Influence of elevated CO_2 and temperature on yield attributes of rice and wheat in central India

Abstract:

Elevated CO_2 and rising temperature are the major climate changing drivers to attain sustainability in agriculture. The current experiment was carried out to evaluate the extent of impact of climate changing factors on rice and wheat crop. Field experiment was carried out under a Free Air CO_2 Enrichment (FACE) condition. The treatments consisted of ambient CO_2 and temperature, elevated $CO_2$of 600ppm + ambient temperature, ambient CO_2 + elevated temperature (+2°C), ambient CO_2+elevated temperature (+3°C), elevated $CO_2$of 600 ppm + elevated temperature (+2°C) and elevated $CO_2$600ppm + elevated temperature (+3°C). The plant yield attributes were biomass, tillers per plant, productive tillers per plant, failure tillers per plant, total number of grains per panicle, failure grains per panicle and test weight. Elevated CO_2stimulated biomass and other yield attributes in both crops. However, elevated temperature inhibited yield attributes. Elevated CO_2enhanced biomass but elevated temperature reduced biomass of crops. Elevated CO_2 influenced tillers per plant in rice by -26.9% to 16.6% and in wheat by 3.7% to 25.9%. Elevated temperature affected number tillers up to 26.9%. Number of productive tillers in rice ranged from -28.5% to 21.4% and in wheat by -29.1% to 36%. In wheat the number of grains per panicle varied from -24.3% to 6%. Test weight of grains varied from -9.1% to 4.6% in rice. Combined effect of elevated $CO_2$and elevated temperature had differential effect on crops. Study highlights that yield attributes and productivity of rice and wheat crop will be affected under elevated CO_2 and rising temperature in central part of India and warrants necessary interventions to alleviate climate stress.

Key words: Elevated CO_2, temperature, rice-wheat, yield, India

Introduction

Climate changing drivers are generally referred to greenhouse gasses (GHG) and the atmopsheric temperature. One of the most important GHG is CO_2. Currently, the atmospheric CO_2 concentration stands at 421 parts per million (ppm), marking it to increase 50% from the era of industrial revolution(Brewer 2024). The surgeof CO_2 concentration is being at a rate of 3% annually(Meena 2020). Projections suggest that CO_2 concentration can increase to a value between 550–700 ppm by 2050 and 650–1200 ppm by 2100 (Semba et al. 2022; Sinto et al. 2022; Verma et al. 2022).The escalating atmospheric CO_2 concentration is causing rise in global temperatures. Projections indicate that atmospheric temperature may rise to 2.5°C by 2050 and potentially up to 6.4°C by the century's end(Fry 2020; Lee et al. 2021). This shift is may lead to severe extreme climatic events, such as heat waves and droughts, which may affect agriculture severely (Tripathy et al. 2023; Vijai et al. 2023).

Wheat (*Triticum aestivum*) and rice (*Oryza sativa*), are the primary food crops which feeds about 90% of the world's population, are vulnerable to climate change impacts (Neupane et al. 2022). Food production need to rise 70% by 2050 to meet population demands. Understanding how wheat and rice respond to elevated CO_2 and temperature becomes imperative for addressing food security (Farooq et al. 2023).Several experiments have been carried out to understand the climate impact (Tian et al. 2014; Wang et al. 2018, 2019; Broberg et al. 2019; Ben Mariem et al. 2021; Marcos-Barbero et al. 2021; Abdelhakim et al. 2022). For evaluating the impact of climate changing factors on crop yield, Free Air CO_2 enrichment (FACE) system is preferred as it offers more realistic insights into crop responses(Peng et al. 2020; Xu et al. 2020; Burgess et al. 2023).HigherCO_2 concentration in air can enhance leaf photosynthesis of C_3 species, including wheat, rice, and many other cereal crops, leading to increased yields(Hussen 2020; Rezaei et al. 2023).Enhanced yield due to elevated CO_2 levels interpretation cautiously for two primary reasons. First, higherCO_2 often comes with rising air temperatures. This temperature increase typically accelerates the developmental of crops. Warming found to shorten the growth periods of rice crop by about 2.7 days per degree Kelvin rise for early cultivars. It may delay 4.8 days per degree Kelvin for late rice varieties. Secondly, crop yields respond less favorably to elevated CO_2 levels. This discrepancy could be attributed to a phenomenon known as photosynthetic acclimation to elevated CO_2. Research suggests that over time, plants adjust to elevated CO_2 levels, leading to a diminished response in terms of crop yield (Toreti et al. 2020; Moore et al. 2021). Differences in the responses of wheat and rice to elevated CO_2 and temperature underscore the need for tailored mitigation strategies. Wheat may exhibit a more positive response to elevated CO_2than rice, but the impact of temperature may vary between the two crops (Ben Mariem et al. 2021; Wang and Liu 2021).An experimentindicate that the stimulation observed in crop yield under elevated $CO_2$was attributed to higher photosynthesis(Yin 2013). Impact of elevated CO_2on ricediffersdepending on growth phase of crop (Wang et al. 2020a; Ben Mariem et al. 2021). Similarly, wheat also exhibit differential response to climate factors. Understanding the complexities of yield component responses to elevated CO_2 and temperature for both rice and wheat is important to address food security under climate change (Zhu et al. 2023).

The current experiment was undertaken with a primary objective to evaluate the influence of climate factors on yield of rice and wheat. Study also aims to evaluate whether the elevated CO_2 levels can mitigate the adverse effects of temperature on wheat and rice.

Materials and methods:

Experimental site and weather conditions

The FACE system was established at ICAR-Indian Institute of Soil Science, situated in the Bhopal district of Madhya Pradesh, India. Positioned between latitudes 21°6’N - 26°30’N, this area experiences a semi-dry tropical monsoon climate. With a mean annual temperature of 28°C (ranging from 11°C to 45°C) and precipitation ranging from 1000 to 1200 mm during the period of 2018–2023, it lies centrally within the country. The soil type is black (Vertisol) and is used for continuous rice–wheat rotation.

