EFFECTS OF ELEVATED CO_2 AND TEMPERATURE ON PRODUCTIVITY OF THREE MAIN CROPPING SYSTEMS IN PUNJAB STATE OF INDIA—A SIMULATION ANALYSIS

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Commission VIII, WG VIII/6

KEYWORDS: CO2, Maximum and Minimum temperatures, Crop Productivity, Sensitivity, Rice-Wheat, Maize-Wheat, Cotton-Wheat.

ABSTRACT:

Global climate change can affect yields of agricultural crops are likely to be affected due to rise in CO_2 and temperature, apart from other factors. In this context, the present study aimed at to assess the effects of elevated ambient CO_2 concentration, maximum and minimum temperatures alone and in combinations on crop productivity of three major cropping systems (maize-wheat, rice-wheat and cotton-wheat) of Punjab state of India. Series of climates were synthesized by increasing CO_2 levels from 350 to 700ppm at interval of 70ppm and temperatures (maximum and minimum) from existing to 20% rise at 5% interval of the recorded data at Punjab Agricultural University, Ludhiana. Simulations were made for 15 years (1991-2005) using CropSyst model. The simulated results indicated that on doubling the CO_2 level of the existing (350ppm) at existing temperature, yields of grain in maize, paddy in rice and seed-cotton in cotton were increased by 6.5, 4.9 and 5.5%, respectively. In wheat, the magnitude of benefit varied from 3.8 to 12 percent depending upon the previous crop in rotation. In a complete rotation of cropping system, percent increase in wheat equivalent yield was 7.6 in maize-wheat, 7.5 in rice-wheat, and 4.7 in cotton-wheat system, respectively. Unlike effect of CO_2, crop yields were decreased with increase in temperature. The percent decrease in yields of maize, rice and cotton were 42, 23 and 56 with increased maximum temperature (20% of the existing) and 24, 13 and 28 with increased minimum temperature, respectively. In the cropping systems of maize-wheat, rice-wheat and cotton-wheat, percent decrease in wheat equivalent yield was 2, 23, and 39 with maximum and 12, 11 and 17 with minimum temperature, respectively. Sensitivity factors estimated by fitting a multiplicative model to the simulated data indicated that the crop yield is more sensitive to increase in maximum temperature than minimum and CO_2. The interaction of temperature and CO_2 suggest that decrease in yield due to increased maximum temperature by 1.0, 1.8 and 0.3 ºC or minimum by 1.8, 2.0 and 0.7ºC of the existing temperatures can be levelled off by increased yield at double concentration of the CO_2 than the existing in maize, rice and cotton crops.

1. INTRODUCTION

The Inter-government Panel for Climate Change (IPCC) has compiled the magnitude of change in CO2 and temperature under climate change scenario for different parts of the world. According to this, CO2 level may increase to 397-416 ppm by 2010 and 605-755 by 2070. These gases can cause a giant green house effect and thereby make the earth warmer. The reports state that average surface temperature across the globe has shot up 0.74 ºC in the past century. The mean global surface temperature exhibited an increase over the past decade with particularly sharp increase since the 1970's (Gadgil, 1996). In the past 150 years, the hottest years witnessed were since 1995. The all India mean annual temperature derived from 73 stations showed a significant warming of 0.4ºC over the last 100 years, which is comparable to global mean trend of 0.3ºC increase per hundred years (Hingane et al, 1985). Hundal and Prabhjot Kaur (2001) have reported gradual increasing minimum temperature of about 0.4 -1.6ºC over the past 30 years at Ludhiana (India). Increase in CO2 and temperature affect the crop productivity directly (physiological processes of the plants–photosynthesis, respiration, evapotranspiration and phenology) and indirectly (weather induced incidences of diseases and thermal and water stresses). As per the HadCM3 projections, there can be rise of maximum temperature upto 5.860 C and minimum temperature upto 6.080 C under A2 scenario, in Punjab, during 2071-2100 period compared to baseline of 1961-1990. The global atmospheric concentration of carbon dioxide, which is 379 ppm in 2005, is increasing at an average (1995–2005) rate of 1.9 ppm per year. In view of this futuristic change in climate, it is imperative to assess their quantitative impact on crop productivity in a given region. It is reported that productivity of food grain could drop by 30% in the next 30 years (Chingappa, 2007). The crop growth and yield generally have positive relation with atmospheric CO2 and antagonistic with temperature. The crop productivity is increased with increased carbon dioxide (Kimball, 1983; Cure and Acock, 1986; Allen et al, 1997; Kimbal et al, 2002) and decreased with increased air temperature (Seddigh et al, 1984 a & b); Rosenzweig and Hillel, 1998). But little is known how much increase in temperature at given level of increased CO2 concentration, will level off the beneficial effect of CO2. The present study was undertaken with the objective to (i) generate information on magnitudes of direct and interactive effects of increased CO2, maximum temperature and minimum temperature on yield of maize, rice, cotton and wheat crops individually and in cropping systems, (ii) to find the increase in maximum and minimum temperatures, that will level off the beneficial effect of increased CO2 at a given level.

