J. Agr. Sci. Tech. (2023) Vol. 25(3): 661-672

Sensitivity Analysis of Wheat Cultivar HD2967 to Weather Parameters Using CERES-Wheat Model

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ABSTRACT

This study was conducted to examine the sensitivity of weather parameters and CO_2 concentration to wheat production under two irrigation regimes *viz.* full irrigation and limited irrigation, using CERES-Wheat model. Field experiment data from the 2016-17 and 2017-18 *rabi* seasons on wheat cultivar HD-2967 with three sowing dates and five irrigation regimes were used to calibrate and validate the CERES-Wheat crop simulation model. Validation results indicated very good agreement between simulated and observed values under five, four, and three irrigations regimes as compared to lower irrigation regimes. Under full irrigation and limited irrigation, grain yield sensitivity to incremental unit of mean temperature from 1 to 3°C revealed a decrease of 6 to 22% and 8 to 16%, respectively. Temperature decreases of 1-3°C resulted in a gradual increase in yield of 10-28 and 6.5- 20%, respectively, under full and limited irrigation. The combined effect of higher mean temperature and lower solar radiation revealed that wheat yield was more sensitive to temperature than solar radiation. Furthermore, the combined effect of mean temperature and CO_2 level revealed that higher levels of CO_2 concentration yielded the greatest benefits with a 1 °C increase in temperature, but further increases in temperature reduced the beneficial effect of elevated CO_2 level under both irrigation conditions.

Keywords: CO_2 concentration, DSSAT, Food security, Solar radiation, Temperature effects, *Triticum aestivum* L..

INTRODUCTION

Climate change and climatic variability are the primary cause of variations in global food production. The growth and development of plants are directly related to interactions of various environmental factors (Oseni and Masarirambi, 2011; Kersebaum and Nendel, 2014). A plant will behave and respond differently in different interactions. According to the sixth Assessment Report (AR6) of the Inter-Governmental Panel on Climate Change (IPCC, 2021), global surface temperatures will continue to rise until at least the mid-century under all climate change scenarios. The IPCC report also predicted a decrease in water availability for food production in arid and semi-arid regions (IPCC, 2014). Weather changes will have a significant impact on food availability, accessibility, and utilization, directly affecting global food security (Gu *et al*., 2010).

Wheat (*Triticum aestivum* L) is India's most widely grown food grain crop. It plays a very critical role in nutritional and food security of the country, as it is the second most important cereal crop after rice, contributing to 13% of the global wheat supply (Zaveri and Lobell, 2019). Wheat production can be impacted by climate change both directly and indirectly. The biggest obstacle to future wheat production, according to recent studies on climate changes projected by Global Climate Models (GCMs), is increasing heat stress and lack of water available for irrigating crops (Jahan *et al.,* 2014). Wheat crops generally progress more quickly to anthesis and maturity as temperatures rise, and have a shorter growth

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[DOI: 10.22034/jast.25.3.661]

period resulting in less time available for grain-filling, which ultimately leads to poor grain yield (Jahani Doghozlou and Emam, 2022). Deficit irrigation is used for growing crops under limited water supply conditions. Several studies have found that targeting irrigation applications to the most vulnerable growth stages increases crop productivity and water use efficiency (Geerts and Raes, 2009; Li-li *et al.*, 2018; Bisht and Shaloo, 2022).

The Decision Support System for Agrotechnology Transfer (DSSAT) embedded with CERES-Wheat (Ritchie *et al*., 1988) is a process-based simulation model that allows users to quantify crop yield variability in response to seasonal weather variability and climate change impacts (Rosenzweig *et al*., 2014; Liu *et al*., 2016). Process-based crop simulation models are useful tools for quantifying the effects of climate change and developing effective adaptation and mitigation strategies (He *et al*., 2018; Qian *et al*., 2019), because they take into account the interaction between climatic variables and crop management and their effects on crop productivity. Using mathematical equations, these models can dynamically and quantitatively describe the process of crop growth, development, and yield formation. A crop simulation model that has been well calibrated and validated can be used as a technological tool to simulate crop growth and yield under various irrigation regimes (Hoogenboom *et al.*, 2010; Pal *et al.*, 2015). The goal of this research was calibrating and validating the CERES-Wheat crop simulation model for simulating wheat growth and yield, as well as to assess the sensitivity of growth and yield to weather parameters under full and limited irrigation regimes.