Soil physico-chemical properties

The soil is a heavy clayey vertisol and the experimental site was characterized by 5.7 g kg^{-1}organic carbon, 225 mg kg^{-1}available N, 12.75 mg kg^{-1}available P, and 230 mg kg^{-1} available K. The soil had sand 15.2%, silt 30.3%, clay 54.5%. The electrical conductivity (EC) was 0.43 dS m^{-1}, and the pH of soil was 7.5.

Free Air CO_2 **Enrichment (FACE) system**

FACE system comprised was comprised of eight octagonal rings fitted on fields across various sites, each with comparable agronomic practices. The CO_2 exposure system was meticulously designed and assembled using cutting-edge technology. It involved CO_2 gas cylindersfitted with two-stage regulators connected to a gas mixing compressor (Elgi, India), which was directly connected to CO_2 exposure system of FACE system rings in experimental field. These FACE system rings were tailored to meet the specific requirements of experimental crops, featuring 8-meter-diameter 'rings' covering an area of 50 square meters per plot.

To ensure uniform CO_2 concentration within the rings, one E-sense extended-range 10000 ppm CO_2 sensor (Senseair, part of the Asahi Kasei Group, headquartered in Delsbo, Sweden) was installed above the canopy in each plot, evenly distributed in two concentric circles, facilitating automatic CO_2 pumping control. The consistency of CO_2 concentration within the rings was maintained through automatic adjustments controlled through pneumatic valves installed on each field.

For infrared heating, facility was designed following the principles outlined by (Kimball et al. 2008). Each field had eight infrared heaters (1000 W, 240 V, 45 cm long, 10 cm wide; Elestein-FSR/1, Elstein-Werk M. Steinmetz GmbH & Co. KG, Northeim, Germany), which were adjusted weekly to maintain a height of 1.2 m above the crop canopy during the growth cycle. The shading effect of these heaters over the open circle (50 m^2) was approximately 5.5%.

The infrared thermometers used were sensitive to radiation in the range of 8.0–14 µm, minimizing interference from atmospheric absorption or emission bands outside this range. Thus, the heaters fitted generally did not emit short wavelengths radiation those might be influence photosynthesis. Crop canopy temperature was measured by sensors (PT 500, Sensography International, Pune, India) fitted at the top of the canopy. Readings of both CO_2 and temperature were automatically monitored and recorded at every minute using a data-logger (TC-800, Ambetronics Scientific Inc., Maharashtra, India). All these components were interconnected through WiFi. System was operated by using software programs (InduSoft Web Studio v8.1 and USR-VCOM, M/s Moreson, India) placed in a control room.

Experimental set up

The experiment was conducted to simulate future climate conditions anticipated for the period 2040-2050. This projection included atmospheric CO_2 levels ranging between 550-650 ppm and a corresponding rise in global mean surface air temperature of 2-3 °C under the A2 emission scenario. The experiment comprised six treatments. Treatment 1,referred as T1 - ambient CO_2& ambient Temperature, T2 - Elevated CO_2& ambient Temperature, T3 -

Ambient CO_2& elevated Temperature, T4- Ambient CO_2& elevated Temperature, T5- Elevated CO_2& elevated Temperature, T6 - Elevated CO_2& elevated Temperature.

Initially, during the first two years (2019-20 and 2020-21), each of the treatments (T1, T2, T3, and T5) were replicated in two rings with identical infrastructure, following a block split-plot design. After two years (2021-22 and 2022-23), experiments were conducted with six treatments (T1-T6), each with a single replication.Carbon dioxide enrichment was implemented during daytime, with canopy temperature regulated both during the day and night. To prevent potential artifacts arising from heterogeneity among crop seedlings during the winter phase of wheat and any effects of transplanting shock in rice, CO_2 and temperature treatments were initiated within the FACE system only after the crops had established well and achieved homogeneity within each plot, typically at the early tillering stage of crop(Ruiz□Vera et al. 2015).

Crop cultivation and agronomical practices

In each experimental season, plots were planted with winter wheat, HI-1605(Pusa Ujala) and rice, PB-1 (Pusa Basmati-1).Standard cultivation practices were performed in all experimental plots. For wheat, seeds were sown in rows 10-12 cm apart at a rate of 120 kg seed per ha,resulting in aplant density of approximately 250-300 plants /m^2. For rice, direct seeded rice (DSR) method was used. Spacing of hills was maintained at 12 x 22.4 cm (equivalent to 37 hills / m^2). Fertilizer dose followed as recommended dose of fertilizer (RDF) at 120:60:40 kg/ha of N:P:K respectively. About 50 percent of nitrogen and 100 percent of P and K were applied at sowing time(basal dose). Remaining doses of nitrogen was applied as two splitat different growth stages of both crop.

Yield attributes

Agronomical data was collected by using standard agronomical methods during the experimental years.Biomass yield was estimated as total biomass, straw weight and grain yield at the end of every cropping season and represented as quintal per hectare or Q/ha in rice and wheat during 2019-23. The rice and winter wheat were harvested at the maturity stage from 1 m^2 area of experimental plot and converted in biomass yield Q/ha(Kaur et al. 2023).

Yield attributes were estimated **as** number of tillers per plant, productive tillers per plant, failure tillers per plant, total number of grains per panicle, failure grains per panicle and test weight (g/1000 grains). The parameters were estimatedat the end of every cropping season in rice and wheat. The five plants sample were collected randomly from each plot and their number of tillers, productive tillers and failure tillers estimated. From these plant sample five randomly selected panicles for measuring number of grains per panicle from each plot were counted carefully and averaged to obtain during investigation. The thousand grains randomly selected and counted from each plot for test weight in both crop(Singh et al. 2021).

Results

The economic yields of crops depend on a number of characters which are known as yield attributes.Yield attributing characters were estimated as plant biomass,number of tillers per plant, productive tillers per plant, failure tillers per plant, total number of grains per panicle, failure grains per panicle and test weight (g/1000 grains). The parameters were estimatedat the end of every cropping seasonin rice and wheat during 2019-23.

