



Climate change impacts on yield, evapotranspiration and nitrogen uptake in irrigated maize (*Zea mays*)–wheat (*Triticum aestivum*) cropping system: a simulation analysis

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ABSTRACT

Considering the present trends of global climate change, atmospheric CO₂ and temperature levels are likely to increase in future, which will affect yields, water and nitrogen requirements of the crops in a given region. The present study concerns quantification of direct and interactive effects of the elevated CO₂ (from 350 to 700ppm) and temperature (from existing to 3°C higher) on yield, nitrogen uptake and evapotranspiration (ET) of optimally irrigated (IW/Pan E ratio=0.9) and fertilized (120 kg/ha) maize–wheat cropping system on texturally variable soils. IW and Pan E are amounts of irrigation water and open pan evaporation, respectively. Averaged over 30 years simulations with the already calibrated and validated CropSyst model showed that by increasing CO₂ concentration from 350 to 700ppm in maize and wheat, yields were increased by 17 and 57%, ET decreased by 14 and 3 mm; and nitrogen uptake increased by 12 and 44 kg/ha respectively. The effect of increased CO₂ was more in wheat (C₃ plant) than that in maize (C₄). At 350ppm CO₂ with temperature 3°C higher than the existing in maize and wheat crops, crop durations of maize and wheat were shortened by 12 and 23 days, ET decreased by 30 and 50 mm, nitrogen uptake decreased by 31 and 27 kg/ha and subsequently yields were reduced by 37 and 15%, respectively. The interaction of CO₂ and temperature indicates that even 700ppm level of CO₂ was not able to maintain the existing maize yield beyond one degree increase in temperature. In case of wheat, yield levels were well maintained at 700ppm level of CO₂ even at higher level of temperature (3°C). Increased levels of irrigation (IW/Pan E ratio=1.25) and nitrogen (150 and 180 kg/ha) were not able to outweigh the negative effect due to increased temperature than the existing in this cropping system.

Key words: Climate change, CO₂ temperature interaction, Crop simulation, Evapotranspiration, Maize–wheat system, N-uptake, Yield

Climatic parameters such as atmospheric CO₂ concentration, temperature, precipitation (rainfall), humidity, light intensity and duration along with water and nutrient status of the soil are important to determine the plant growth and agricultural crop production. Deviation of any of these parameters from their optimum range limits the plant growth and ultimately affects the crop yield. In the present scenario of changing climate, levels of atmospheric CO₂ concentration and temperature are rising. In the pre-industrialization period, CO₂ concentration in the atmosphere was about 280ppm. Since industrialization, it started increasing and reached a

level of 315ppm in 1967 and 356ppm by 1993 (Schimel *et al.* 1995). At present, atmospheric CO₂ concentration is 385ppm which is about 38% higher than the pre-industrial levels (NOAA 2008) and is expected to reach 450–550ppm in 2050 and 700ppm by the end of the 21st century. Higher concentrations of CO₂ along with other green house gases like CH₄, N₂O, O₃, chlorofluorocarbons caused green house effect and have resulted in rise of average global surface temperature by 0.74°C±0.18°C over the past 100 years (Trenberth and Jones, 2007). According to the Intergovernmental Panel on Climate Change (IPCC) 4th assessment report (Meehl and Stocker 2007), average global air warming of 1.8°C can occur under the B1 scenario and 4°C under the A1F1 scenario by the end of the 21st century. A number of free air carbon dioxide enrichment experiments (FACE), open top chamber (OTC), temperature gradient tunnel (TGT) and simulation studies related to climate change by the changing individual climatic parameter and crop

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productivity have been conducted in the different regions of the world (Dhakhwa *et al.* 1997, Baker *et al.* 1992). Increased CO₂ level is reported to enhance crop yields by increasing photosynthetic rates (Kimball and Idso 1983, Kimball *et al.* 2002) but the magnitude of yield response varies among C₃, C₄ and Crassulacean Acid Metabolism (CAM) plants. On the other hand increased temperature reduces crop yields by increasing respiration and shortening the crop growth period (Tao *et al.* 2008) and the literature shows that the net effect (positive or negative) of interactions between increased CO₂ and temperature is different in different regions having different climatic conditions. Therefore, this study was undertaken to assess the magnitude of impact of climate change for this region on maize–wheat cropping system with the specific objectives: (1) to quantify the direct and interactive effects of increasing CO₂ and temperature on yield, nitrogen uptake and evapotranspiration of the maize–wheat cropping system, and (2) to assess the potentialities of applied additional irrigation and nitrogen levels to mitigate climate change effects.