MATERIALS AND METHODS

Details of Field Experiments and Data Collection

Field experiments on wheat cultivar HD-2967 were conducted during the 2016-2017 and 2017-2018 *Rabi* seasons at the Water Technology Centre, ICAR-Indian Agricultural Research Institute (IARI), New Delhi (latitude: 28° 38' 23" N, longitude: 77° 09' 27" E). The crop was sown in a split plot design in sandy loam soil, with three dates of sowing as the main plot treatments and five irrigation levels as subplot treatments. The three dates of sowing were 15th November, 30th November, and 15th December. The irrigation regimes were, I_1: Crown Root Initiation (CRI), I_2: CRI and tillering, I_3: CRI, tillering, and jointing, I_4: CRI, tillering, jointing, and flowering, and I_5: CRI, tillering, jointing, flowering, and dough stage. CRI is the transition zone between root and shoot and is the critical stage for the first irrigation to the standing crop, which occurs 20-25 days after sowing. The rate of irrigation was 50 mm at each specified stage. The rate of irrigation at different stages under different irrigation regimes is shown in Table 1. Fertilizer doses of Nitrogen (N), Phosphorus (P_2O_5), and potassium (K_2O) were applied at the recommended rates of 120, 60, and 40 kg ha^{-1}, respectively. The full doses of P_2O_5 and K_2O, as well as half the dose of N, were applied as basal doses at the time of sowing, with the remaining half dose of N top dressed in equal amounts during the crop's tillering and booting stages.

The dates of major phenological stages viz. emergence, tillering, jointing, flowering and dough stage were determined by observing the crop every day for each plot based on the Zadoks scale (Zadoks *et al.*, 1974; Tottman, 1987). Plant population (plants m^{-2}) was counted from an area of 1 m^2 of each plot approximately 20 to 30 days after sowing. The aboveground biomass was sampled by carefully digging all plants from a 10 cm row length of selected area of each experimental plot. Tiller numbers were recorded from the same sample by counting for each plot. Stem, leaves and spikes of the plants were separated and sun dried for 3-4 days to lose excess moisture, then, separately placed in brown paper bags and oven dried at 60°C for 48 hours till the

[DOI: 10.22034/jast.25.3.661]

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samples attained a constant weight (Jaradat, 2009). Subsequently, the dry weight of stems, leaves and spikes was recorded to determine the dry matter partitioning of biomass at different growth stages. During the entire growth period, the Leaf Area Index (LAI) was measured seven days apart using a Canopy Analyzer (LP-80). The aboveground biomass and grain yield at harvest were calculated by harvesting an area of 1 m^2 from each experimental plot and converting it to hectare. The data pertaining to the physical and chemical properties of soil of the experimental field were obtained from the published literature (Ajdary *et al.*, 2007). The daily maximum and minimum air temperature, sunshine hours, and rainfall were obtained from the ICAR-Indian Agricultural Research Institute's Agrometeorological Observatory in New Delhi, India. The ambient weather conditions during *rabi* seasons of 2016-2017 and 2017-2018 are shown in Figure 1.

Description of the Model Used

The CERES-Wheat model of DSSAT (Decision Support System of Agrotechnology Transfer) version 4.6 was used to simulate growth and yield using crop characteristics, weather/climate, soil, and management data from field experiments (tillage, sowing, plant population, irrigation and fertilizer schedule, harvest schedule etc.) (Hunt *et al.,* 2001). Based on radiation interception, degree-day accumulation, soil water and N balance, and environmental stresses, the model simulates growth and yield (Jones *et al.,* 2003).

