matures in 120 to140 days. A plant population of 120 plants m^{-2} with a row-spacing of 22.5 cm for wheat was maintained. Fertilizer to supply 50 kg ha^{-1} N to wheat was applied at the time of sowing, with another 50 kg ha^{-1} N applied at crown root initiation stage (CRI) (25 days after sowing). Wheat crop was grown under irrigated condition. One pre-sowing irrigation of 8 cm was applied to the wheat crop 48 hrs before sowing by flooding, the remaining five irrigations of 6 cm each were applied by

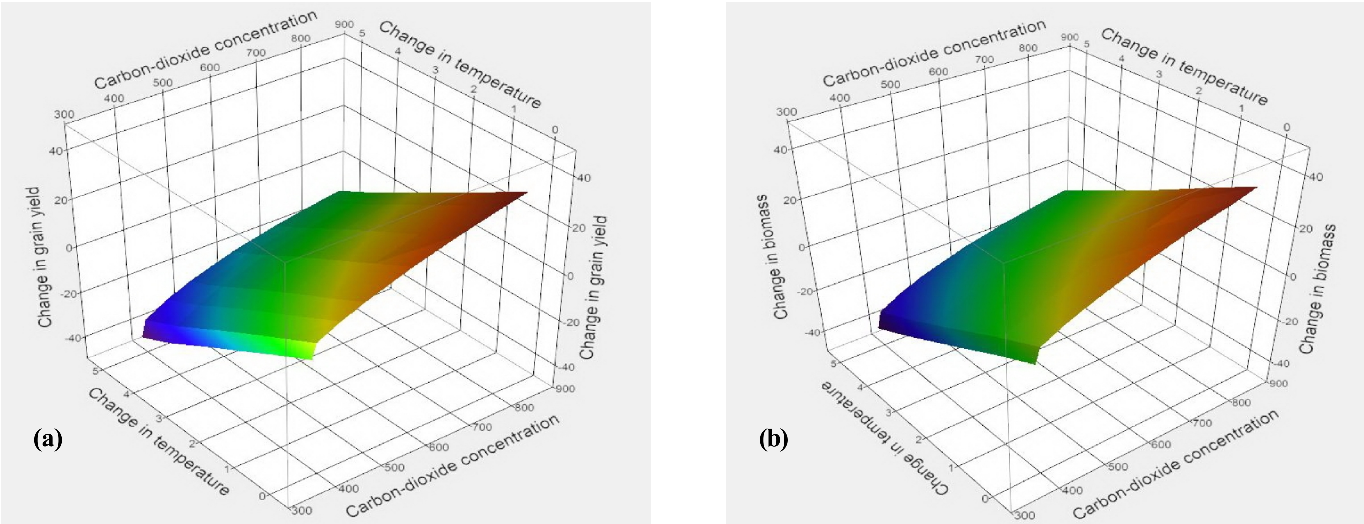

Fig. 1 : Combined effects of change in temperature and CO_2 concentration on percent change in (a) wheat grain and (b) biomass yield.

flooding at 20 days interval from CRI stage. A total of six irrigations were applied to wheat including the pre-sowing irrigation.

RESULTS AND DISCUSSION

Effect of temperature on wheat yield

The effect of increase in temperature, CO_2 on wheat grain yield and biomass yield is presented in Fig. 1a and 1b. Increasing the temperature by 1 to 5 °C over the base value decreased both the grain and total biomass yield of wheat. Increasing the temperature by 1 °C from the baseline, there was decrease in grain yield and total biomass by 8.4% and 7.8%, respectively. Further increasing the temperature by 3 and 5 °C from the baseline scenario, the grain yield was estimated to be reduced by 26% and 42%, respectively. Similarly the estimated biomass yield was reduced by 25% and 41% under same magnitude change in temperature from the baseline. Temperatures greater than 34 °C have been found to decrease wheat yields by up to 50% due to increased leaf senescence (Asseng *et al*., 2011). An increase in winter temperature of 0.5 °C would thereby translate into a 10% reduction in wheat production in the high yield states of northern India (Sinha and Swaminathan, 1991). Similar trend in wheat yield with increase in temperature using DSSAT was also reported by Patil *et al*., (2009).