MATERIALS AND METHODS

The impact of climatic variability on yield, nitrogen uptake and ET of maize–wheat cropping system 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 (Abraha and Savage 2006, Mall *et al.* 2004) for studying the impact of climate change. They used either generated or real weather data. In the present study, daily weather data of rainfall, maximum and minimum temperature, maximum and minimum relative humidity and wind speed for the years 1971–2000 recorded at the meteorological weather station at Punjab Agricultural University, Ludhiana (30°56'N, 75°52'E and 247 m above mean sea level) was used. The solar radiation for the years was generated using ClimGen model from the real data on solar radiation from 1991 to 1995. CropSyst (Cropping Systems Simulation Model) model was used to simulate the impact of climate change on maize–wheat cropping system. This model has already been calibrated and validated in this region for different cropping systems (Jalota *et al.* 2005, 2009, 2010 and 2011) and elsewhere (Abraha and Savage 2006, Tubiello *et al.* 2007). This model has different input files namely soil, location, crop, management and weather parameter file. The data used for model initialization, soil properties and crop parameters are given elsewhere (Harsimran Kaur 2009). Climate variability was created by varying the atmospheric CO₂ level as 350, 450, 550 and 700 ppm at existing temperature; and increasing temperature (maximum, minimum and mean) by 1, 1.5, 2, and 2.5 to 3°C of the actual data in daily weather files. First, simulations were run to quantify the effects of CO₂ and temperature individually on the yield of maize–wheat

cropping system at the recommended irrigation (IW/Pan E ratio=0.9) and nitrogen management (N₁₂₀ kg/ha). Thereafter interactive effects were evaluated by changing the levels of CO₂ and temperature simultaneously. For the mitigation treatments, simulations were run by changing water and nitrogen levels higher than recommended. The treatment combinations were CO₂ × mean temperature × N (120 kg/ha) × IW/Pan E ratio (1.25), CO₂ × mean temperature × N (150 kg/ha) × IW/Pan E ratio (1.25), CO₂ × mean temperature × N (180 kg/ha) × IW/Pan E ratio (1.25), CO₂ × mean temperature × N (150 kg/ha) × IW/Pan E ratio (0.9), CO₂ × mean temperature × N (180 kg/ha) × IW/Pan E ratio (0.9). These combinations of simulations were repeated for three soil textures, viz loamy sand, sandy loam and silt loam soils. As crop response to the elevated CO₂ is different in C₃ (wheat) and C₄ (maize), therefore crop growth ratio parameter (growth at elevated CO₂ level to the growth at baseline CO₂ level or enhancement factor) was inserted in the both maize and wheat crop files. The default values of enhancement factors were changed from 1.0 to 1.11 for maize and 1.27 for wheat as suggested by Tubiello *et al.* 2007.

RESULTS AND DISCUSSION

Baseline simulations

Simulated results showed that evapotranspiration (ET) increased with the fineness of the soil texture (Table 1). In silt loam soil compared to that in loamy sand soil, ET was higher by 25% in maize and 37% in wheat. These simulated results corroborates the findings of Jalota and Prihar (1986), who reported higher soil evaporation from silt loam than loamy sand soil due to the self mulching nature of the loamy sand soil on quicker drying. On silt loam soil, biomass and yield in maize were increased by 4–5% than loamy sand soil (Table 1). Similarly in wheat, biomass (28%) and yield (34%) were increased but the magnitude of increase was comparatively higher than in maize. Nitrogen uptake was also increased with fineness of the soil texture in both the crops; however, the uptake was more in wheat than maize

Table 1 Effect of soil type on biomass, yield, evapotranspiration (ET), drainage (D) and nitrogen uptake (NU) in maize–wheat system at baseline level of CO₂ and at existing temperatures

Soil type	Maize					
	Biomass (kg/ha)	Yield (kg ha)	ET (mm)	D (mm)	NU (kg/ha)	
Loamy sand	7246	3621	326	438	94	
Sandy loam	7366	3682	353	411	94	
Silt loam	7592	3796	406	231	95	
	Wheat					
	Loamy sand	7339	3426	285	108	123
	Sandy loam	7884	3718	316	87	134
Silt loam	9431	4604	392	46	149	

(Table 1). Higher nitrogen uptake in wheat (C_3) was probably due to higher biomass and less nitrogen-use efficiency than maize (C_4) crop.