CERES-Wheat Model Calibration and Validation

For model calibration, wheat experimental data from the year 2016-2017 of the treatment combination of full Irrigation (I_5) regime and 15th November sowing date, as well as soil and weather data, were used. The genetic coefficients were derived for wheat variety HD 2967 iteratively using the GLUE coefficients estimator option of the DSSAT version 4.6 software. The model was then validated by running it with independent data from the remaining treatment combinations of the field experimentation in 2016-2017 and all treatment combinations in 2017-2018. The performance of the CERES-Wheat model was then assessed using two statistical indices: RMSEn (normalized Root Mean Square Error) and d index (index of agreement):

$$RMSEn = \frac{\sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}} \times 100}{\bar{O}}$$

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(|S_i'| + |O_i'|)^2}\right], \quad 0 \le d \le 1$$

Where, *Si*= Simulated value of i^{th} measurement, *Oi*= Observed value of i^{th} measurement, $\bar{O}$= The mean of Observed values, *n*= Number of observations, $S_i' = S_i - \bar{O}$, and $O_i' = O_i - \bar{O}$.

Sensitivity Analysis

The calibrated and validated model was used to assess the sensitivity of model output (phenology and grain yield) to weather parameters. Sensitivity analysis indicates how “sensitive” are the model output parameters to changes in the input parameters. Mean temperature (±1 to ±3°C), solar radiation (±1 to ±3 MJ m^{-2} d^{-1}) and CO_2 concentration (+100, +200, +300 and +400 ppm above the current concentration of 400 ppm) were chosen for sensitivity analysis. The analysis was performed for two irrigation scenarios *viz*. (1) Full irrigation (five irrigations i.e. I_5– Irrigation at crown root initiation, tillering, jointing flowering and dough stage) and (2) Limited irrigation (three irrigations i.e. I_3– Irrigation at crown root initiation, tillering and jointing) under sowing date of 15th November. Thereafter, the model was run

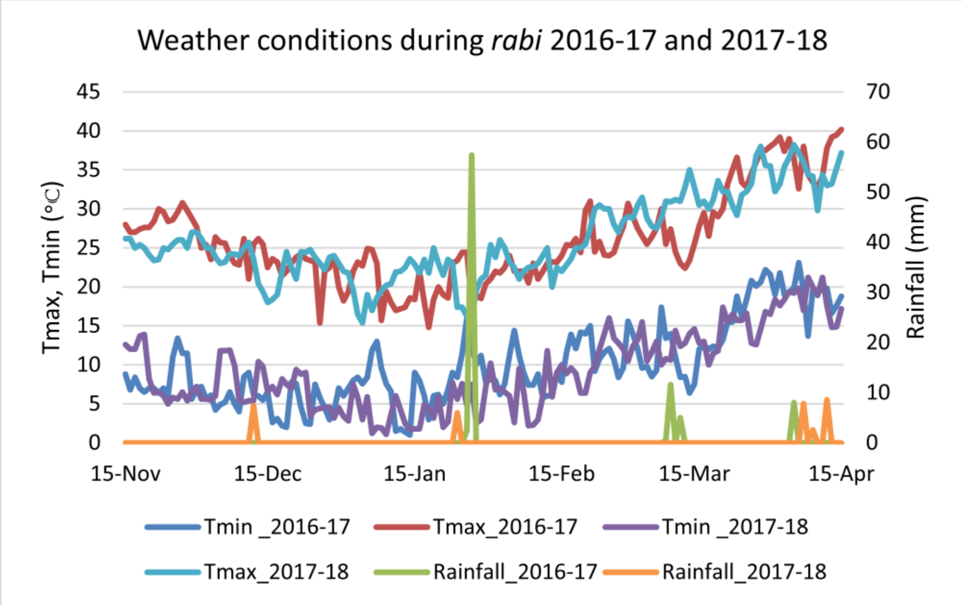


Figure 1. Temperature and rainfall conditions during *rabi* seasons of 2016-2017 and 2017-2018.

