Research Article

EFFECT OF CLIMATE CHANGE AND CO_2 CONCENTRATION ON GROWTH AND YIELD OF RICE AND WHEAT IN PUNJAB: SIMULATIONS USING CSM-CERES-RICE AND CSM-CERES-WHEAT MODELS

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ABSTRACT

Recent trends of a decline or stagnation in the yield of rice and wheat in rice-wheat (RW) systems of the Indo-Gangetic Plains (IGP) have raised serious concerns about the regional food security. The effect of future climate change on crop production adds to this complex problem. The validated CSM-CERES-Rice and CSM-CERES-Wheat (Ver. 4.0) data were used to test the sensitivity of the models in Punjab, India. The models were sensitive to climatic parameters (temperature, CO_2 concentration, solar radiation and rainfall) on yields of both crops. Simulated rice yields were sensitive to weather as there was 13% less yield of rice in 1999 than in 2001. Similarly, simulated wheat yields were also sensitive to weather, with the highest yield in 2001, and the lowest in 2003. Increments in both maximum and minimum temperatures by $4^{O}C$, decreased rice yield by 34% and wheat yield by 4% as compared to base scenario with current weather data. By increasing $4^{O}C$ for both maximum and minimum temperature along with an increase in solar radiation by $1MJ/m^2/day$, rice yield decreased by 32% as compared to base scenario while wheat yields were not affected. With the increase in maximum and minimum temperatures by $4^{O}C$, and also an increase in CO_2 concentration by 20 ppm from the standard CO_2 concentration of 335 ppm, the reduction in rice yield was 33%, but in wheat yield was only 3%. Rainfed wheat yield increased by 7%, by increasing daily rainfall by 1.5 times, and by 13%, by doubling the rainfall, both after 96 days of sowing (DAS) to maturity. Lowering rainfall to zero, for each day after 96 DAS to until maturity reduced wheat yield by 18%. The increasing maximum and minimum temperatures irrespective of whether the CO_2 concentration increased or not, seemed to have more adverse effects on rice than to wheat. Simulations demonstrated that CSM-CERES-Rice and CSM-CERES-Wheat are sensitive to CO_2 and climatic parameters, and can be used to study the impact of future climate change on rice and wheat productivity in RW systems in Asia.

Key words: CSM-CERES-Rice, CSM-CERES-Wheat, climate change, yield, phenology

INTRODUCTION

Rice and wheat are the two most important cereals in Asia. Rice-Wheat (RW) systems are of immense importance for food security in South Asia and China, providing 85% of the total cereal production and 60% of the total calorie intake in India. In spite of the large research efforts to lift the rice and wheat yields, there are still large gaps between biologically and climatically achievable potential yields and research station and on farm yields (Timsina and Connor, 2001, Timsina *et al.*, 2004). Further, there are now reports of decline or stagnation in the yield of rice and wheat in the RW system which have raised concerns about the regional food security.

Climate influences plant life in many ways and can inhibit, stimulate, alter or modify crop performance. Its components (temperature, solar radiation, rainfall, relative humidity and wind velocity) independently or in combination, can influence crop growth and productivity. All over the world concerns now exist about the possible climate change caused by an increase in the concentration of green house gases such as CO_2, CH_4 and N_2O in the atmosphere (Watson *et al.*, 1996). Using general circulation models (GCM), it has been predicted that a doubling of the current CO_2 levels in the atmosphere will cause an increase of 1.5 to $4.0^{0}C$ in average global surface air temperature, with accompanying changes in rainfall pattern by the end of the 21st century (Cohen, 1990; Adams *et al.*, 1995). Climate change via increasing atmospheric CO_2 concentration can affect global production through changes in photosynthesis and transpiration rates. For the Indian sub-continent, it is predicted that the mean atmospheric temperature will increase by $1\text{-}4^{0}C$ (Sinha and Sawaminathan, 1991).

Although the solar radiation received at the surface will be variable geographically, on average, it is expected to decrease by about 1% (Hume and Cattle, 1990).