Effect of elevated CO₂

Increased CO₂ levels improved the grain yield in both maize and wheat crops (Fig 1). However, the effect of increased CO₂ was more pronounced in wheat than maize. This may be ascribed to higher radiation-use efficiency and relative growth ratio of wheat (C_3) than maize (C_4) at elevated levels of CO₂. Similar trend of increased yield at higher CO₂ in C_3 crops (field experiments) has already been documented in literature by the researchers (Bender *et al.* 1999, Kimball *et al.* 1995). As far as the effect of soil texture is concerned, it was more pronounced in wheat than in maize. The reason could be that in the maize crop the effect of soil texture was nullified by sufficient availability of soil moisture through frequent precipitation during the rainy season that coincides with maize growing season, while during drying period wheat crop drew water for long period only from the soil having more water holding capacity. Since water-holding capacity at field capacity of silt loam was higher (0.32 m³/m³) than sandy loam (0.19 m³/m³) and loamy sand (0.14 m³/m³) soils, therefore yield of wheat on silt loam was higher than on the

other soils at all levels of CO₂. Nitrogen uptake was increased in both maize and wheat due to increased growth under elevated CO₂ conditions. Under loamy sand soil, nitrogen uptake was increased from 94 to 99, 103 and 106 kg N/ha in maize and from 123 to 134, 137 and 138 kg N/ha in wheat at CO₂ levels from 350 to 450, 550 and 700ppm, respectively.

Similarly in sandy loam soil, nitrogen uptake increased from 94 to 99, 103 and 107 kg N/ha in maize and from 134 to 153, 166 and 176 kg N/ha in wheat, respectively. In silt loam soil, the corresponding values were from 95 to 101, 104 and 108 kg N/ha in maize and 149, 173, 189 and 205 kg N/ha in wheat respectively. Under elevated CO₂, crop duration remained unaffected and was similar to that under baseline conditions. These results are in line with the results reported (simulated) by Iglesias and Minguez 1997. ET generally decreased with increasing CO₂ level in both maize and wheat crops on all the three soils but the differences in the ET were marginal 1–5%. In fact the difference in ET at various levels of CO₂ depends upon the relative magnitudes of decrease in stomatal conductance and increase in the leaf area (Li *et al.* 2004).

Effect of increased temperature

The CropSyst model is daily thermal time step model in which crop growth duration is a function of accumulation of growing degree days. Increase in either maximum or minimum temperatures or in both influences the crop growth development, crop phenology, duration of crop cycle which eventually affects the yield (Xiao *et al.* 2007). Total duration of maize and wheat crops was decreased by 12 days in maize and 23 days in wheat with 3°C increase in mean temperature. The effect of increased mean temperature on yields of maize and wheat crops (averaged across all soils at 350ppm CO₂ level) is given in Fig 2. Yield decreased with increase in temperature, but the magnitude of decrease varied with the crop and temperature. With every degree increase in maximum, minimum and mean temperatures, maize yield was decreased by 366, 139 and 454 kg/ha, respectively. In

