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Simulating Wheat Yield under Changing Temperature, Carbon Dioxide and Solar Radiation Levels in Bangladesh

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Abstract- The wheat crop in the tropical region will be most sufferers because of increased temperature in future. Calibrated and validated DSSAT (CERES-Wheat) model was used to evaluate the impact of increased temperatures (1-3°C), elevated CO_2 (450 and 550 ppm) levels and radiation changes (5% and 10% increase and decrease) on the yield of wheat in Bangladesh. The highest grain yield of 5194 kg ha^{-1} was obtained from BARI Gom-28 followed by BARI Gom-27 (4866 kg ha^{-1}) and BARI Gom-26 (4573 kg ha^{-1}) under existing temperature conditions. Wheat yield at Gazipur increased with elevated atmospheric CO_2 concentration but decreased with the increase in temperature. On an average, 11.95, 18.97 and 22.82 percent yield reductions were observed with 1, 2 and 3-degree rise in temperatures, respectively under ambient CO_2 level at Gazipur. About 2-4% yield compensations are likely if the CO_2 level is increased up to 550 ppm. In Dinajpur area, grain yield of wheat (BARI Gom-28) also reduced by about 6-25% depending on temperature rise.

Keywords: *wheat yield, CERES-wheat model, solar radiation, temperature, co_2 concentration, bangladesh.*

GJSFR-D Classification: *FOR Code: 070106*

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Simulating Wheat Yield under Changing Temperature, Carbon Dioxide and Solar Radiation Levels in Bangladesh

S. Ishtiaque [α], R. Sen [σ], M. A. H. S. Jahan [ρ], Apurba K. Choudhury [Ѡ], S. Akhter [¥], F. Ahmed [§], Jatish C. Biswas [χ], M. Manirruzaman [v], M. Muinnuddin Miah [Ө], M. M. Rahman [ζ], A. S. M. M. R. Khan [£], Naveen Kalra [€] & M. B. Hossain [₣]

Abstract- The wheat crop in the tropical region will be most sufferers because of increased temperature in future. Calibrated and validated DSSAT (CERES-Wheat) model was used to evaluate the impact of increased temperatures (1-3ºC), elevated CO_2 (450 and 550 ppm) levels and radiation changes (5% and 10% increase and decrease) on the yield of wheat in Bangladesh. The highest grain yield of 5194 kg ha^{-1} was obtained from BARI Gom-28 followed by BARI Gom-27 (4866 kg ha^{-1}) and BARI Gom-26 (4573 kg ha^{-1}) under existing temperature conditions. Wheat yield at Gazipur increased with elevated atmospheric CO_2 concentration but decreased with the increase in temperature. On an average, 11.95, 18.97 and 22.82 percent yield reductions were observed with 1, 2 and 3-degree rise in temperatures, respectively under ambient CO_2 level at Gazipur. About 2-4% yield compensations are likely if the CO_2 level is increased up to 550 ppm. In Dinajpur area, grain yield of wheat (BARI Gom-28) also reduced by about 6-25% depending on temperature rise. BARI Gom-28 gave the highest grain yield (5006 kg ha^{-1}) with 10% increase in solar radiation but, grain yield decreased and the yield was 4182 kg ha^{-1} with the reduction of solar radiation by 10%. About 4.43% and 7.70% yield increase was predicted if solar radiation increases by 5 and 10%, respectively compared to no radiation changes; whereas 4.94% and 10.02% yield reductions was simulated with 5 and 10% decrease in solar radiation, respectively. Reduction in solar radiation and rise in temperature would reduce wheat yield in Bangladesh, although increased atmospheric CO_2 levels might reduce the yield reduction rates.

Keywords: wheat yield, CERES-wheat model, solar radiation, temperature, co_2 concentration, bangladesh.

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I. Introduction

Wheat is one of the vital cereals in Bangladesh (BBS, 2014). In general, the productivity of wheat is lower compared to other parts of South Asia, which could be primarily because of short growth duration. Prevailing weather conditions largely dictate crop growth duration and, so does grain yield. Weather elements directly influence the physiological processes of the crop, which affect vegetative and, reproductive stages (Win, 2014). Inter and intra-seasonal variability in temperature, rainfall and, solar radiation may have a significant effect on growth and yield of wheat (Ahmed and Hassan, 2011). The global atmospheric temperature is increasing along with changes in CO2 concentration and depletion in the ozone layer, crop production will be affected significantly (IPCC, 2014).