Table 1. Irrigation rate at various stages under various irrigation regimes.

Irrigation regimes	Irrigation (mm) applied at different stages					Total irrigation applied (mm)
	CRI	Tillering	Jointing	Flowering	Dough stage	
I_1	50	-	-	-	-	50
I_2	50	50	-	-	-	100
I_3	50	50	50	-	-	150
I_4	50	50	50	50	-	200
I_5	50	50	50	50	50	250

for these combinations of irrigation scenarios and sowing date under the present weather and CO_2 conditions as well as changed weather and CO_2 conditions. The percent change in the output of model under present weather and CO_2 conditions were computed with respect to the output of the present weather and CO_2 conditions for both irrigation scenarios.

RESULTS AND DISCUSSION

In the calibration process, genetic crop coefficients were generated for wheat cultivar HD 2967 and the model was fine tuned for simulating the growth and yield of wheat. The model provided very accurate estimates for phenology [anthesis and physiological maturity (DAS)], grain yield, biomass yield, and maximum Leaf Area Index (LAI) (Bisht and Shaloo, 2022). Further, the calibrated CERES-Wheat model was validated for simulating the anthesis (DAS), physiological maturity (DAS), maximum LAI and grain yield under different irrigation treatments (Table 2). Results of validation showed very good agreements between simulated and observed values for phonological stages as well as grain yield under higher irrigation regimes i.e. I_5, I_4 and I_3 [*i.e.*, Anthesis (DAS) RMSEn= 1.22, 1.79 and 2.55%, d= 0.99, 0.98 and 0.97; Physiological maturity (DAS) RMSEn= 1.92, 2.35 and 4.31%, d = 0.98, 0.97 and 0.92; Maximum LAI RMSEn= 10.4, 12.9 and 17.6%, d = 0.91, 0.82, 0.69; Grain yield (kg ha^{-1}) RMSEn= 3.1, 6.6 and 8.1%, d= 0.99, 0.95 and 0.89, respectively], however, poor agreements were observed under lower irrigation regimes such as I_1 and I_2.

[DOI: 10.22034/jast.25.3.661]

Sensitivity Analysis

Effect of temperature change on phenology and grain yield

The phenology of a crop refers to the timing of its different growth stages, such as germination, anthesis, and physiological maturity. Temperature is the primary driving variable for plant phenological development: increasing and decreasing temperatures can have significant effect on phenology and growth duration of wheat (Table 3). The results indicated that increased mean temperature by 1 to 3°C reduced anthesis timing by 6 to 17 days and 5 to 15 days under both full and limited irrigation, respectively. Similarly, the drastic reduction in timing of physiological maturity was observed by increasing mean temperature from 1 to 3°C. High temperatures, in general, influence phenological processes, shorten crop growing-periods, and thus limit the crop's ability to intercept solar radiation (Xiao *et al*., 2015). On the other hand, decreasing temperature from 1 to 3°C increased the timing of anthesis and physiological maturity by 8 to 24 days and 7 to 23 days, respectively, under full irrigation and 7 to 20 days and 5 to 18 days, respectively, under limited irrigation conditions. Therefore, increasing temperatures reduced growth duration of wheat, while decreasing temperature increased growth duration of wheat.

Grain yield sensitivity to incremental unit of mean temperature from 1 to 3°C resulted in a gradual decline in crop yield under both full (6-22%) and deficit (8-16%) irrigation conditions (Figure 2). In contrast, temperature reductions of 1 to 3 °C resulted in a gradual increase in grain yield of 10-28 and 6.5-20.3% under full irrigation and deficit irrigation conditions, respectively (Figure 2). Such behavior of the CERES-wheat model was primarily due to a decrease in wheat growth duration with an increase in mean temperature and vice versa. Haris *et al*. (2013) and Jahan *et al*. (2018) reported similar findings, namely, that higher temperatures during the growing season reduced growth duration, lowering wheat grain yield, and vice versa.