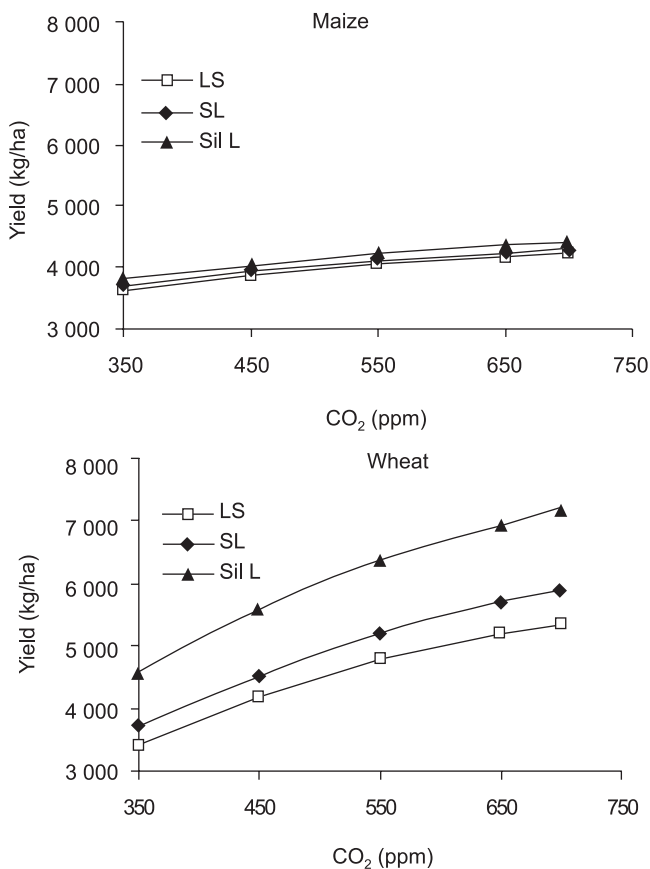


Fig 1 Effect of elevated CO₂ on the maize and wheat crop yields on different textured soils

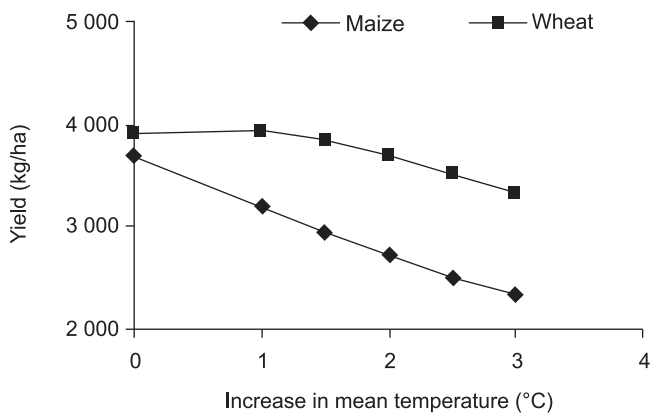


Fig 2 Effect of increased maximum, minimum and mean temperature at baseline level of atmosphere CO₂ (350ppm)

wheat, the corresponding decrease in yield with increase in maximum and mean temperature was 91, and 192 kg/ha respectively. Unlike maximum temperature, every degree increase in minimum temperature resulted in increased wheat yield by 41 kg/ha. These values indicated that adverse effect of higher temperature was more negative with maximum temperature than minimum temperature in both the crops, and in maize than in wheat crop. The effect of mean temperature was additive and was more negative than the individual maximum or minimum temperature (Dhakhwa *et al.* 1997). The effect of temperature was modified with crop and soil texture (Fig 3). The effect of soil texture was negligible in maize. In wheat, more yields were realized on silt loam than sandy loam and loamy sand but the effect of temperature was more in silt loam (19%) than sandy loam (13%) and loamy sand soils (11%). These results support the results of Ludwig and Asseng 2006 who reported more decrease in yield on medium- than light- textured soils. With 3°C increase in temperature than the existing, evapotranspiration (averaged across different soil textures) was decreased by 30 and 50 mm in maize and wheat crops. The corresponding values for nitrogen uptake decrease were 31 and 27 kg/ha.