Effect of carbon dioxide on wheat yield

With doubling the CO_2 concentration from 350 to 700 ppm, the grain yield of wheat was increased by 26%, whereas the biomass yield was increased by 27%. From the Fig. 1, it was also revealed that increasing the CO_2 concentration from 350 to 850 ppm, the grain yield of wheat was increased by 33%. Similar observation was recorded for biomass too. A doubling of CO_2 concentration generally increases photosynthesis and can lead to a substantial increase in wheat growth and yield (Annette, 2003). Based on these research reports, on an average a 25–30% increase in wheat grain yield by doubling the CO_2 concentration from current average atmospheric CO_2 concentration (from 350 to 700 ppm) has been forecast. So the beneficial effects of elevated CO_2 on wheat yield may be due to changes in photosynthesis or in water-use efficiency. Using CERES-wheat, Lal *et al*., (1998), found that under elevated CO_2 levels, yields of wheat increased significantly (28% for a doubling of CO_2).

Interactive effects of temperature and carbon dioxide

From the Fig. 1 it was observed that wheat grain yield under +1 °C and 400 ppm CO_2 concentration was at par with the yield obtained from the baseline climate. The combination of a 450 ppm CO_2 and a 1 °C temperature increase stimulated wheat grain yield by 2.6%, and biomass yield by 3.5% compared to baseline scenario. However, the combination of a 450 ppm CO_2 and a 2 °C temperature increase reduced wheat yield and biomass by 5.4% and 4.6%, respectively over base (Fig 1). Similarly, yield obtained from +3 °C and 700 ppm CO_2 was at par with yield from the baseline scenario (Fig. 1a and 1b). In similar situations, the grain yield obtained from the base was at par with the yield obtained from 2 °C + 500 ppm CO_2 concentration. Similar wheat yield was also obtained from 4 ^{o}C + 800 ppm CO_2 and baseline climate. However, the results may work when similar situation arises under future climate. Further increase