Biomass (BM) yield was estimated as total biomass, straw wt. and grain yield at the end of every cropping season and represented as q/ha. in rice and wheat during 2019-23. Plant total biomass, straw weight and grain yield were estimated at the harvest stage of crop and represented as q/ha. In rice,total biomass varied from63.7 to 121.1,straw weight varied from 45.12to 74.85 and grain yield varied from 17.6 to 47(Fig.1). In case of wheat total biomass was in the range of 87.4 to 151.22, straw weight 62 to 87.4and grain yield ranged by 22.87 to 61.82 during the cropping period (Fig. 2). In both crop,total biomass, straw biomass and grain yield was highest in treatment T2 and lowest in treatment T4.

Total number of tillers occurred differently in both crops (Fig.3). In rice, total number of tillersper plantvaried from 8.75to 12.25 in 2019,9.5 to 13 in 2020,9.5 to 13 in 2021 andit was in the range of 9 to 14 in 2022. Similarly, in wheat, total number of tillers varied from 6 to 9 in 2020,5to 8.5 in 2021,5.5 to 8.25 in 2022 and5 to 8.5 in 2023.

Number of productive tillers varied in both crops under the influence of climate changing factors (Fig. 3). In rice,productive tillers per plant varied from8.25 to 11.25 in 2019, 8.25 to 12.75 in 2020, 8.5 to 12.5 in 2021 andit was in the range of 7.5 to 12.75 in 2022. Similarly, in wheat, productive tillers varied from5.25 to 8.5 in 2020,4.25 to 8 in 2021, 5.25 to 7.75 in 2022 and 4.5 to 8.25 in 2023.

Number of failure tillers estimated to define relative failure of tillers in the crops (Fig. 3). In rice, number of failure tillers per plant varied from 0.5 to 1.25 in 2019, 0.25 to 1.25 in 2020, 0.25 to 1.5 in 2021 and it was in the range of 1.25 to 2.75 in 2022. Similarly, in wheat, failure tillers varied from 0.5 to 0.75 in 2020, 0.5 to 0.75 in 2021, 0.25 to 0.5 in 2022 and 0.25 to 0.5 in 2023.

Total number of grains per panicle estimated to indicate crop yield per panicle (Fig. 4). Number of grains per panicleestimated from a randomly selected individual productive tiller of a plant. In rice, it varied from 122.75 to 172 in 2019, 123.75 to167.75 in 2020, 119.5 to 168.25 in 2021 and 113.25 to 168.5 in 2022. In wheat, it varied from 35.25 to 44.5 in 2020, 34.25 to 42.5 in 2021, 31 to 42.75 in 2022 and 32 to 43.5 during 2023.

Number of failure grains/ panicle was estimated as the difference between total number of grains and number of healthy grains per panicle (Fig. 4). It is an indicator of grain yield reduction under kind of stresses of plant. In rice, number of failure grains/panicle varied from

8.75 to 13.25 in 2019, 7.5 to 12.5 in 2020, 6 to 16.25 in 2021 and 4.25 to 15 in 2022. Similarly, in wheat, it varied from 1.25 to 2.25 in 2020, 1.75 to 2.5 in 2021, 1.25 to 3 in 2022 and 1.75 to 2.75 in 2023.

In rice, test weight varied from 20.27 to 22.3 in 2019, 20.4 to 22.6 in 2020, 20.2 to 22.45 in 2021 and 19.8 to 22.4 in 2022 (Fig. 5). Similarly, in wheat, the value varied from 39 to 41.8 in 2020, 39 to 41.8 in 2021, 37.1 to 42.7 in 2022 and 37.9 to 41.77 in 2023.

Yield attributes of crops under different treatments were compared over control (T1) to evaluate how climate factorsaffected yield.In rice the effect of climate factors on number of tillers varied from -26.9% to 16.6%. Total number of tillers was stimulated by treatments T2 and was inhibited by treatments T3, T5, T4 and T6. Inhibition ranged from 2% to 26.9%. Stimulation was up to 16.6%. Maximum stimulation was observed in T2 and maximum inhibition was in T6. In wheat the effect of climate factors on number of tillers varied from -25.9% to 33.3%. In wheat, total number of tillers was stimulated by treatments T2 and was inhibited by treatments T3, T5, T4 and T6. Inhibition ranged from 3.7% to 25.9%. Stimulation varied from 13.7% to 33.3%. Maximum stimulation was in the treatment T2 and maximum inhibition was in T4.In case of elevated temperature (T3 and T4) and combined effect of elevated $CO_2$of 600ppm + elevated temperature (T5, and T6) had negative effect onthis parameterin both crops. In rice the effect of climate factors on number of productive tillers ranged from -28.5% to 21.4%.

It was stimulated by treatments T2 and was inhibited by treatments T3, T5, T4 and T6. Inhibition ranged from 11.9% to 28.5%. Stimulation varied from 8.6% to 21.4%. Maximum stimulation was in the treatment T2 and maximum inhibition was in T3.In wheat the effect of climate factors on number of productive tillers ranged from -29.1% to 36%. It was stimulated by treatments T2 and was inhibited by treatments T3, T5, T4 and T6. Inhibition ranged from

7.4% to 29.1%. Stimulation varied from 14.8% to 36%. Maximum stimulation was in the treatment T2 and maximum inhibition was in T3.

In case of elevated temperature (T3, and T4) and combine effect of elevated CO_2 600ppm + elevated temperature (T5, and T6) had positive effect on failed tillers in both crops.

In rice the effect of climate changing drivers on number of grains per panicle was with the factor of -19.5% to 20.2%. It was stimulated by treatments T2 and was inhibited by treatments T3, T5, T4 and T6. Inhibition ranged from 5% to 19.5%. Stimulation varied from 16.4% to 20.7%. Maximum stimulation was in the treatment T2 and maximum inhibition was in T6.In wheat the effect of climate changing drivers on number of grains per panicle was with the factor of -24.3% to 6%. It was stimulated by treatments T2 and was inhibited by treatments T3, T5, T4 and T6. Inhibition ranged from 5.2% to 24.3%. Stimulation varied from 4.2% to 6%. Maximum stimulation was in the treatment T2 and maximum inhibition was in T4.