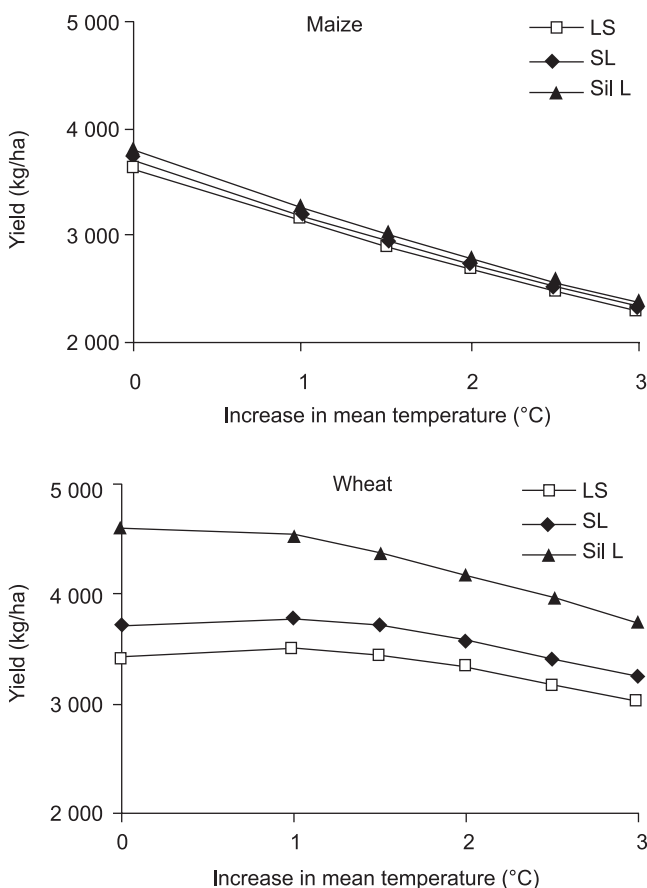


Fig 3 Effect of increased maximum, minimum and mean temperature at baseline level of atmosphere CO₂ (350ppm)

Interactive effects of CO₂ × temperature on yield, nitrogen uptake and ET

At all levels of CO₂, yield of maize crop was declined due to increased temperature; however yields with higher CO₂ concentration were more than that of baseline yield. The effect of temperature was negative to the extent that even 700ppm of CO₂ was unable to maintain yield equal to the baseline at temperature beyond one degree higher than the existing temperature (Table 2). This implies that to offset the negative effect of 1°C increased temperature in maize, double CO₂ concentration is required than baseline level of 350ppm. Because of the high negative effect of increased temperature even the higher levels of irrigation and nitrogen were found ineffective and did not produce any mitigating effect in maize. On the other hand in case of wheat, positive effect of increased CO₂ (700ppm) was so pronounced that it counterbalanced the negative effect of temperature even up to 3°C higher than the existing. Similar to yield, nitrogen uptake in maize was higher under increased CO₂ than that under baseline conditions because of high yield and decreased with increased temperature. Evapotranspiration (ET) was decreased by 11% in maize and 16% in wheat at elevated CO₂ level of 700ppm CO₂ and 3°C higher temperatures than the baseline. The difference in the yields of maize and wheat could be explained according to the growth ratios and radiation, use efficiency values which were added in the model in response to the increasing levels of CO₂. Growth ratio and radiation-use efficiency values were comparatively higher for wheat than maize as already mentioned in the materials and methods. These parameters were added for getting differential response in wheat (C₃) and maize (C₄) to increased level of CO₂. Experimental studies showed that the increase in photosynthesis rate in response to elevated CO₂ would be less in maize (C₄) than wheat (C₃) because of very efficient CO₂ assimilation cycle of maize crop. Therefore, the values of these parameters were higher in wheat than maize (Donatelli *et al.* 2002, Tubiello *et al.* 2007).

Sensitivity analysis

Sensitivity of the crop yield to climatic parameters (CO₂, maximum and minimum temperatures) was assessed by a multiplicative model (1). The values of intercept (α), sensitivity coefficient for CO₂ (γ_1), minimum temperature (γ_2) and maximum temperature (γ_3) and coefficient of determination (R²) are given in the Table 3.

$$\left(\frac{Y}{Y_{\max}}\right) = \Pi_{i=1}^n \left(\frac{\text{CO}_2/\text{CO}_{2e}}{\text{CO}_2}\right)^{\gamma_1} \left(\frac{T_{\min}/T_{\min e}}{T_{\min}}\right)^{\gamma_2} \left(\frac{T_{\max}/T_{\max e}}{T_{\max}}\right)^{\gamma_3} \quad (1)$$

Here Y/Y_{\max} is ratio of yield to maximum yield and subscript e in T_{max}, T_{min} and CO₂ represents the existing level.

The point to be noted is that the values of coefficient of determination were very high ranging from 0.988 to 0.996 indicating that yield variation can be explained by these

Table 2 Effect on yield, nitrogen uptake (kg/ha) and ET with increase in mean temperature at different levels of irrigation and nitrogen averaged over three different textured soils