Wheat yield, in general, depends on varietal character, inputs and agronomic management practices, soil properties and weather conditions. As wheat is a thermo-sensitive crop, and grown in the winter season in Bangladesh, the duration is relatively shorter. So, minimum temperature during January and maximum temperature in February determine the wheat yield (Aggarwal and Kalra, 1994; Kalra et al., 2008). Besides, solar radiation also influences the growth and yield of wheat (Kalra et al., 2006). Wheat yield reduction could be 400 kg ha^{-1} per 1°C increase in temperature (Rai et al., 2004). However, increase in atmospheric CO_2 level and, solar radiation has a positive effect on wheat yield. Increase in atmospheric CO_2 stimulates photosynthesis and inhibits photo-respiration in wheat (Amthor, 2001). The Combined effect of temperature, CO_2 concentration rise and solar radiation change is imperative for growth and yield of crops that can be simulated through models (Aggarwal et al., 2006; Aggarwal et al., 1994; Aggarwal and Kalra, 1994).

Crop model is a practical tool and has recently been accepted worldwide (Droogers and Hunink, 2012). It can put together weather, soils, genotype, and crop management that influence crop yield and economic returns. It can also be used in future climate change scenarios analyses that cannot be evaluated rapidly or economically through field experimentation (Clemente et al., 2005). A particular strength of crop model is its ability to quantify the variability of crop performance due to variability in seasonal weather conditions and to predict the long-term impacts of climate change and land use and land cover change options.

Increase in atmospheric temperature and CO_2 levels is a scientific fact and such situations will affect crop sector in Bangladesh. However, it is costly and time-consuming to create futuristic climate scenarios for studying climate change impacts on wheat production in Asian countries. DSSAT is a dynamic crop simulation model, which can competently be used to predict the performance of wheat against the changing climate. So, in the present study, DSSAT Version 4.6 (CERES-Wheat) was used to evaluate the interactions of temperature, CO_2 levels and radiation changes on wheat yield in Bangladesh.

II. Materials and Methods

a) Soil and climate of the experimental site

The simulation study was carried out at Bangladesh Agricultural Research Institute (BARI), at Gazipur (23.59°N and 90.24°E, and 8 m above mean sea level) and Dinajpur (25.63°N and 88.63°E, and 39 m above sea level). Soil characteristics of Gazipur and Dinajpur are shown in Table 1a & 1b and Table 2a & 2b, respectively. Gazipur soil belongs to Grey Terrace Soil, with silty clay loam texture and Dinajpur soil belongs to Grey Flood Plain Soil, having sandy loam texture. These values were used to develop particular profiles that to be added to Soil. Sol file use for running of DSSAT.

Climatic data were collected from the weather station of Gazipur and Dinajpur under the Department of Metrology, Government of Bangladesh. Daily values of various climatic elements (historical weather datasets) were used to prepare annual weather files, by running Weatherman- a module in DSSAT, required for running of the model. Monthly averaged maximum and minimum temperatures, total rainfall and sunshine hours of the two study sites Gazipur and Dinajpur were presented in Table 3a and 3b, respectively.

b) Model description

DSSAT v.4.6 model (CERES-Wheat Crop Simulation Model) was used for the present study. The model runs with six datasets viz. Soil file, Weather file, Genetic coefficients file, Experimental file (X file), Annual file (A) and Time-course file (T file) (Hoogenboom, 2000; Hoogenboom et al., 2003). Soil data includes soil characteristics such as site latitude and longitude, soil type and soil series, pH, bulk density, soil texture and soil nutrient status like N and C content. Weather file includes daily temperature (both maximum and minimum), humidity, solar radiation, rainfall, etc. DSSAT model requires some of crop management data (crop, variety, planting date, row and plant spacing, fertilizer levels, tillage practices and organic amendments) in the experimental file (X file) to simulate crop productivity. Data on physiological stages of crop growth such as anthesis date, days to maturity and grain yield were also included in Annual (A) file. The time course values of biomass, yield and leaf areas are used to prepare T file. These files were for calibration and validation and subsequent use in climate change impact analysis on wheat.