In rice the effect of climate changing drivers on number of failure grain per panicle varied by -29.1% to 150%. In T2, was negatively affected by 5.4% to 29.1%. It was stimulated by treatments T3, T5, T4, and T6 and was inhibited by treatments T2. Inhibition ranged from 5.4% to 29.1%. Stimulation varied from 24.3% to 150%. Maximum stimulation was in the treatment T6 and maximum inhibition was in T2.In wheat the effect of climate changing drivers on number of failure grain per panicle varied by -16.6% to 100%. In T2, was negatively affected by 0% to 16.6%. It was stimulated by treatments T3, T5, T4, and T6 and was inhibited by treatments T2. Stimulation varied from 25% to 100%. Maximum stimulation was in the treatment T4.In T2 (elevated CO_2 600ppm) had negative effect on both crops. In case of elevated temperature (T3, and T4) and combine effect of elevated CO_2 600ppm + elevated temperature (T5, and T6) had positive effect on both crops.

In rice the effect of climate changing factors on test weight was varied from -7.5% to 8.2%. It was stimulated by treatments T2 and was inhibited by treatments T3, T5, T4 and T6. Inhibition ranged from 1.4% to 7.5%. Stimulation varied from 2.9% to 4.9%. Maximum stimulation was in the treatment T2 and maximum inhibition was in T4.

In wheat the effect of climate changing factors on test weight was varied from -9.1% to 4.6%. It was stimulated by treatment T2 and was inhibited by treatments T3, T5, T4 and T6. Inhibition ranged from 0.2% to 9.1%. Stimulation varied from 2.7% to 4.6%. Maximum stimulation was in the treatment T2 and maximum inhibition was in T4.

In rice, under ambient condition (T1), test weight was decreased by 0.6% to 2.4% during 2020-22. In T2, it was increased by 0.4% to 1.5%. In T3, it increased by 0.6% to 1.9%. In T5, test weight was increased by a factor of 0% to 4.8%. In T4, it was decreased by a factor of 1.9% in 2022. In T6, it was decreased with the value of1.2% in 2022. In case of wheat, in T1, test weight was decreased by 0.3% to 1.4% over the years. In T2, it was increased by a factor of 2.2% over the years. In T3, test weight was increased 2.4% during the years. In T5, it was decreased by 0.9% during 2021-23. In T4, test weight was increased by a factor of 3.3% during 2023. In T6, it was increased by 1.4% during 2023.

Discussion

The economic output of crops relies on various traits, often referred to as yield attributes or yield-contributing characteristics.Yield-contributing traits result from the accumulation of dry matter in plants and its subsequent translocation to develop yield attributes.In rice and wheat, yield is influenced by indirect traits such as tillering ability, seed setting rate, and grains per panicle, as well as direct traits like the number of panicles per unit area or per plant, the number of filled grains per panicle, and the weight of 1000 grains(Oladosu et al. 2018; Li et al. 2019).

Climate change significantly impacts crop yield attributes and biomass yield. It is estimated that a 1°C increase in temperature can reduce global crop yields by 10–20% (Liu et al. 2021). By the end of this century, global atmospheric temperatures are expected to rise by 2–4°C or more, posing a threat to crop production (Alotaibi 2023). Changes in daily weather conditions could lead to permanent extreme climate shifts, affecting agriculture worldwide(Aragón et al. 2021). These extreme temperature changes, especially during sensitive stages like flowering, anthesis, and the milking stage, significantly impact wheat and rice yield, grain weight, and other yield attributes at the end of the season (Impa et al. 2021; Sattar et al. 2023). For instance, when temperatures reached 36 ± 2°C during anthesis, wheat yield decreased by 13%, with most grains becoming sterile(Zahra et al. 2021). Such temperature increases can lead to heat stress, a severe threat to rice and wheat production, particularly during reproductive and grain-filling phases(Farhad et al. 2023). Previous studies have shown that exposure to temperatures above the optimum range for wheat at anthesis and grain-filling stages (12 to 20°C) can significantly reduce grain yield by more than 20%(Ullah et al. 2022). All physiological processes of wheat and rice plants are sensitive to temperature and can suffer permanent damage from heat. Heat stress during anthesis can increase floret abortion, and temperatures over 30°C during floret formation may lead to complete sterility(Lohani et al. 2020; Qi and Wu 2022). Heat stress during the reproductive stage can result in pollen sterility, tissue dehydration, lower CO_2 assimilation, increased photorespiration, and reduced resource capture due to accelerated growth and senescence, consequently reducing yield(Goud et al. 2022; Farhad et al. 2023). While increased CO_2 levels can enhance the rate of photosynthesis and water efficiency, this does not necessarily lead to higher yield or biomass in C_3 plants like wheat(Tausz-Posch et al. 2020). Wheat yield depends not only on the rate of photosynthesis but also on the duration of the active photosynthetic phase and the grain's sink capacity (Zhang et al. 2021a).

In rice the effect of elevated temperature and elevated CO_2 on total biomass, straw yield and grain yield varied from -33.8% to 11.17%, -24.9% to 9.99% and 49.5% to 14.7%, respectively during 2019-22. Similarly, in wheat the yield parameters were affected by 19.4% to 21.9%, 14.9% to 22.2% and -54.5% to 22.7%, respectively during 2020-23. Under elevated temperature, biomass and grain yield reduced in both crops. Results indicated that means elevated temperature inhibited plant growth by altering various enzymatic and physiological processes in plant. Photosystem II (PSII) is the most sensitive component of the photosynthetic apparatus(Moustakas et al. 2022). Heat-induced oxidative stress causes the dissociation of the oxygen-evolving complex (OEC) in PSII, inhibiting electron transport from the OEC to the acceptor side of PSII(Wang et al. 2022). Rubisco is the key enzyme that converts carbon dioxide into carbohydrates during photosynthesis(Iñiguez et al. 2021; Selvan et al. 2024). However, as temperatures rise, Rubisco "relaxes," causing its CO_2-binding pocket to become less precise(Yadav 2020).

Over control under elevated CO_2 condition, total biomass, straw yield and grain yield increased in some extend by stimulating photosynthesis and stomata conductance mechanisms in both crops. Rising CO_2 levels in the atmosphere drive an increase in plant photosynthesis, a phenomenon called the carbon fertilization effect(Tausz□Posch et al. 2020; Walker et al. 2021). Most of this increase in photosynthesis is attributed to carbon dioxide fertilization. Enhanced photosynthesis leads to greater growth in some plants.