Crop	CO ₂ (ppm)	Nitrogen (kg/ha)	IW/Pan E ratio	Yield			Nitrogen uptake			ET		
				Ex	Ex+1°C	Ex+3°C	Ex	Ex+1°C	Ex+3°C	Ex	Ex+1°C	Ex+3°C
Maize	350	120	0.9	3700	3195	2337	94	83	64	362	351	332
			1.25	3695	3192	2332	95	83	64	371	360	343
		150	0.9	3700	3195	2334	95	83	64	363	351	333
			1.25	3695	3192	2332	95	83	64	371	360	343
		180	0.9	3663	3195	2334	94	83	63	360	351	333
			1.25	3695	3192	2332	95	83	64	371	360	343
	700	120	0.9	4314	3717	2713	107	95	73	347	338	322
			1.25	4309	3713	2710	107	95	73	356	346	331
		150	0.9	4315	3717	2713	107	95	73	348	337	321
			1.25	4309	3713	2710	107	95	73	356	346	331
		180	0.9	4314	3716	2713	107	94	72	348	338	321
			1.25	4309	3713	2710	107	95	73	356	346	331
Wheat	350	120	0.9	3916	3932	3339	135	127	108	331	320	281
			1.25	4158	4184	3502	140	130	111	350	339	297
		150	0.9	3917	3932	3338	137	129	108	332	320	281
			1.25	4158	4184	3502	141	131	111	350	339	297
		180	0.9	3906	3932	3337	137	128	108	330	320	281
			1.25	4158	4184	3502	142	131	111	350	339	297
	700	120	0.9	6131	6119	5206	173	168	148	329	316	277
			1.25	6444	6461	5463	174	170	151	345	333	291
		150	0.9	6166	6139	5207	182	174	150	329	316	277
			1.25	6499	6489	5468	185	177	154	345	333	291
		180	0.9	6176	6143	5207	187	176	150	329	315	280
			1.25	6516	6500	5468	192	181	155	345	333	291

Ex, existing temperature; Ex+1°C and Ex+3°C represent one and three degree higher temperature than the existing

factors and the values of coefficient were positive for CO₂ and negative for temperature (Table 3). More negative values of coefficient for maximum temperature indicated that yield reduction by increase in maximum temperature was more than by minimum temperature. Further, the values of sensitivity coefficients of temperatures were found to be

Table 3 Sensitivity coefficients for CO₂, T_{max}, T_{min} as influenced by soil texture in maize and wheat crop

Crop and Soil texture	Á	γ ₁	γ ₂	γ ₃	R ²
<i>Maize</i>					
Loamy sand	0.861	0.225	-1.006	-4.1687	0.996
Sandy loam	0.863	0.223	-1.032	-4.268	0.996
Silt loam	0.870	0.209	-1.097	-4.290	0.994
<i>Wheat</i>					
Loamy sand	0.658	0.641	0.206	-0.399	0.988
Sandy loam	0.650	0.654	0.173	-0.518	0.989
Silt loam	0.660	0.631	-0.011	-0.834	0.988

increased with fineness of soil texture (Ludwig and Asseng 2006).

Mitigation effects

Effect of increased irrigation: At existing (350ppm) and elevated (700ppm) levels of CO₂, increased irrigation water was not able to mitigate the negative effect of increased temperature in maize. It may be ascribed to the reason that the soil water was sufficient (because of rainy season) to meet the needs of crop at particular temperature and CO₂ level. On the other hand in case of wheat, there was a positive effect of increased irrigation (from IW/Pan-E ratio 0.9 to IW/Pan-E ratio of 1.25) on the yield at both levels of CO₂ (350ppm and 700ppm). The increase in yield was 8, 8 and 2% (at 350 or 700ppm) on loamy sand, sandy loam and silt loam soils respectively. Though the effect of increased irrigation was positive at high temperatures (3 degree increase in mean temperature) but its magnitude was reduced from 8 to 6 and from 2 to 1% in sandy loam and silt loam soils respectively.

Effect of increased nitrogen application

In maize, the simulated yields at higher rate of nitrogen (150 and 180 kg N/ha) was comparable to that at recommended level (120 kg N/ha).

These results of the present study suggest that increased temperature in future will certainly decrease yields. Increased CO₂, irrigation and nitrogen levels may not be able to outweigh the negative effect of increased temperature in maize, however, in wheat increased CO₂ levels in the atmosphere and more of irrigation than the existing may increase yield. Therefore, for the crops susceptible to climate change, it is imperative to focus research on reducing temperature effects by using crop residues as mulch, managing light use by changing the crop geometry, developing drought and temperature tolerance crops and better matching phenology to ensued environment due to climate change.

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