2. MATERIALS AND METHODS

The impact of climatic variability on yield of crops was studied by simulation approach, which is relatively less expensive, time saving, and easier than actual experimentation. This approach has been employed by a number of researchers in different parts of the world for a number of crops (Peart et al, 1989; Abraha and Savage, 2006; Mall et al, 2004; Tubiello and Evert, 2002; Peng et al, 2004) for studying the impact of climate change. They used either generated or real weather data. In the present study, weather data on daily rainfall, maximum temperature, minimum temperature, maximum and minimum relative humidity and wind speed was recorded at the meteorological weather station at Punjab Agricultural University, Ludhiana, India (30°56'N, 75°52'E and 247 m m.s.l) for the years 1991-2005. The solar radiation for the years was generated using ClimGen model from the real data on solar radiation from 1991 to 1995. In a separate study it has been found that ClimGen model generates solar radiation close to the observed in different climatic situations in Punjab (Bal et al, 2008). Climatic variability was created by increasing the CO_2 level from 350ppm (existing) to 700ppm with 20% interval. Both, maximum and minimum temperatures were increased up to 20% of the existing with incremental interval of 5%. The levels of CO_2 and temperatures (maximum and minimum) were five for each. The major reason for taking incremental scenarios is that they capture a wide range of potential changes. In the study one variable at a time was modified and its effect on the crop yield was assessed with the dynamic simulation model of CropSyst (Stockle and Nelson, 1999; Stockle et al, 1994; Stockle et al, 2003), while taking all other climate variables to be as per existing. Crop yields of rice-wheat, maize-wheat and cotton-wheat cropping systems were simulated and simulations were made for 15 years (1991-2005). This model is physiologically based model and has already been validated in this region for different cropping systems (Jalota et al, 2005, 2009a and 2009b) and elsewhere (Abraha and Savage, 2006; Anwar et al, 2006; Tubiello et al, 2006). As this model simulates crop growth and yield taking into account effects of weather, crop, soil and management parameters, yields of maize-wheat, rice-wheat and cotton-wheat cropping systems were simulated. The soil and crop parameters used in the model are described in other studies (Jalota et al, 2009a & b). Soil physical (texture, bulk density and hydraulic conductivity) and chemical (EC, pH, OC, ammonical nitrogen and nitrate nitrogen) properties of experimental field were determined up to 1.8 m soil depth with 0.15 m depth interval following the standard procedures. The sand, silt and clay contents, bulk density and hydraulic conductivity were determined by pipette, core and constant head method, respectively (Jalota et al, 1998). EC, pH and OC were measured with Solu Bridge (Chopra and Kanwar, 1976), potentiometric (Jackson, 1973) and wet digestion (Walkley and Black, 1934) methods, respectively. Ammonical-and nitrate-nitrogen were determined by Kjeldahal distillation method (Keeney, 1982).

The interactive effects of the climatic parameters on the simulated yield were assessed by applying a multiplicative model given below:

$$(Y/Y_a) = \alpha \prod (CO_2/CO_{2e})^{\gamma_1} (Tmax/Tmax_e)^{\gamma_2} (Tmin/Tmin_e)^{\gamma_3} \quad (1)$$

Where Y = crop yield (kg ha^{-1}),

Y_e = existing crop yield (kg ha^{-1}),

CO_2 = elevated concentration,

CO_{2e} = existing concentration,

Tmax = maximum temperature and

$Tmax_e$ = existing maximum temperature,

Tmin. = minimum temperature and

$Tmin_e$ = existing minimum temperature,

$\prod$ = multiplication and

$\gamma_1, \gamma_2, \gamma_3$ = the sensitivity factors for CO_2, T max. and T min., respectively