Crop simulation models can be used to understand the influence of climatic variables on crop growth and yield when conventional field experiments have limitations because of various confounding factors. They can potentially provide a scientific approach to study the impact of current and future climate change on agricultural production (Rosenzweig and Parry, 1994; Adams *et al.*, 1995). For example, major rice models indicate a reduction in yield of about 5% per ^{0}C rise in mean temperature (Matthews *et al.*, 1995), and would largely offset any increase in yield as a consequence of increased CO_2. In their review, Timsina and Humphreys (2003) have revealed the marked effects of climate change in rice and wheat production in various countries in Asia and Australia. Qureshi and Iglesias (1994) reported that the effect of temperature is more significant in wheat yield. For example wheat yield was dramatically reduced under both dry land and irrigated conditions of Pakistan due to a shorter season caused by temperature increase. Likewise, increased use of N fertilizer and plant population slightly reduced the negative impacts of climate change on wheat yield than in rice in India (Rao and Sinha, 1994). Several studies have been done to develop an integrated assessment of the effect of the climate change on regional and global food supplies and demand.

CSM-CERES-Rice and CSM-CERES-Wheat models are process based, management-oriented models that can simulate the growth and development of rice and wheat as affected by varying levels of weather, water, nitrogen, and cultivar characteristics (Jones *et at.,* 2003). The model processes indicate the effects of elevated CO_2 and changed climatic parameters such as increased or decreased temperatures, rainfall and solar radiation. These models have been validated and tested across the world, including many countries in Asia (Timsina and Humphreys, 2003) and in N-W India (Timsina *et al.*, 2004), and hence are suitable for investigating the sensitivity of both rice and wheat yields to CO_2 and climate change parameters. This study was therefore undertaken to test the sensitivity of these models in terms of yield and growth duration of rice and wheat to changes in major climatic parameters such as temperature, rainfall, CO_2 and solar radiation.

MATERIALS AND METHODS

Changes in CO_2 concentration, temperature, solar radiation, and rainfall were considered to test the sensitivity of yield and growth duration of rice and wheat simulated by CSM-CERES-Rice and CSM-CERES-wheat (ver.4.0) to CO_2 and climatic parameters. A continuous flooding treatment with 120 kg N/ha for rice, and the treatment with 390 mm irrigation with 120 kg N (60+60)/ha for wheat were chosen as 'base or standard scenario' for rice and wheat, respectively. Weather data (2001 for rice and 2001-02 for wheat) were used for the 'base scenarios' or 'standard treatments' and various changes to CO_2 concentration and climatic parameters were made. Both models were first run for 5 years of weather data from Ludhiana, Punjab to see the sensitivity of the models to various weather years.

Sensitivity of the models to climate change parameters was carried out for an increase or decrease in solar radiation by 1MJ/m^2/day, increase or decrease of maximum and minimum temperatures by 4^{O}C, and for an increase of CO_2 concentration by 20 ppm to the 2001 weather data for rice and 2001-02 for wheat. There was only about 23 mm rainfall during the wheat season, and all was after February 11 (96 days after sowing, DAS). Therefore, in wheat, the effect of rainfall was also simulated by multiplying the rainfall amount by 0, 1, 1.5 and 2 for each day after 96 DAS of wheat, because wheat is sensitive to soil moisture content after heading, requiring irrigation. The climate change simulations were accomplished by using the Environmental Modification Section of File X. (Experimental file) used to run the model (Jones *et al.,* 2003)

RESULTS AND DISCUSSION

Sensitivity of CSM-CERES-rice and CSM-CERES-wheat to weather

The models were run using 5 years of weather data (1999 to 2003) from PAU, Ludhiana. Results showed that the simulated yields of both crops were sensitive to various weather years. There exists a declining trend in simulated rice yield for the consecutive years and it was the lowest (87% or 13% lower than 2001, the standard weather) for 1999. There were, however, not marked differences on days to anthesis and to physiological maturity for different weather (Table-1). The lowest rice yield in 1999 was related to lower solar radiation, higher average temperature, and lower rainfall during the rice season resulting in decreased photosynthesis and increased respiration rates, where as in 2001 all these climatic parameters had reverse trends resulting in higher rice yield (Figures 1-3 and weather Figures 4-7).