c) Impact evaluation of climate change on wheat

Four separate studies were simulated to predict climate change impact on wheat yield. Effect of temperature and CO_2 concentration on BARI Gom-25, BARI Gom-26, BARI Gom-27 and BARI Gom-28 at Gazipur location was studied. Temperature rises considered were 0, 1, 2 and 3°C and CO_2 levels were 380 and, 450 ppm Effects of increased temperatures (0, 1, 2 and 3°C) and CO_2 concentration (380, 450 and 550 ppm) on BARI Gom-28 were studied for Dinajpur location. Effect of solar radiation change on BARI Gom-26 yield was simulated by considering both reduction and increase in solar radiation (5 and 10%) and compared with no changes. Interaction effect of rising temperature and solar radiation on grain yield of BARI Gom-26 was studied considering 0, 1 and 2°C rise in temperature and 0 and 10% reduction in solar radiation.

d) Genetic coefficients

Genetic coefficients of BARI Gom-25, BARI Gom-26, BARI Gom-27 and BARI Gom-28 were computed by using GLUE module of DSSAT and are shown in Table 4. Here, P1V means optimum vernalizing temperature, required for vernalization expressed in days; PID indicates photoperiod response (% reduction in rate/10 h drop in pp). P5 means grain filling (excluding lag) duration (°C-d). G1, G2 and, G3 specify kernel number per unit canopy weight at anthesis (#/g), standard kernel size under optimum conditions (mg) and standard, non-stressed mature tiller wt (incl grain) (g dwt); respectively. PHINT indicates the interval between successive leaf tip appearances expressed in °C-d.

e) Model application

DSSAT Version 4.6 model (CERES-Wheat) was run for historic 30 years from 1980 to 2010 AD. Predicted wheat yields were generated using Seasonal Module run of DSSAT. Scenarios (on by historic runs) were collated to assess the sensitivity of the crop performance to changes in temperature, CO_2 concentration and, solar radiation.

III. Results and Discussions

a) Calibration and validation of DSSAT

Figure 1 shows the performance of the CERES-Wheat model based on observed and simulated yields of BARI Gom-25, 26, 27 and 28. The simulated yields were very close to observed yields and followed a 1:1 line, indicating that the model was performing well for simulating the yield of wheat grown in Bangladesh environment. The trend line showed satisfactory predictability as seen through high R^2 value.

b) Effect of temperatures and CO_2 concentration on wheat yield at Gazipur

The effects of elevated CO_2 concentration and temperature rise on grain yield of wheat are shown in Figure 2. Grain yield of all wheat varieties increased with the increase of CO_2 levels but decreased with higher temperatures. BARI Gom-28 gave the highest grain yield of 5194 kg ha^{-1} followed by BARI Gom-27 (4866 kg ha^{-1}) and BARI Gom-26 (4573 kg ha^{-1}) under no temperature increased conditions. The decrease in wheat yield because of temperature rise by 1, 2 and 3°C at 380 ppm CO_2 level was 11.95, 18.97 and 22.82 percent, respectively. In the same location with 550 ppm CO_2 concentration, simulated wheat yield reductions were 6.56%, -0.19% and -3.89% because of rising in temperature by 1, 2 and 3°C, respectively compared to ambient climatic conditions (Table 5). Similar findings were reported by Lobell et al. (2012) for northern India. Compensating yield factor for cereals under increased temperature conditions is often referred by the CO_2 fertilization (Boulidam, 2012).

Simulated average grain yields of wheat as influenced by increased temperature rise at varying CO_2 concentrations are prsented in Table 5. On average over varieties, about 10.58%, 16.92% and, 20.38% yield reductions were observed because of 1, 2 and 3°C temperature rise, respectively. Temperature plays a massive role for growth and yield of wheat (Aggarwal et al., 2006) and optimum temperature limit for physiological activities of wheat is probably exceeded in the tropical region (Hogan, 1991). Pre-anthesis and post-anthesis high-temperature stress reduced the photosynthetic efficiency of the crop (Wang et al., 2011) and thus reduces yields. You et al. (2009) also observed a significant reduction in wheat yield because of temperature rise. They reported 3-10% reduction in wheat yields due to 1.8°C rising in temperature.