Effect of Radiation Change on Grain Yield

Increased solar radiation from 1 to 3 MJ m^{-2}

Table 2. Validation results of CERES-Wheat model.

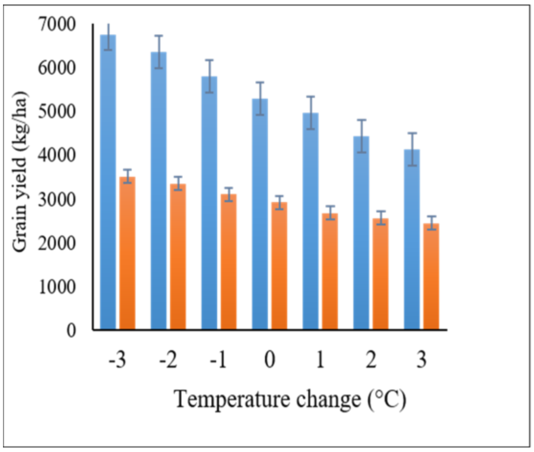
Treatments	Anthesis (DAS)				Physiological maturity (DAS)			
	S_{mean}	O_{mean}	RMSEn (%)	d	S_{mean}	O_{mean}	RMSEn (%)	d
I5	103	102	1.20	0.99	127	125	1.92	0.98
I4	104	102	1.79	0.98	127	124	2.35	0.97
I3	103	100	2.55	0.97	125	120	4.31	0.92
I2	101	93	9.3	0.60	134	117	14.81	0.51
I1	101	93	8.7	0.61	133	117	15.08	0.52
	Maximum LAI				Grain yield (DAS)			
Treatments	S_{mean}	O_{mean}	RMSEn (%)	d	S_{mean}	O_{mean}	RMSEn (%)	d
I5	5.75	5.05	10.4	0.91	4740	4643	3.06	0.99
I4	5.85	5.20	12.88	0.82	4464	4221	6.56	0.95
I3	4.35	4.00	17.59	0.69	2696	2552	8.12	0.89
I2	3.59	2.97	22.9	0.61	2015	1614	25.13	0.62
I1	3.55	2.6	26.9	0.50	1755	1394	26.84	0.48

S_{mean}: Mean of model Simulated values, O_{mean}: Mean of Observed experimental values

[DOI: 10.22034/jast.25.3.661]

Table 3. Effect of change in mean temperature on phenology of wheat.

Change in Temperature (°C)	Change in anthesis (DAS)		Change in physiological maturity (DAS)	
	Full irrigation	Limited irrigation	Full irrigation	Limited irrigation
+1	-6	-5	-5	-4
+2	-11	-8	-12	-11
+3	-17	-15	-18	-16
-1	8	7	7	5
-2	16	14	14	12
-3	24	20	23	18