Table 1. Sensitivity of simulated yield and phenology of rice to weather

Weather years	Simulated grain yield (kg/ha)	Percentage yield	Anthesis (days)	Physiological maturity (days)
2001[a]	7933	100	79	110
1999	6863	87	79	110
2000	7695	97	79	110
2002	6980	88	76	109
2003	7466	94	79	111

[a]Standard weather year for rice

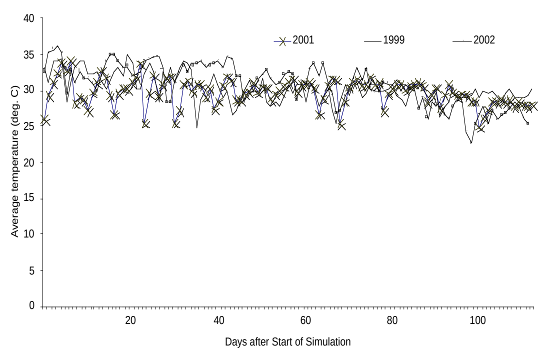

Figure 1. Daily average temperature (^{0}C) during rice season at PAU

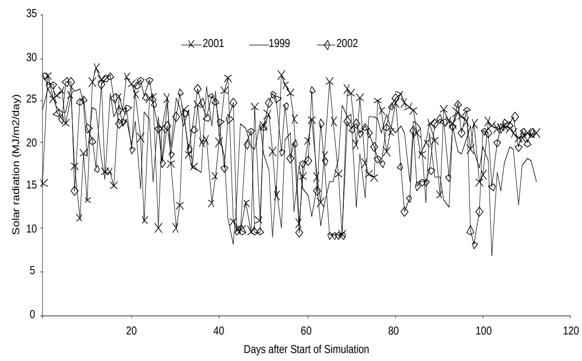

Figure 2. Daily solar radiation (MJ/m^2/day) during rice season at PAU

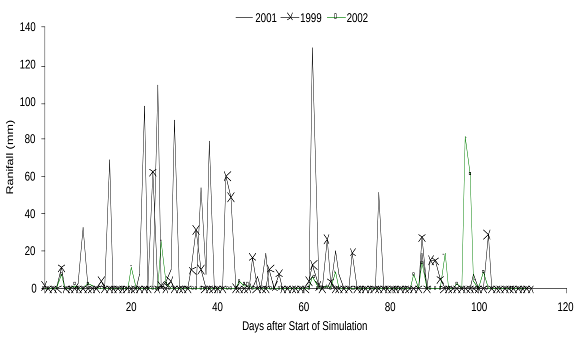

Figure 3. Daily rainfall (mm) during rice season at PAU

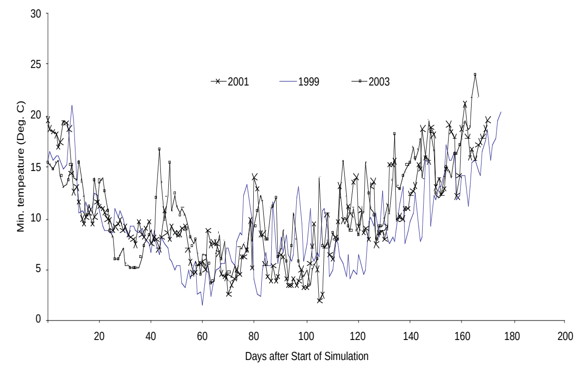

Figure 4. Daily minimum temeprature(^{0}C) during rice season at PAU

There also exists a declining trend in simulated wheat yield for the consecutive years with the lowest in 2003 (88% of yield for 2001, the standard weather). The lower wheat yield in 2003 was due to high maximum daily temperature during crop growth especially after flowering, low solar radiation and comparatively less rainfall during the wheat season (Table-2). Figures 4 to 7 clearly revealed that all the weather parameters had optimum values for wheat in 2001, with lower daily minimum and maximum temperature, higher solar radiation, and quite high rainfall. Wheat requires cool temperatures and a long growing period for its higher yield potential.