Table 5 shows the fertigation effects of increased CO_2 levels on wheat yields. Up take of more CO_2 from the air by the plants are positivily influenced on growth processes (Ackerman and Stanton, 2013) and thus adverse effects of increased temperatures are compensated to a noticeable extent (Basak, 2010).

c) Effect of temperatures and CO_2 concentration on wheat yield at Dinajpur

Grain yield of BARI Gom-28 decreased with increase in temperature (Fig. 3). The highest grain yield was 5944 kg ha^{-1} at 380 ppm CO_2 under ambient temperature conditions. Irrespective of CO_2 levels, yield reductions were 6.74%, 17.46% and, 24.50%, respectively under 1, 2 and 3°C temperature rise. Temperature rise primarily reduces crop growth duration, especially grain filling duration and thus reduction in grain yield. Similar results were reported by Kalra et al. (2008) for wheat in New Delhi environment. Ackerman and Stanton (2013) also found similar trends of yield reduction because of elevated temperature. On the other hand, increased atmospheric CO_2 levels improved grain yield of wheat. The highest grain yield of BARI Gom-28 was 5327 kg ha^{-1} at550 ppm CO_2 concentration, which was followed by 450 ppm CO_2 (4837 kg ha^{-1}). The lowest grain yield was recorded 4499 kg ha^{-1} with existing CO_2 concentration of 380 ppm. Net availability of photosynthate is the driven force of plant growth and development. Photosynthesis is a process that absorbs CO_2 from the air and converts it into organic compounds such as sugars. If the limiting factor in this process is the amount of CO_2 available to the plant, then an increase in the atmospheric concentration of CO_2 could act as a fertilizer, providing additional nutrients and allowing faster growth. Growth could be limited by the availability of CO_2 in case of wheat as it is belonging to C_3 plant and it is responsive to CO_2 concentration resulting in increased growth and yield (Ainsworth et al., 2008; Ainsworth and McGrath, 2010).

Experimental data from greenhouse and laboratory studies also indicated that the photosynthesis, growth and water use efficiency of tropical plants increased at higher CO_2 levels (Hogan et al., 1991).

d) Effect of solar radiation change on the yield of wheat

Five levels of solar radiation changes like no change, 5% reduction, 10% reduction, 5% increase and

10% increase were investigated with BARI Gom-28 (Figure 4). Increased solar radiation showed a positive impact on grain yield of wheat. The highest grain yield (5006 kg ha^{-1}) of BARI Gom-28 was simulated when solar radiation was increased by 10% followed by 5% increase in solar radiation (grain yield was 4854 kg ha^{-1}). Grain yield decreased with the reduction in solar radiation. Reduction in solar radiation by 5% and 10% resulted in 4.94% and 10.02% decrease in grain yield, respectively. The yield increased 4.43% and 7.70% was predicted by the no radiation change. These findings corroborate the results of Ahemd et al. (2011), who reported yield response to changes in solar radiation intercepted by the canopy. Similar results were also reported by Kalra et al. (2006) while evaluating the effect of aerosols on the yield of wheat, rice and, sugarcane.

e) Effect of solar radiation reduction and temperature rise on the yield of wheat

The Combined effect of solar radiation reduction and temperature rise on grain yield of BARI Gom-26 is shown in Figure 5. The reduction in solar radiation and increase in temperature reduced wheat yield. The highest grain yield (4648 kg ha^{-1}) of BARI Gom-26 was predicted under no radiation change and, no temperature rise. Grain yield of wheat reduced by 11.42% because of the 1°C rise in temperature and it was 21.40% for 2°C temperature. Similarly, 10% reduction in solar radiation caused 9.87% yield penalty compared to ambient radiation condition. In case of 2°C temperature rise and 10% reduction in radiation, grain yield was only 3291 kg ha^{-1}, which was 29.20% lower than ambient conditions. Similar results have been reported by Ahmed et al. (2011) and Li et al. (2010). Because of enhanced industrial and other anthropogenic activities, the aerosols concentration is increasing in the atmosphere resulting in reduced solar radiation (direct plus diffused) reaching the earth's surface. Developing the climate change scenarios is the changes in temperature and humidity are also associated with the presence of aerosol, its needs to be consider because cooling phenomenon may take place.