2.1 Description of the CropSyst Model

CropSyst model was chosen as it is a process based, simple, multi-year, multi-crop, daily time step cropping system simulation model. Further, its performance for periodic biomass and leaf area index and yield of crop in rice-wheat (Jalota et al, 2005, Chakraborty, 2008, Jalota 2009a) and maize-wheat (Jalota et al, 2009b) systems has been tested. The model is designed to study the effect of cropping system management on crop productivity, water and N balance and the environment (Stockle et al., 1994; Stockle and Nelson, 1999). Simulations were made by selecting a location and soil, and building crop rotations with management schedule. The location parameters included longitude, latitude, weather files and ET models. Effect of elevated temperature and CO2 was made by changing the temperatures in the weather file and CO2 in the crop file, respectively. The soil parameters included specification of soil layers, thickness, texture, bulk density, cation exchange capacity, pH, volumetric water content at water potentials of - 30 kPa (Field Capacity) and -1500 kPa (Wilting Point). The management options in the model included cultivar selection, crop rotation, irrigation, nitrogen fertilization, tillage operations and residue management. The crop file comprised of parameters related to classification, growth, morphology and phenology of the crop to represent different crops and crop cultivars. Model outputs derived were phenological schedule and crop yield.

3. RESULTS AND DISCUSSION

3.1 Actual Temperatures during different Crop Periods

Based on 15-year data (1991-2005), the mean, standard deviation and range of the maximum and minimum temperatures were determined. During rice, maize and cotton crops the means of maximum temperatures were 34.1, 34.6 and 34.1ºC with the range varying from 32.7 to 36.6, from 33.3 to 37.0 and from 32.8 to 35.7ºC, respectively. The standard deviation (SD) varied from 0.6 to 0.7ºC. The corresponding values of mean minimum temperatures in were 25.1, 25.5, 23.0 ºC with range varying from 24.3 to 25.5, from 24.6 to 26.2 and from 21.9 to 23.9 ºC, respectively. The SD varied from 0.4-0.5ºC. In wheat, mean maximum and minimum temperatures were 23.4 and 9.4ºC with range varying from 21.6 to 24.8 and from 8.6 to 10.9ºC, respectively. These existing ranges of the values of maximum and minimum temperatures are more than the optimum temperature range for rice, maize, cotton and wheat.

3.2 Impact on Crop Productivity

3.2.1 Elevated CO_2: The simulated yields of the crops were increased with increasing CO_2 content; however, the magnitude of increase was different in all the crops. By doubling the exiting concentration of CO_2, the increase in yields was 6.5, 4.9 and 5.5 percent in maize, rice and cotton, respectively (Figure 1). In wheat after maize, rice and cotton increase was 8.0, 12.0 and 3.9 per cent, respectively. The respective values for maize-wheat, rice-wheat and cotton-wheat were 7.6, 7.5 and 4.7 percent. More yield of crops at higher CO_2 concentration is due to more photosynthesis (Kimball, 1983; Cure and Acock, 1986; Allen et al, 1997; Kimbal et al, 2002).