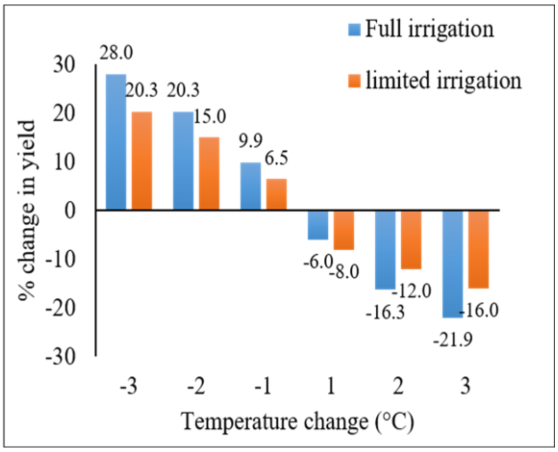


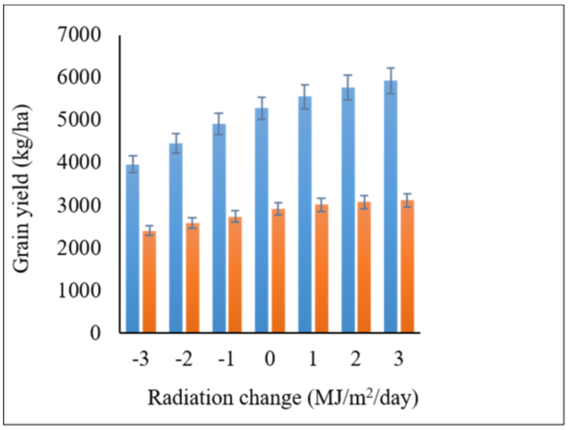
Figure 2. Effect of change in mean temperature on grain yield of wheat.

d^{-1} increased grain yield by 5 to 12%, while decreased solar radiation from 1 to 3 MJ m^{-2} d^{-1} resulted in a 7 to 24% decrease in wheat grain yield under full irrigation conditions (Figure 3). Similarly, for the limited irrigation conditions, the same results were noticed. Zhao *et al.* (2017) found similar results, reporting that increasing solar radiation by 1 MJ/m^2/day increased wheat yield by 154 kg ha^{-1}. The negative effects of reduced solar radiation on wheat yield (Yadav *et al*., 2017) could be due to a reduction in Photosynthetically Active Radiation (PAR) available for biomass and yield production, and vice versa (Chen *et al.*, 2012).

Interactive Effects of Mean Temperature and Solar Radiation

The interactive effect of change in mean temperature and solar radiation is shown in Table 4. According to the findings, increasing the temperature by 1 to 3°C and decreasing the solar radiation level by 1 to 3 MJ m^{-2} d^{-1} reduced wheat grain yield significantly. The increase in temperature caused a greater reduction than the decrease in solar radiation, which revealed that the grain yield was more sensitive to temperature change while relatively less sensitive to radiation change. The simulated results revealed that crop yield was reduced due to decreased solar radiation and shortened crop growth period caused by temperature increase (Chen *et al*., 2012). The reduced solar radiation and increased temperature reduced the interception of net Photosynthetic Active Radiation (PAR). Less PAR interception resulted in lower biomass production, resulting in lower yield in wheat under increasing temperature and reduced light. Hundal and Kaur (2007) and Yadav *et al*. (2015) also reported similar findings.

[DOI: 10.22034/jast.25.3.661]



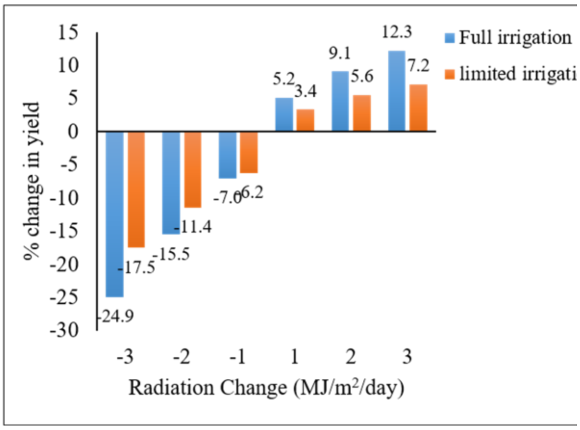


Figure 3. Effects of change in solar radiation on grain yield of wheat.