IV. Conclusion

Climate change and climatic variability are concerns for Bangladesh, where the frequency of occurrence of extreme climatic/episodic events have increased over the last couple of decades. There is a need to understand the interaction of changes in various climatic elements for growth and yield of wheat. DSSAT Version 4.6 was used for evaluating the interaction amongst temperature rise, solar radiation changes and increase in CO_2 levels. Four varieties of wheat, commonly grown in this region, were undertaken. The model was calibrated and validated for two growing environments of Bangladesh viz. Gazipur and Dinajpur. The model was subsequently run with historical weather (past 30 years) data on temperature, radiation and, CO_2 concentration. In general, wheat yield decreased with the increase in temperature, primarily because of reduced crop growth duration. Elevated CO_2 could nullify the effect of increased temperature to some extent. The decrease in solar radiation, which is expected due to enhanced industrial and other anthropogenic activities, likely to decrease wheat yield further. The results from the present investigations indicated significant interaction amongst these prime climatic elements towards the realization of the wheat yield, and also demonstrating the potential of crop simulation models, DSSAT, in assessing the impact of climate change and its variability on growth and yield of crops and cropping systems.

Acknowledgements

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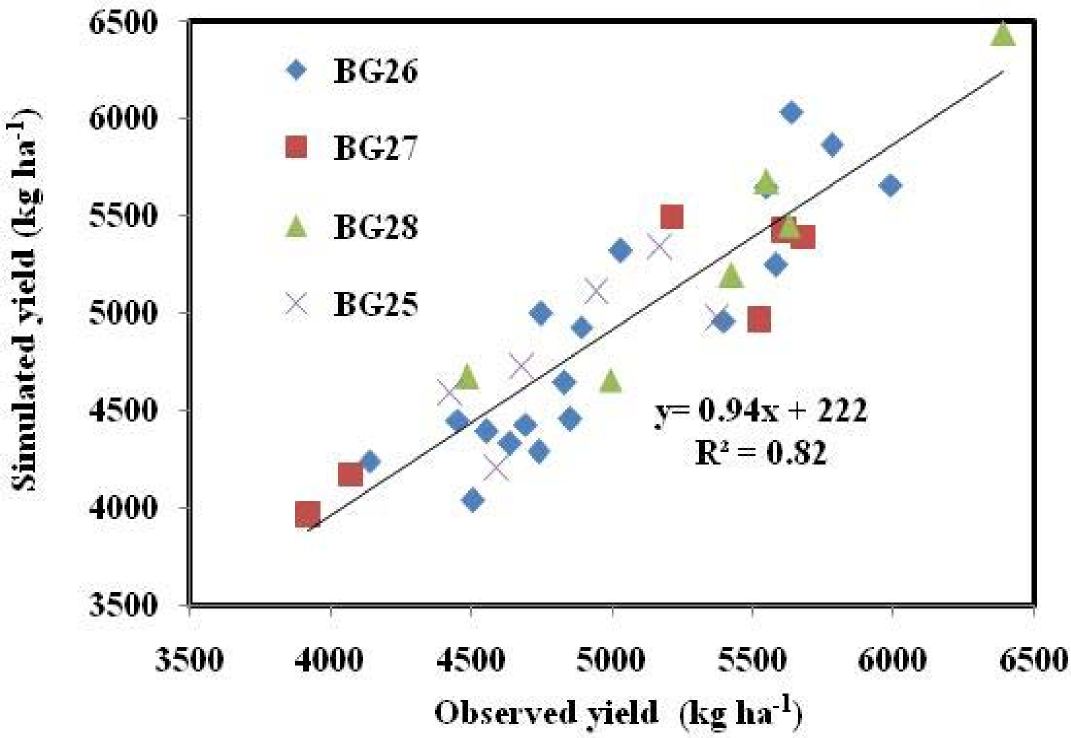

Fig. 1: Performance of CERES-Wheat model based on observed verses simulated yield of BARI Gom-25, 26, 27 and 28