Current study highlighted that elevated CO_2 (eCO_2) significantly promoted rice tillering. Similar results were observed in rice under elevated CO_2(Zhou et al. 2021). In an experiment with rice-wheat systems, eCO_2 positively improved the number of grains per panicle and improved test weight in both crops(Radha et al. 2023).

Experiments on wheat production have shown that high temperatures combined with increased CO_2 concentrations can be harmful and decline the crop yield attributes (Pequeno et al. 2021). Elevated CO_2 levels increases nitrogen sink capacity but also shorten the photosynthetic period, resulting in poor growth and reduced yield (Gao et al. 2021). Increase in CO_2concentration and temperature can disrupt positive aspects of crop growth(Hamann et al. 2021). A study revealed that doubling CO_2 and raising temperatures by 1.5 to 4°C negatively impacted the wheat yield attributes(Zhang et al. 2021b).

Increasing atmospheric carbon dioxide levels have led to higher photosynthetic rates, increased biomass growth, and greater numbers of tillers, grains per panicle, and improved test weight(Fabre et al. 2020; Wang et al. 2020b), ultimately boosting seed yield for many globally important C_3 food and feed crops(Bhargava and Mitra 2021; Ebi et al. 2021). Rising CO_2 levels in the atmosphere drives plant photosynthesis, which is referred as the carbon fertilization effect (Tausz□Posch et al. 2020; Walker et al. 2021). It is reported that during the period of 1982 and 2020, global plant photosynthesis has increased by 12 %, in correlation to 17% increase in atmospheric CO_2 levels(Liu et al. 2023). Most of this increase in photosynthesis is attributed to CO_2 fertilization, which enhances growth and yield attributes in some plants.

Elevated temperatures (eTemp) negatively affect yield attributes by various means. One is through disrupting enzymes involved in photorespiration and photosynthesis (Rubisco) (Abasi et al. 2023). Rubisco plays key role to convert$CO_2$to carbohydrates during photosynthesis(Iñiguez et al. 2021; Selvan et al. 2024). However, as temperatures rises, conformation of Rubisco enzyme changes making it unable to capture CO_2(Yadav 2020). In this case Rubisco fixes O2 instead of CO_2(Karimova and Safarova 2023). At even higher temperatures, Rubisco enzyme is completely deactivated(Scafaro et al. 2023). Under higher nitrogen fertilizer application Rubisco content of plant increases. Thus higher N fertilizer application may alleviate negative effect of elevated temperature on photosynthesis (Zhang et al. 2022a).Heat stress can also damage the permeability of the thylakoid membrane and affect photosynthesis(Kulke et al. 2023). This results in decreased chlorophyll content in plant (Moustakas et al. 2022). Negative effect of climate changing drivers on plant yield attributes could be the result of declined plant photosynthesis.

Conclusion

Climate changing drivers had differential impact on yield parameters of rice and wheat. Treatment T2 (elevated CO_2at 600ppm) had positive effect on plant biomass, number of tillers in both crops. In case of elevated temperature (T3, and T4) and combined effect of elevated CO_2 600ppm + elevated temperature (T5, and T6), number of tillers declined in both crops.Elevated CO_2 was beneficial for both crops. Hence, it stimulated yield attributes in rice and wheat.But warming had negative effect onyield attributes of both rice and wheat crops. Study concluded that climate changing factors will affect the yield of rice and wheat by declining the parameters including biomass, tillers, grains per panicle, and grain weight. Further research warranted to evaluate strategies to offset the negative effect of elevated temperature for sustainable production of rice and wheat under climate change in central India.

References:

Abasi F, Raja NI, Ehsan M, et al (2023) Adaptation strategies with respect to heat shock proteins and antioxidant potential; an era of food security and climate change. Int J Biol Macromol 128379

Abdelhakim LOA, Zhou R, Ottosen C-O (2022) Physiological responses of plants to combined drought and heat under elevated CO_2. Agronomy 12:2526

Alotaibi M (2023) Climate change, its impact on crop production, challenges, and possible solutions. Not Bot Horti Agrobot Cluj-Napoca 51:13020–13020

Aragón FM, Oteiza F, Rud JP (2021) Climate change and agriculture: Subsistence farmers' response to extreme heat. Am Econ J Econ Policy 13:1–35

Araya A, Prasad PVV, Gowda PH, et al (2020) Potential impacts of climate change factors and agronomic adaptation strategies on wheat yields in central highlands of Ethiopia. Clim Change 159:461–479

Ben Mariem S, Soba D, Zhou B, et al (2021) Climate change, crop yields, and grain quality of C3 cereals: A meta-analysis of [CO_2], temperature, and drought effects. Plants 10:1052

Bhargava S, Mitra S (2021) Elevated atmospheric CO_2 and the future of crop plants. Plant Breed 140:1–11

Brewer T (2024) Climate Change: An Interdisciplinary Introduction. Springer Nature

Broberg MC, Högy P, Feng Z, Pleijel H (2019) Effects of elevated CO_2 on wheat yield: non-linear response and relation to site productivity. Agronomy 9:243

Burgess AJ, Masclaux□Daubresse C, Strittmatter G, et al (2023) Improving crop yield potential: Underlying biological processes and future prospects. Food Energy Secur 12:e435

Ebi KL, Anderson CL, Hess JJ, et al (2021) Nutritional quality of crops in a high CO_2 world: an agenda for research and technology development. Environ Res Lett 16:064045

Fabre D, Dingkuhn M, Yin X, et al (2020) Genotypic variation in source and sink traits affects the response of photosynthesis and growth to elevated atmospheric CO_2. Plant Cell Environ 43:579–593

Farhad M, Kumar U, Tomar V, et al (2023) Heat stress in wheat: a global challenge to feed billions in the current era of the changing climate. Front Sustain Food Syst 7:1203721

Farooq A, Farooq N, Akbar H, et al (2023) A critical review of climate change impact at a global scale on cereal crop production. Agronomy 13:162