Table 2. Sensitivity of simulated grain yield and phenology of wheat to weather

Weather years	Simulated grain yield (kg/ha)	Percentage yield	Anthesis (days)	Physiological maturity (days)
2001[a]	5720	100	117	156
1999	5732	100	117	156
2000	5705	100	119	161
2002	5243	92	117	158
2003	5048	88	119	159

[a]Standard weather year for rice

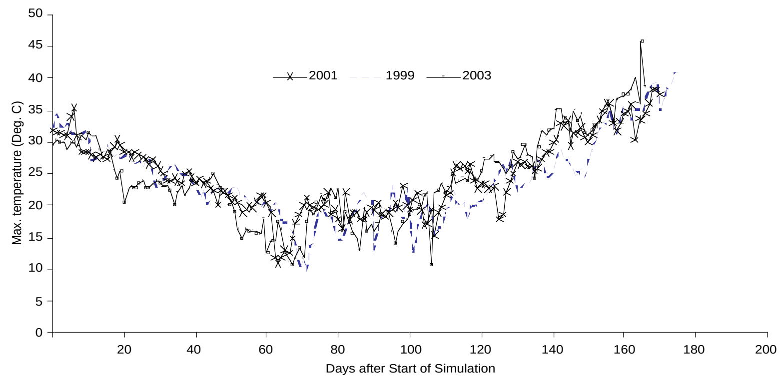

Figure 5. Daily maximum tempearture (^{0}C) during rice season at PAU

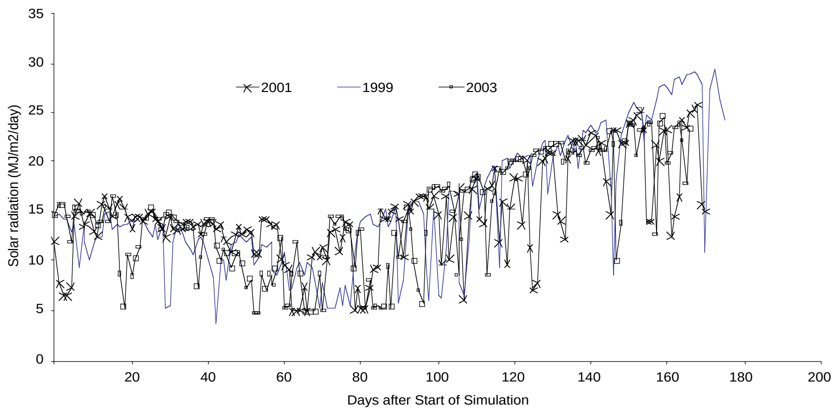

Figure 6. Daily solar radiation (MJ/m^2/day) during rice season at PAU

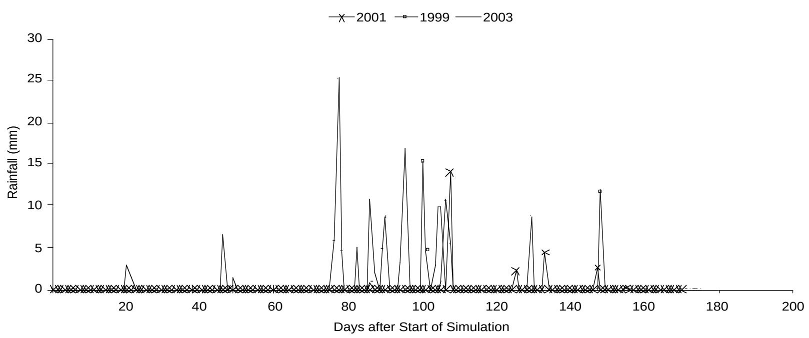

Figure 7. Daily rainfall (mm) during rice season at PAU

Sensitivity to climate parameters in rice

Sensitivity of yield simulated by CSM-CERES-Rice to climatic parameters was tested for the continuous flooding treatment (Table 3). The results showed that as compared to rice yield (8391 kg/ha) for the standard treatment, the yield was 17% higher for the decrease in both maximum and minimum temperature by $4^{O}C$, but 34% lower for their increase by $4^{O}C$. Increased temperature decreased growth duration by 9 days, while decreased temperature increased growth duration by 24 days. Decreasing both maximum and minimum temperature by $4^{O}C$ and increasing solar radiation by $1MJ/m^2/day$, increased the rice yield by 18% and growth duration by 24 days showing the interactive effect of temperature and solar radiation. These results are similar to those of Imai (1988) who also reported that yield decreased drastically with increasing temperature under climate change. With a decrease in temperature, vegetative and grain filling periods became long and produced higher yields, but with an increase in temperature the reverse is true. Thus, in the current study, the longest crop growth period of 133 days was for both reduction in maximum and minimum temperatures by $4^{O}C$ and reduction in solar radiation by $1MJ/m^2/day$.