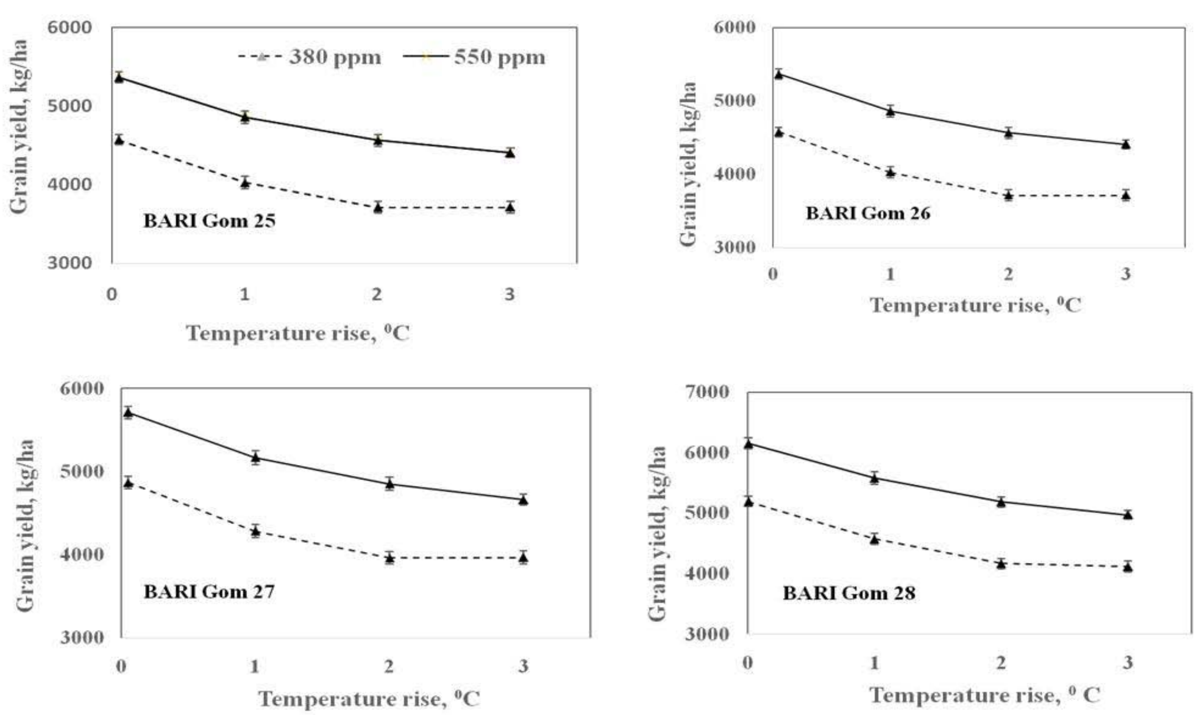

Fig. 2: Effect of increased temperature and CO_2 concentration on grain yield of wheat varieties at Gazipur, Bangladesh