Fry G (2020) Albedo Changes Drive 4.9 to 9.4 C Global Warming by 2400. In: 2020 5th International Conference on Universal Village (UV). IEEE, pp 1–14

Gao B, Hu S, Jing L, et al (2021) Alterations in source-sink relations affect rice yield response to elevated CO_2: a free-air CO_2 enrichment study. Front Plant Sci 12:700159

Goud EL, Singh J, Kumar P (2022) Climate change and their impact on global food production. In: Microbiome under changing climate. Elsevier, pp 415–436

Hamann E, Blevins C, Franks SJ, et al (2021) Climate change alters plant–herbivore interactions. New Phytol 229:1894–1910

Hussen A (2020) Review on: response of cereal crops to climate change. Adv Biosci Bioeng 8:10.11648

Impa SM, Raju B, Hein NT, et al (2021) High night temperature effects on wheat and rice: Current status and way forward. Plant Cell Environ 44:2049–2065

Iñiguez C, Aguiló-Nicolau P, Galmés J (2021) Improving photosynthesis through the enhancement of Rubisco carboxylation capacity. Biochem Soc Trans 49:2007–2019

Karimova TA, Safarova MA (2023) THE IMPACT OF CLIMATE CHANGE ON PLANTS GROWTH AND DEVELOPMENT. In: Актуальные проблемы математики и естественных наук. pp 148–151

Kaur C, Kumar S, Singh K (2023) Effect of integrated nutrient management on growth and yield of wheat (Triticum aestivum L.) under system of wheat intensification. J Cereal Res 15 2 273-276 Httpdoi Org10251742582-26752023 120083:

Kimball BA, Conley MM, Wang S, et al (2008) Infrared heater arrays for warming ecosystem field plots. Glob Change Biol 14:309–320

Kulke M, Weraduwage SM, Sharkey TD, Vermaas JV (2023) Nanoscale simulation of the thylakoid membrane response to extreme temperatures. Plant Cell Environ 46:2419–2431

Lee J-Y, Marotzke J, Bala G, et al (2021) Future global climate: scenario-based projections and near-term information. In: Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, pp 553–672

Li R, Li M, Ashraf U, et al (2019) Exploring the relationships between yield and yield-related traits for rice varieties released in China from 1978 to 2017. Front Plant Sci 10:430305

Li S, Wu F, Zhou Q, Zhang Y (2024) Adopting agronomic strategies to enhance the adaptation of global rice production to future climate change: a meta-analysis. Agron Sustain Dev 44:23

Liu W, Ye T, Jägermeyr J, et al (2021) Future climate change significantly alters interannual wheat yield variability over half of harvested areas. Environ Res Lett 16:094045

Liu Y, Wu C, Wang X, Zhang Y (2023) Contrasting responses of peak vegetation growth to asymmetric warming: Evidences from FLUXNET and satellite observations. Glob Change Biol 29:2363–2379

Lohani N, Singh MB, Bhalla PL (2020) High temperature susceptibility of sexual reproduction in crop plants. J Exp Bot 71:555–568

Marcos-Barbero EL, Pérez P, Martínez-Carrasco R, et al (2021) Screening for higher grain yield and biomass among sixty bread wheat genotypes grown under elevated CO_2 and high-temperature conditions. Plants 10:1596

Meena P (2020) IMPACT OF GREENHOUSE GASES ON HUMAN HEALTH

Moore CE, Meacham-Hensold K, Lemonnier P, et al (2021) The effect of increasing temperature on crop photosynthesis: from enzymes to ecosystems. J Exp Bot 72:2822–2844

Moustakas M, Moustaka J, Sperdouli I (2022) Hormesis in photosystem II: a mechanistic understanding. Curr Opin Toxicol 29:57–64

Neupane D, Adhikari P, Bhattarai D, et al (2022) Does climate change affect the yield of the top three cereals and food security in the world? Earth 3:45–71

Oladosu Y, Rafii MY, Magaji U, et al (2018) Genotypic and phenotypic relationship among yield components in rice under tropical conditions. BioMed Res Int 2018:

Peng B, Guan K, Tang J, et al (2020) Towards a multiscale crop modelling framework for climate change adaptation assessment. Nat Plants 6:338–348

Pequeno DN, Hernandez-Ochoa IM, Reynolds M, et al (2021) Climate impact and adaptation to heat and drought stress of regional and global wheat production. Environ Res Lett 16:054070

Qi B, Wu C (2022) Potential roles of stigma exsertion on spikelet fertility in rice (Oryza sativa L.) under heat stress. Front Plant Sci 13:983070

Radha B, Sunitha NC, Sah RP, et al (2023) Physiological and molecular implications of multiple abiotic stresses on yield and quality of rice. Front Plant Sci 13:996514

Rezaei EE, Webber H, Asseng S, et al (2023) Climate change impacts on crop yields. Nat Rev Earth Environ 4:831–846

Ruiz□Vera UM, Siebers MH, Drag DW, et al (2015) Canopy warming caused photosynthetic acclimation and reduced seed yield in maize grown at ambient and elevated [CO 2]. Glob Change Biol 21:4237–4249

Sattar A, Nanda G, Singh G, et al (2023) Responses of phenology, yield attributes, and yield of wheat varieties under different sowing times in Indo-Gangetic Plains. Front Plant Sci 14:1224334

Scafaro AP, Posch BC, Evans JR, et al (2023) Rubisco deactivation and chloroplast electron transport rates co-limit photosynthesis above optimal leaf temperature in terrestrial plants. Nat Commun 14:2820

Selvan ST, Chandrasekaran R, Muthusamy S, et al (2024) Eco-technological method for carbon dioxide biosorption and molecular mechanism of the RuBisCO enzyme from unicellular microalga Chlorella vulgaris RDS03: a synergistic approach. Biomass Convers Biorefinery 14:4191–4209

Semba RD, Askari S, Gibson S, et al (2022) The potential impact of climate change on the micronutrient-rich food supply. Adv Nutr 13:80–100

Singh AK, Yadav RS, Kumar D, et al (2021) Outcomes of yield attributes, yield and economics of Rice (Oryza sativa L.) through applied the various planting methods and weed management practices. Pharma Innov J 10:1135–1139