Table 3. Sensitivity of simulated yield of rice to temperature, CO_2 concentration, and solar radiation

Maximum Temp (^{O}C)	Minimum Temp (^{O}C)	CO_2 Conc. (ppm)	Solar radiation ($MJ/m^2/d$)	Simulated yield (kg/ha)	Yield change (%)	Growth duration (days)
0[a]	0	335	0	8391	100	108
+4	+4	335	0	5517	66	99
-4	-4	335	0	9842	117	133
+4	+4	+20	0	5604	67	99
-4	-4	+20	0	9853	117	132
0	0	+20	0	8439	101	108
0	0	335	+1	8590	102	108
0	0	335	-1	8179	97	108
+4	+4	335	+1	5717	68	99
+4	+4	335	-1	5369	64	99
-4	-4	335	+1	9877	118	132
-4	-4	335	-1	9433	112	133
+4	+4	+20	+1	5814	69	99
-4	-4	+20	-1	9759	116	132
-4	-4	+20	+1	9583	114	132

[a]Standard treatment (120 kg N/ha continuous flooding)

It has been reported that the elevated CO_2 promotes dry-matter production in rice more than grain yield through the enhancement of net assimilation rate and leaf area, even if temperatures remain substantially high (Imai *et al.*, 1994). At elevated CO_2, light intensity positively affects photosynthesis and increased temperature promotes both photosynthesis and leaf area (Imai and Murata, 1979). Both the numbers and length of crown roots increase with elevated CO_2 because of increased photosynthates partitioning to roots. Scientific findings also suggest that net leaf photosynthesis rate of rice is substantially increased by temporary elevated CO_2 concentration (30-50% at 700-1000µl/l) when compared with the normal CO_2 level of about 350µl/l (Imai and Okamoto-Sato, 1991). This is caused by the suppression of photo-respiration by high CO_2 relative to O_2 in the atmosphere, and is progressed, within limit, under higher light intensity and temperature conditions (Imai and Murata, 1979), rather than the suppression of dark respiration rate (Imai and Nomura, 1992).

Sensitivity to climatic parameters in wheat

As compared to simulated wheat yield (5720 kg/ha) for the standard treatment, or the base run, the increase in yield was 15% higher with the reduction in both maximum and minimum temperature by $4^{O}C$, while the increment by $4^{O}C$ decreased the yield by 4%. Increased temperature decreased growth duration by 12 days, while decreased temperature increased growth duration by 16 days (Table 4).

Reduction of maximum and minimum temperatures by $4^{O}C$ with increment in solar radiation by 1 MJ/ m2/day, increased the yield by 22% and growth duration by 16 days revealing the interactive effect of temperature and solar radiation. The requirement of minimum temperature is important in wheat because the minimum vernalisation requirement for wheat is completed only in the presence of low temperature. The growth duration was shortened (only 144 days) and yield was decreased with the increment in temperature, irrespective of whether CO_2 concentration or solar radiation was increased or decreased. Increasing temperatures reduced growth duration, and probably decreased photosynthesis, increased water use, and reduced water use efficiency as reported by Imai (1988). The reduction of maximum and minimum temperatures by 4^{O}C along with increased CO_2 concentration by 20 ppm and increased solar radiation by 1MJ/m2/day increased the crop growth duration (172 days) as well as yield (7020 kg/ha). With 4^{O}C reduction in both maximum and minimum temperatures and with an increment of CO_2 concentration by 20 ppm, the increment in yield was 16%, while with increased temperature, and increased CO_2, the reduction in yield was only 3%. The increased temperature and reduced solar radiation decreased the net photosynthetic active radiant (PAR) interception (Figure 8). The less interception of PAR caused lower assimilate formation in wheat (Figure 9) and produced lower yield under increasing temperature and reduced light. Other studies also demonstrated that increased CO_2 concentration and decreased temperature increased growth duration and yield, while increased temperature shortened growth duration and reduced leaf area, biomass and yield (Timsina *et al.* 1997; Rao and Sinha, 1994; Qureshi and Iglesias, 1994).