Table 4. Interactive effects of mean temperature and solar radiation on grain yield**.**

Temperature change (°C)	Radiation change (MJ m^{-2} d^{-1})	Change in yield (%)	
		Full irrigation	Limited irrigation
+1	-1	-10.0	-7.2
	-2	-15.4	-11.2
	-3	-22.5	-16.2
+2	-1	-19.3	-14.8
	-2	-22.2	-18.3
	-3	-24.5	-22.6
+3	-1	-29.7	-24.4
	-2	-32.4	-27.8
	-3	-36.5	-31.1

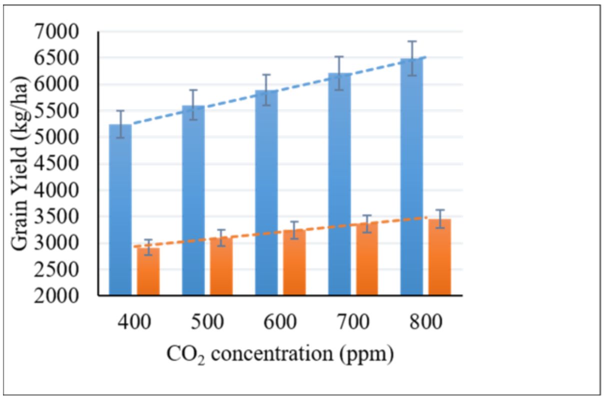
Effects of Elevated CO_2 Concentration

Under both full and deficit irrigation conditions, the gain yield increased when the CO_2 concentration was increased by 100 to 400 ppm over the current concentration of 400 ppm. (Figure 4). The increase in grain yield was 6.9 to 23.8% under full irrigation and 6.2 to 18.8% under deficit irrigation condition. The enhanced grain yield with elevated CO_2 concentration may be attributed to higher net photosynthesis rate and reduced transpiration rate per unit area, which often enhances crop water use efficiency (Beadle *et al*., 1993).

Interactive Effects of Temperature and CO_2 Concentration

The combined effect of temperature and CO_2 concentration on grain yield of wheat is depicted in Table 5. The results revealed that the beneficial effects of elevated CO_2 concentrations were obtained with 1°C increase in mean temperature, but further increase in mean temperature reduced the beneficial effect under both conditions. At lower concentrations, i.e., 500 ppm, a reduction in gain yield was observed even with a 1°C increase in mean temperature, indicating a high sensitivity of wheat yield to temperature changes. The 3°C increase in mean temperature almost cancelled out the

[DOI: 10.22034/jast.25.3.661]



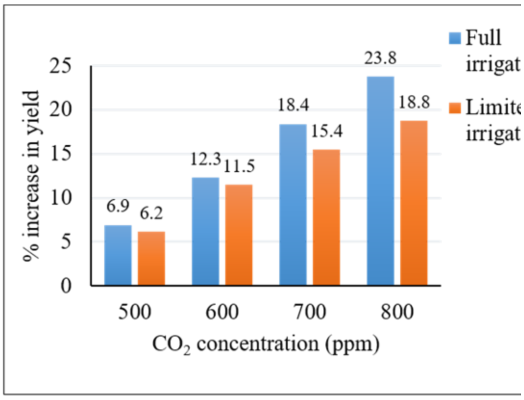


Figure 4. Effect of elevated CO_2 concentration on grain yield.

positive effect of higher CO_2 concentration (800 ppm), resulting in a 2% increase in grain yield under full irrigation and a 4.4% decrease under deficit irrigation. Further, the relatively more reduction in yield was under deficit irrigation as compared to full irrigation, which indicated that water stress combined with the temperature stress would offset to a great extent, the positive effect of higher CO_2 concentration on wheat grain yield. Other researchers (Leakey *et al*., 2009; Lobell *et al*., 2012; Mohanty *et al*., 2015) found that as temperature increased, wheat yield decreased, but elevated CO_2 levels increased yield due to increased photosynthetic activities, which may compensate for the negative effect of temperature. However, the yield increase due to elevated CO_2 level are variable with increased temperature (Kimball, 2016) because higher temperatures can reduce plant growth by increasing the rate of respiration faster than the rate of photosynthesis (Högy and Fangmeier, 2008). Thus, the increased CO_2 level to some extent can minimize the negative impacts of increased temperature, but the effect is dependent on the specific temperatures and CO_2 levels (Anwar *et al*., 2007**;** Chandran *et al*., 2021; Jägermeyr *et al*., 2021).