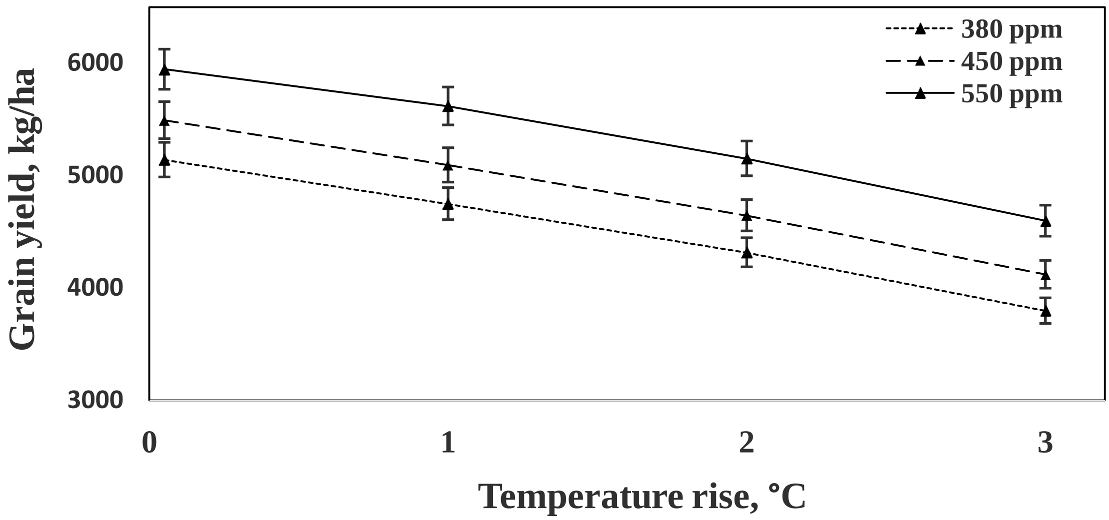

Fig. 3: Effect of increased temperatures and CO_2 concentrations on grain yield of BARI Gom-28 at Dinajpur (30 years run)

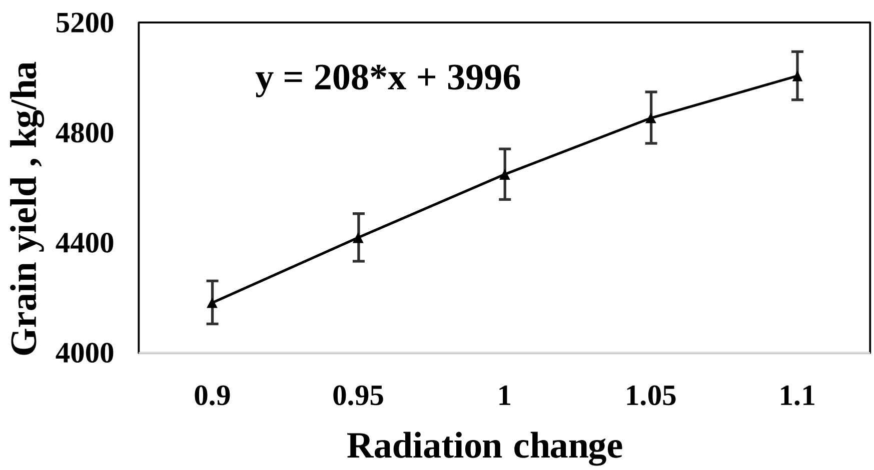

Fig. 4: Effect of solar radiation changes on grain yield of BARI Gom-26 (30 years run) at Gazipur

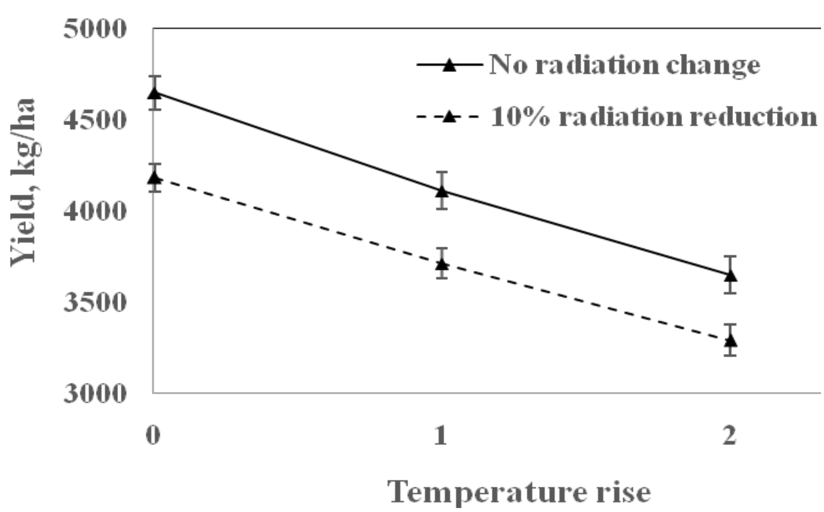

Fig. 5: Eeffect of solar radiation reduction and temperature rise on grain yield of wheat BARI Gom-26 (30 years run) at Gazipur

Table 1a: Physical properties of experimental soil (Gazipur location)

Soil layer (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk density (Mg m^{-3})
0-15	30.84	46.42	22.74	1.52
15-30	20.84	47.35	31.81	1.53
30-60	20.48	40.24	39.28	1.56
60-90	23.48	43.71	32.81	1.57
90-120	19.84	42.35	37.81	1.61
120-150	18.84	45.21	35.95	1.63
150-180	19.36	46.28	34.36	1.66