Table 4. Sensitivity analysis of wheat with changes in temperature, CO_2 concentration and solar radiation

Max. Temp. (^{o}C)	Min. Temp. (^{o}C)	CO_2 Conc. (ppm)	Solar radiation (MJ/m^2/d)	Rainfall (mm)	Simulated yield (kg/ha)	Yield change (%)	Growth duration (days)
0[a]	0	335	0	0	5720	100	156
+4	+4	335	0	0	5483	96	144
-4	-4	335	0	0	6563	115	172
+4	+4	+20	0	0	5574	97	144
-4	-4	+20	0	0	6621	116	172
0	0	+20	0	0	5763	101	156
0	0	335	+1	0	5964	104	156
0	0	335	-1	0	5463	96	156
+4	+4	335	+1	0	5789	101	144
+4	+4	335	-1	0	4941	86	144
-4	-4	335	+1	0	6951	122	172
-4	-4	335	-1	0	6153	108	172
+4	+4	+20	+1	0	5842	102	144
-4	-4	+20	-1	0	6211	109	172
-4	-4	+20	+1	0	7020	123	172
0	0	335	0	x 1[b]	4622	100	156
0	0	335	0	x 0	3784	82	156
0	0	335	0	x 1.5	4950	107	156
0	0	335	0	x 2.0	5223	113	156

[a] Standard treatment -120 kg N/ha (40+40+40) with 390 mm irrigation water, [b] Standard treatment -120 kg N/ha (40+40+40) as rainfed

The sensitivity of wheat yield to rainfall showed that lowering the rainfall to zero on each day reduced wheat yield by 18%, but growth duration was unaffected. As compared to standard treatment (4622 kg/ha) wheat yield was increased to 4950 kg/ha (7% higher) by increasing the rainfall by 1.5 times (33.5 mm) and to 5223 kg/ha (13% higher) by doubling (46 mm) the rainfall on each day. It obviously highlights the significance of rainfall to rainfed wheat.

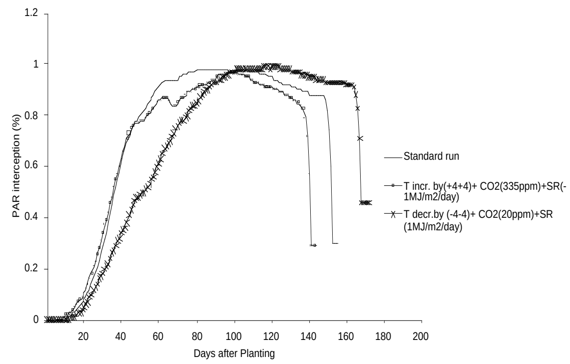

Figure 8. Simulated PAR interception in wheat as influened by changing climate

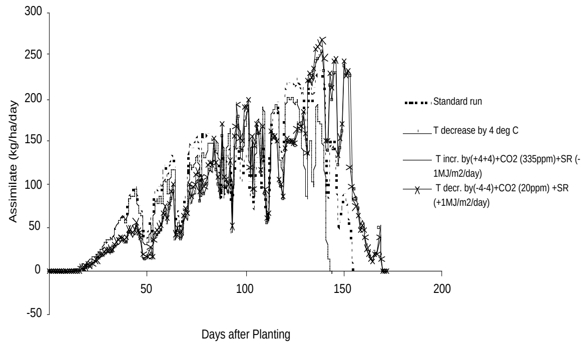

Figure 9. Simulated seasonal assimilate formed in wheat for various climate scenarious

CONCLUSIONS

The CSM-CERES-Rice and CSM-CERES-Wheat models (ver. 4.0) were sensitive to CO_2 and climatic parameters (temperature, solar radiation and rainfall) on the growth and yield of rice and wheat. The sensitivity tests indicated the year 2001/02 was good for both crops in the Punjab. Simulated yields of both crops were reduced by increasing both maximum and minimum temperature by $4^{O}C$ due to reduced growth duration, and was not compensated by increasing CO_2 concentrations by 20 ppm. Increased rainfall increased wheat yield under rainfed conditions. The increased maximum and minimum temperature, irrespective of whether the CO_2 concentration was increased or not, seemed to have more adverse effects on rice yield than on wheat. Closer investigations of model processes and more testing of the models would be required to better examine the sensitivity to various climatic parameters and to adapt to climate change in the future.

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