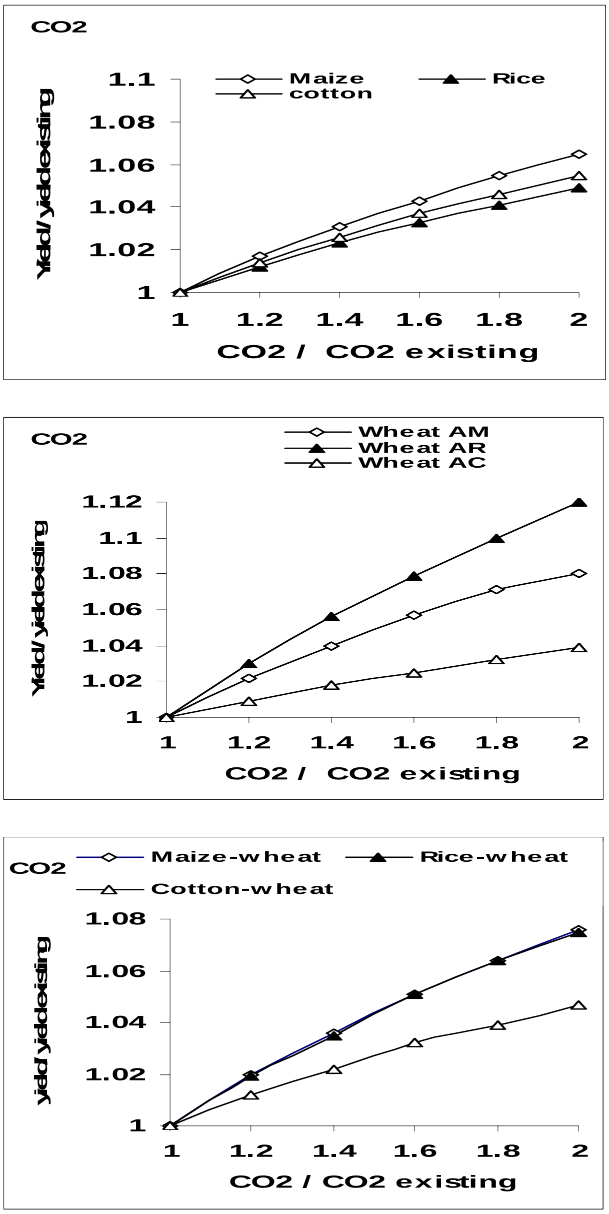

Figure 1. Yields of Maze-, Rice- and cotton-wheat Systems as Influenced by CO_2

3.2.2 Elevated maximum temperature: Unlike effect of CO_2, crop productivity decreased with increase in maximum temperature. Yields of maize, rice and cotton decreased by 42, 23 and 56 percent, respectively, with increase in the maximum temperature by 20 percent of the existing. Yields of wheat after maize, rice and cotton decreased by 12, 23 and 12 percent respectively. In maize-wheat, rice-wheat and cotton-wheat cropping systems, the decrease in yields were 2, 23 and 39 percent, respectively.

3.2.3 Elevated minimum temperature: Like maximum temperature, yields of different crops also decreased with increase in minimum temperature. However the decrease was lesser than that of maximum temperature. The decrease was 24, 13 and 28 percent in maize, rice and cotton, respectively. In wheat decrease was 25 and 7 percent after maize and rice; however yield increased 3 percent after cotton. This may be due to the reason that wheat is sown late in cotton-based system when minimum temperature is lower than the wheat crop sown after maize or rice. In maize-wheat, rice-wheat and cotton-wheat systems the decrease in yield was 12, 11 and 17 percent, respectively.

3.2.4 Elevated mean Temperature: Like individual maximum and minimum temperature, yields of different crops also decreased with increase in mean temperature. The decrease was 49, 26 and 75 percent in maize, rice and cotton, respectively (Figure 2). In wheat decrease was 17, 71 and 14 percent after maize, rice and cotton. In maize-wheat, rice-wheat and cotton wheat systems the decrease was 32, 27 and 53 percent, respectively.

Increased temperature shortens the pheno-phases. This will reduce time for light and water capture and will reduce both light and water use. In the present simulation it was observed that with increase in temperature, the duration of pheno-phases i.e. flowering (F) to grain filling (GF) and from grain filling (GF) to maturity (M) decreased, which can be represented by the following the equations (Table 1).

Crop	Weather Paramete r	Stage	Equation*	R^2
Maize	Tmax	F-GF	y = -0.6199x + 37.433	0.957
		GF-M	y = -0.4783x + 30.498	0.914
	Tmin	F-GF	y = -1.0606x + 44.393	0.955
		GF-M	y = -0.9457x + 38.615	0.955
Wheat	Tmax	F-GF	y = -0.4915x + 26.448	0.88
		GF-M	y = -0.4963x + 21.639	0.84
	Tmin	F-GF	y = -0.7732x + 22.974	0.97
		GF-M	y = -0.7216+ + 17.693	0.82

**The equations are based on Duration (y) vs. Weather parameters*

Table 2: The Equations Between crop Pheno-Phase Duration and Weather Parameters for Maize and Wheat in Different Pheno-Phases.

In maize crop the duration between flowering to grain filling decreased to 0.6 and 0.5 days with every degree increase in Tmax. and 1.1 and 0.9 days with T min., respectively.