Sinto A, Sathee L, Singh D, et al (2022) Interactive effect of elevated CO_2 and nitrogen dose reprograms grain ionome and associated gene expression in bread wheat. Plant Physiol Biochem 179:134–143

Tausz□Posch S, Tausz M, Bourgault M (2020) Elevated [CO 2] effects on crops: Advances in understanding acclimation, nitrogen dynamics and interactions with drought and other organisms. Plant Biol 22:38–51

Tian Y, Zheng C, Chen J, et al (2014) Climatic warming increases winter wheat yield but reduces grain nitrogen concentration in East China. PloS One 9:e95108

Toreti A, Deryng D, Tubiello FN, et al (2020) Narrowing uncertainties in the effects of elevated CO_2 on crops. Nat Food 1:775–782

Tripathy KP, Mukherjee S, Mishra AK, et al (2023) Climate change will accelerate the high-end risk of compound drought and heatwave events. Proc Natl Acad Sci 120:e2219825120

Ullah A, Nadeem F, Nawaz A, et al (2022) Heat stress effects on the reproductive physiology and yield of wheat. J Agron Crop Sci 208:1–17

Verma AK, Singh A, Singh R, et al (2022) Population specific methylome remodeling in high and low elevation populations of Indian west Himalayan Arabidopsis thaliana in response to elevated CO_2. Environ Exp Bot 203:105074

Vijai C, Worakamol W, Elayaraja M (2023) Climate change and its impact on agriculture. Int J Agric Sci Vet Med 11:1–8

Walker AP, De Kauwe MG, Bastos A, et al (2021) Integrating the evidence for a terrestrial carbon sink caused by increasing atmospheric CO_2. New Phytol 229:2413–2445

Wang B, Cai W, Li J, et al (2020a) Leaf photosynthesis and stomatal conductance acclimate to elevated [CO_2] and temperature thus increasing dry matter productivity in a double rice cropping system. Field Crops Res 248:107735

Wang B, Li J, Wan Y, et al (2019) Variable effects of 2 C air warming on yield formation under elevated [CO_2] in a Chinese double rice cropping system. Agric For Meteorol 278:107662

Wang G, Xing M, Hu T, et al (2022) Photosystem II photochemical adjustment of tall fescue against heat stress after melatonin priming. J Plant Physiol 275:153758

Wang W, Cai C, He J, et al (2020b) Yield, dry matter distribution and photosynthetic characteristics of rice under elevated CO_2 and increased temperature conditions. Field Crops Res 248:107605

Wang W, Cai C, Lam SK, et al (2018) Elevated CO_2 cannot compensate for japonica grain yield losses under increasing air temperature because of the decrease in spikelet density. Eur J Agron 99:21–29

Wang X, Liu F (2021) Effects of elevated CO_2 and heat on wheat grain quality. Plants 10:1027

Xu C, Zhang K, Zhu W, et al (2020) Large losses of ammonium-nitrogen from a rice ecosystem under elevated CO_2. Sci Adv 6:eabb7433

Yadav AS (2020) Investigations on the molecular basis of temperature response in plants. Monash University

Yin X (2013) Improving ecophysiological simulation models to predict the impact of elevated atmospheric CO_2 concentration on crop productivity. Ann Bot 112:465–475

Zahra N, Wahid A, Hafeez MB, et al (2021) Grain development in wheat under combined heat and drought stress: Plant responses and management. Environ Exp Bot 188:104517

Zhang C, Zheng B, He Y (2021a) Improving grain yield via promotion of kernel weight in high yielding winter wheat genotypes. Biology 11:42

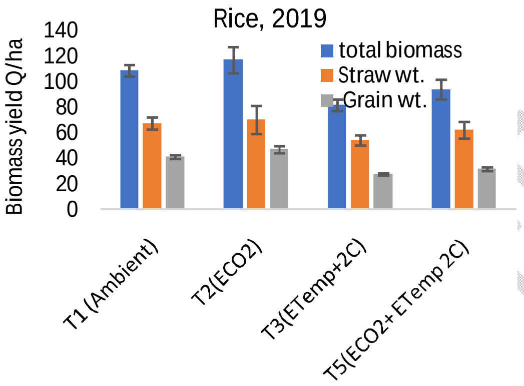
Zhang F, Wen Z, Wang S, et al (2022a) Phosphate limitation intensifies negative effects of ocean acidification on globally important nitrogen fixing cyanobacterium. Nat Commun 13:6730

Zhang G, Ujiie K, Yoshimoto M, et al (2022b) Daytime warming during early grain filling offsets the CO_2 fertilization effect in rice. Environ Res Lett 17:114051

Zhang Y, Niu H, Yu Q (2021b) Impacts of climate change and increasing carbon dioxide levels on yield changes of major crops in suitable planting areas in China by the 2050s. Ecol Indic 125:107588

Zhou J, Gao Y, Wang J, et al (2021) Elevated atmospheric CO_2 concentration triggers redistribution of nitrogen to promote tillering in rice. Plant□Environment Interact 2:125–136

Zhu C, Wolf J, Zhang J, et al (2023) Rising temperatures can negate CO_2 fertilization effects on global staple crop yields: A meta-regression analysis. Agric For Meteorol 342:109737



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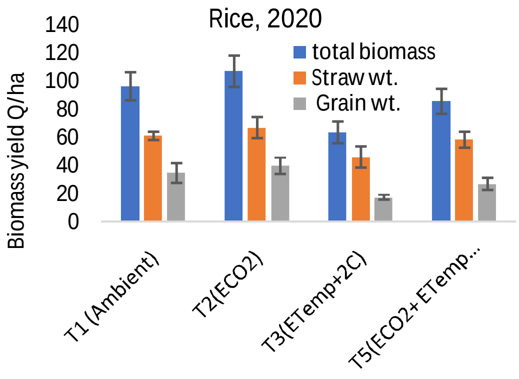