Table 1b: Chemical properties of experimental soil (Gazipur location)

Soil-layer (cm)	pH	Organic carbon (%)	Total N (%)	NO_3^- N (mg kg^{-1})	NH_4^+ N (mg kg^{-1})	Available phosphorous (mg kg^{-1})	Available potassium (meq/100g)
0-15	6.1	1.04	0.11	11.4	1.8	9.06	0.29
15-30	6.2	0.93	0.09	9.8	2.0	8.78	0.27
30-60	6.2	0.77	0.08	7.6	2.2	7.11	0.24
60-90	6.3	0.52	0.06	6.4	2.4	5.63	0.22
90-120	6.4	0.46	0.05	5.3	2.6	5.09	0.18
120-150	6.5	0.41	0.04	4.9	2.8	3.89	0.15
150-180	6.7	0.36	0.03	4.1	2.9	3.21	0.14

Table 2a: Physical properties of experimental soil (Dinajpur location)

Soil layer (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk density (Mg m^{-3})
0-15	61.0	22.7	16.3	1.49
15-30	66.3	11.7	27.3	1.57
30-60	58.3	11.0	30.7	1.59
60-90	55.9	9.4	34.7	1.61
90-120	67.3	14.4	18.3	1.62
120-150	74.3	6.4	19.3	1.67
150-180	74.3	6.3	19.4	1.69

Table 2b: Chemical properties of experimental soil (Dinajpur location)

Oil layer (cm)	pH	Organic carbon (%)	Total N (%)	NO_3^-N (ppm)	NH_4^+N (ppm)	Available phosphorous (ppm)	Available potassium (meq $100g^{-1}$)
0-15	6.1	0.49	0.05	9.8	2.0	6.27	0.26
15-30	6.2	0.28	0.03	7.3	2.1	6.03	0.24
30-60	6.2	0.19	0.02	5.1	2.2	5.18	0.22
60-90	6.3	0.14	0.01	4.7	2.5	4.83	0.19
90-120	6.4	0.13	0.01	4.3	2.7	3.98	0.16
120-150	6.5	0.12	0.01	3.5	3.2	3.19	0.15
150-180	6.7	0.10	0.01	3.0	3.4	2.88	0.13

Table 3a: Weather normals of Gazjpur during growing season of wheat (30 years average)

Month	Average temperature (ºC)		Total rainfall (mm)	Average sunshine hour
	Maximum	Minimum		
November	30.1	16.1	26.1	7.29
December	26.0	12.6	8.2	6.62
January	24.8	12.6	6.5	6.83
February	28.5	14.7	18.9	7.62
March	32.5	18.9	44.8	8.05
April	33.3	21.2	135.1	7.85

Table 3b: Weather normals of Dinajpur during growing season of wheat (30 years average)

Month	Average temperature (°C)		Total rainfall (mm)	Average sunshine hour
	Maximum	Minimum		
November	29.0	16.6	15.3	7.22
December	25.1	12.2	6.9	6.49
January	22.9	10.4	5.9	5.94
February	26.5	13.0	12.7	7.51
March	30.9	17.4	11.4	7.89
April	32.9	21.1	65.7	7.41

Table 4: Genetic coefficients of tested wheat varieties

Variety	P1V	P1D	P5	G1	G2	G3	PHINT
BARI Gom-25	0	92	725	23	46	3.6	70
BARI Gom-26	0	92	730	23	46	3.8	70
BARI Gom-27	0	93	740	24	46	3.9	70
BARI Gom-28	0	96	750	25	47	3.9	70

Table 5: Average (four varieties and historic years) grain yields of wheat as influenced by temperature rise at varying CO_2 levels (figures in parenthesis indicate percent change in yields over ambient condition)

CO_2 concentration	Temperature rise (°C)			
	0	1	2	3
380 ppm	4802	4228 (-11.95)	3891 (-18.97)	3706 (-22.82)
550 ppm	5649 (17.64)	5117 (6.56)	4793 (-0.19)	4615 (-3.89)

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