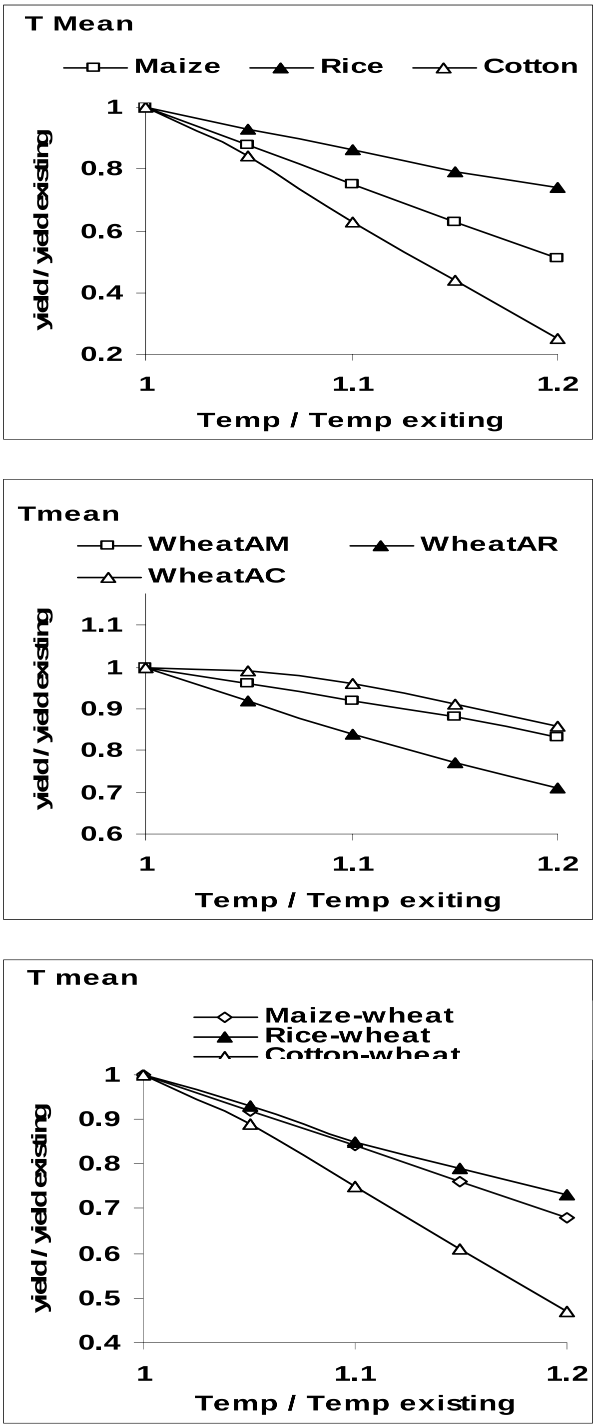

Figure 2. Yields of Maze-, Rice- and Cotton-Wheat Systems as Influenced by Temperature

3.2.5 Interactive effects: Interactive effects of these three climatic parameters were determined from the multiplicative model (1) fitted to the simulated data of different crops and cropping systems. The values of intercept (α), sensitivity factors for CO_2, Tmax and Tmin ($\gamma 1$, γ_2 and $\gamma 3$) and coefficient of correlations (R^2) for different crops and cropping systems are given in Table 2. It is important to note that values of the intercept were near unity and of R^2 was very high ranging from 0.94 to 0.99 for all the crops and cropping systems. Using sensitivity parameters of CO_2, Tmax and Tmin, in the model values of increased Tmax and Tmin, that override the effect CO_2 of increased yield were calculated. It showed that yield increased by doubling the CO_2 level could be levelled off by increasing Tmax by 1.0, 1.8 and 0.3 ºC or Tmin by 1.8, 2.0 and 0.7ºC, respectively in maize, rice and cotton crops. This implies that if there is an increase in temperature by 2ºC and CO_2 level to double of the existing values, crop productivity won't be affected because negative effect by increased temperature will be countered by increased CO_2 level.

Crop	*α	γ1	γ2	γ3	R^2
Rice	1.017	0.069	-1.442	-0.774	0.97
Wheat	1.002	0.163	-1.408	-0.425	0.99
Rice-wheat	1.011	0.105	-1.428	-0.638	099
Maize	1.006	0.092	-2.987	-1.459	0.95
Wheat	0.998	0.117	-0.568	-.088	0.97
Maize-wheat	1.013	0.106	-1.603	-0.703	0.97
Cotton	1.052	0.077	-4.534	-1.806	0.94
Wheat	1.004	0.053	-0.578	0.128	0.98
Cotton-wheat	1.026	0.066	-2.703	-0.966	0.96
*α is intercept, R^2 is coefficient of determination, γ_1, γ_2 and $\gamma 3$ are sensitivity factors for CO_2, maximum temperature and minimum temperature, respectively.					

Table 2. Intercept, sensitivity factors and coefficient of correlation of the equations fitted to different crops and cropping systems

CONCLUSION

The results of the present study indicate that amongst the three cropping systems, cotton-wheat will be affected more adversely than maize-wheat and rice-wheat systems. The adverse effect of increased temperature was more for maximum temperature than minimum temperature. Though increase CO_2 would increase the crop productivity but the magnitude of increase in crop yields was less than that of decrease by the increased temperature.

ACKNOWLEDGEMENT

The work was carried out under the Cropping System Analysis, an EOAM project of Space Application Centre, ISRO, Ahmedabad. The authors are grateful to Dr. J.S. Parihar, Deputy Director RESA, SAC for keen interest in the study.

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