CONCLUSIONS

The study's primary goal was to assess the sensitivity of CERES-Wheat to weather parameters under different irrigation regimes. The findings revealed that temperature had a significant impact on yield and was found to be highly sensitive to wheat yield. A moderate increase in temperature resulted in gradual decrease in yield, while the temperature reduction showed a gradual increase in yield. The interactive effect of temperature and solar

Table 5. Interactive effects of temperature and CO_2 concentration on grain yield.

Change in mean temperature(°C)	% Change in simulated yield							
	CO_2= 500 ppm		CO_2= 600 ppm		CO_2= 700 ppm		CO_2= 800 ppm	
	Full irrigation	Limited irrigation	Full irrigation	Limited irrigation	Full irrigation	Limited irrigation	Full irrigation	Limited irrigation
+1	-0.2	-3.6	6.4	0.9	11.5	11.2	14.1	12.4
+2	-4.5	-10.3	-0.8	-6.8	2.0	-3.4	5.8	-1.6
+3	-10.0	-14.0	-5.1	-10.5	0.1	-7.8	2.1	-4.4

[DOI: 10.22034/jast.25.3.661]

radiation showed that the grain yield was more sensitive to temperature increase than decrease in radiation, strengthens and ascertains the argument in favor of water availability for consumptive use. Further, interactive effect of temperature and CO_2 concentration indicated that the beneficial effect of CO_2 varies with the temperature increase.

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[DOI: 10.22034/jast.25.3.661]

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[DOI: 10.22034/jast.25.3.661]

تجزیه و تحلیل حساسیت کولتیوار HD2967 گندم به پارامترهای آب و هوا با استفاده از مدل CERES-Wheat

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چکیده

این پژوهش با هدف بررسی حساسیت تولید گندم به پارامترهای آب و هوایی و غلظت CO_2 در دو رژیم آبیاری شامل آبیاری کامل و آبیاری محدود با استفاده از مدل CERES-Wheat انجام شد. برای واسنجی و اعتبارسنجی مدل شبیه‌سازیCERES-Wheat ، از داده‌های آزمایش مزرعه‌ای از فصل ربی(rabi) ۱۷-۲۰۱۶و ۱۸-۲۰۱۷ روی کولتیوار HD-2967 گندم با سه تاریخ کاشت و پنج رژیم آبیاری استفاده شد. نتایج اعتبارسنجی نشان‌دهنده تطابق بسیار خوبی بین اعداد شبیه‌سازی شده و مشاهده‌شده در رژیم‌های آبیاری پنج، چهار و سه نوبت آبیاری در مقایسه با رژیم‌های آبیاری کمتر بود. در آبیاری کامل و آبیاری محدود، حساسیت عملکرد دانه به هر واحد افزایشی دمای‌میانگین از ۱ تا ۳ درجه سانتی گراد به ترتیب ۶% تا ۲۲% و ۸% تا ۱۶% کاهش یافت. کاهش دمای ۳-۱ درجه سانتی گراد باعث افزایش تدریجی عملکرد به ترتیب ۲۸-۱۰% و ۲۰- ۶.۵% در شرایط آبیاری کامل و محدود شد. اثر توام میانگین دمای بالاتر و تابش خورشیدی‌کمتر چنین نشان داد که عملکرد گندم نسبت به دما حساس‌تر از تابش خورشیدی است. افزون بر این، اثر ترکیبی میانگین دما و سطح CO_2 نشان داد که CO_2 باغلظت‌های بالاتر، بیشترین فایده را با افزایش دما برابر ۱ درجه سانتی گراد داشت، اما افزایش بیشتردما باعث کاهش اثر مفید غلظت بالای CO_2 در هر دو شرایط آبیاری شد.

[DOI: 10.22034/jast.25.3.661]