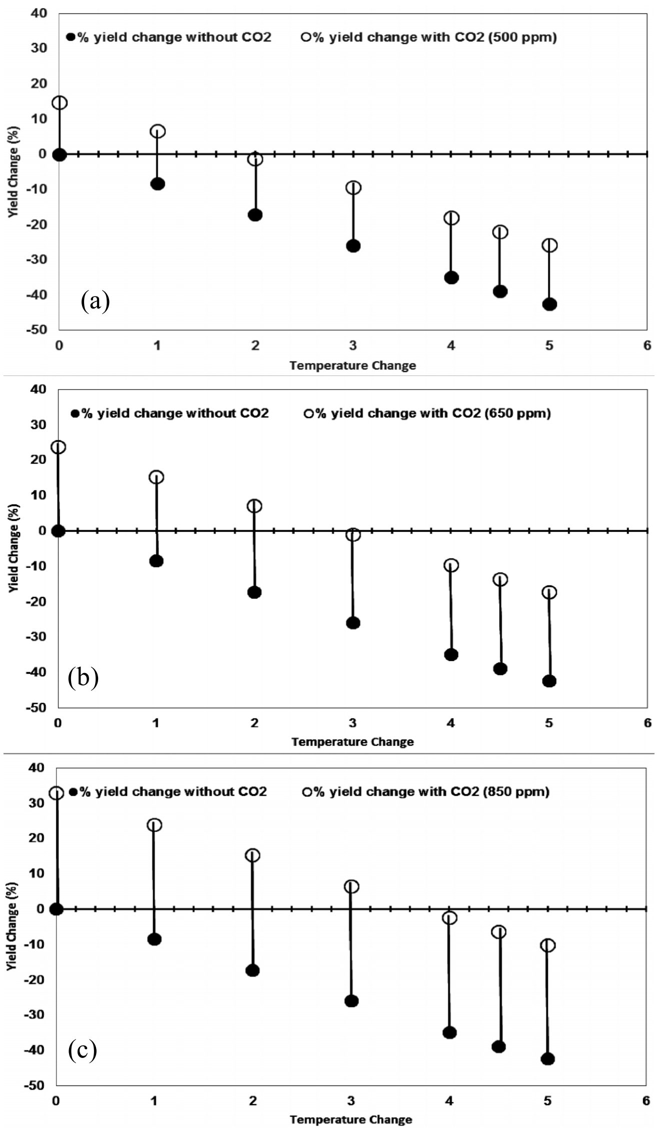

Fig. 2 : APSIM model estimates of wheat yield changes for different levels of temperature

in CO_2 concentration to 850 ppm and temperature to 4.5 °C, the wheat grain was severely affected (Fig. 1a and b). It was observed that increasing the temperature beyond 4 °C resulted in decline in wheat yield even though CO_2 concentration was increased to 800 ppm or 850 ppm. This trend continued to follow with increasing the temperature to 5 °C from the base value. The result shows that an increase in temperature and elevated CO_2 concentration has an interactive effect on wheat yield in a subhumid part of central India.

If we consider RCP 2.5 (IPCC, AR-5, 2013) scenario, wherein near future the CO_2 concentration will go up to 490 ppm and temperature will increase by 1 ˚C (Table1), the yield increase from the interactive effect of 490 ppm CO_2 and 1 ˚C increase in temperature is 6.5% over the base (350 ppm and current climate) whereas with increase in 1 ˚C temperature from base and no increment in CO_2, the yield would have been decreased by 8.4%. Thus, increase CO_2 to some extent negated the negative effect of temperature (Anwar et al., 2007).

Further, the combined simulation of increased temperature and CO_2 on grain yield revealed that at lowered temperature and higher CO_2 it remained at maximum (Fig. 2a, b and c). Similar results were reported by Leakey *et al*., (2009) who reported that in future increased crop yield might be due to fertilization effect of raising CO_2. A positive interaction between elevated CO_2 and high temperature on photosynthesis of C_3 plants has been reported by some investigators (Borjigidai *et al*., 2006), but not by others (Prasad *et al*., 2005). Even though elevated CO_2 can mitigate the detrimental effects of the above-optimal temperatures on crop growth and yield, certainly temperatures near the upper limit for crops will negatively affect yields, regardless of CO_2 concentration (Polley 2002). Several authors have reported interactive effects of temperature and CO_2 on wheat biomass (Mitchell *et al*., 1995;) but the direction of the effects was not always the same or it varied from year to year.

CONCLUSION

The study concludes that a 1 °C temperature increase without elevated CO_2 concentration, reduced wheat grain yield by 8.4%, and biomass yield by 7.8%, respectively while 4.5 °C temperature increase without elevated CO_2 concentration, reduced wheat grain yield by 39% and biomass yield by 37%, respectively. In contrast, elevated CO_2 (from 350 to 500 ppm), without temperature increase, stimulated wheat grain yield by 14.6% and biomass yield by 15%. Furthermore, the combination of a 500 ppm CO_2 concentration and a 1 °C temperature increase stimulated wheat grain yield by 5%. The combination of a 500 ppm CO_2 concentration and a 4.5 °C temperature increase reduced wheat grain yield by 22%. This combined effect on wheat yield may be regarded as the predicted climatic effect over the end of the century (RCP 2.6, IPCC AR 5). This implies that the yield of wheat will increase by 6.5% if RCP 2.6 is followed in the subhumid central India as the result of global climatic changes. The impact of the weeds, diseases and insect pests on crop growth, development and final yield formation are assumed to be controlled, which need to be incorporated in the future studies for better assessment of final yield.

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