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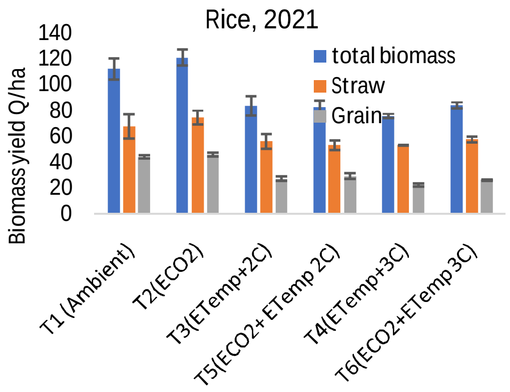

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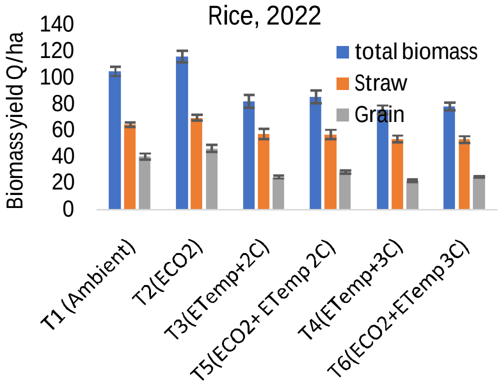
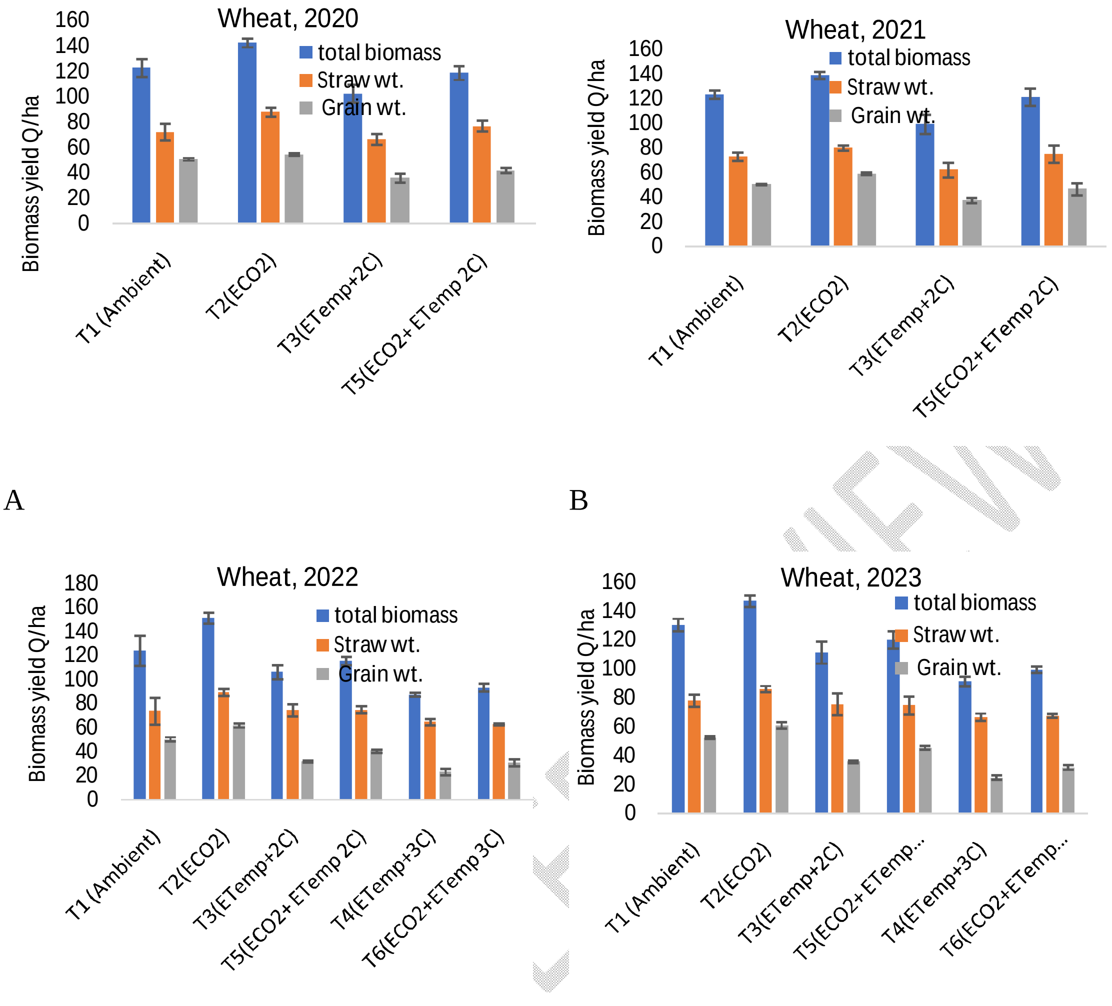


D

Figure 1. Influence of climate changing factors on yield parameters of rice. Rice was cultivated under Free Air CO_2 Enrichment (FACE) system with different treatments. The treatments were ambient condition (T1), elevated CO_2 of 600 ppm (T2), elevated temperature (+2°C) (T3), elevated CO_2 of 600 ppm + temperature (+2°C) (T5), elevated temperature (+3°C) (T4), elevated CO_2 (600 ppm) + elevated temperature (+3°C). Plant samples were collected at maturity stage of crop. Parameters total biomass, straw yield, and grain yield were estimated during different years (A-2019, B-2020, C-2021, D-2022). X axis represents different climate changing factors. Y axis represents yield in quintal per hectare (Q/ha). Each data point represents arithmetic mean and standard deviation as error bar of 4 replicated observations.



A

B

C

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Figure 2. Influence of climate changing factors on yield parameters of wheat. Wheat was cultivated under Free Air CO_2 Enrichment (FACE) system with the different treatments. The treatments were ambient (T1), elevated CO_2 600 ppm (T2), elevated temperature (+2°C) (T3), elevated CO_2 (600 ppm) +temperature (+2°C) (T5), elevated temperature (+3°C) (T4), elevated CO_2 (600 ppm) + elevated temperature (+3°C). Plant sample were collected at maturity stage of crop. Parameters total biomass, straw yield, and grain yield were estimated during different years (A-2020, B-2021, C-2022, D-2023). X axis represents different climate

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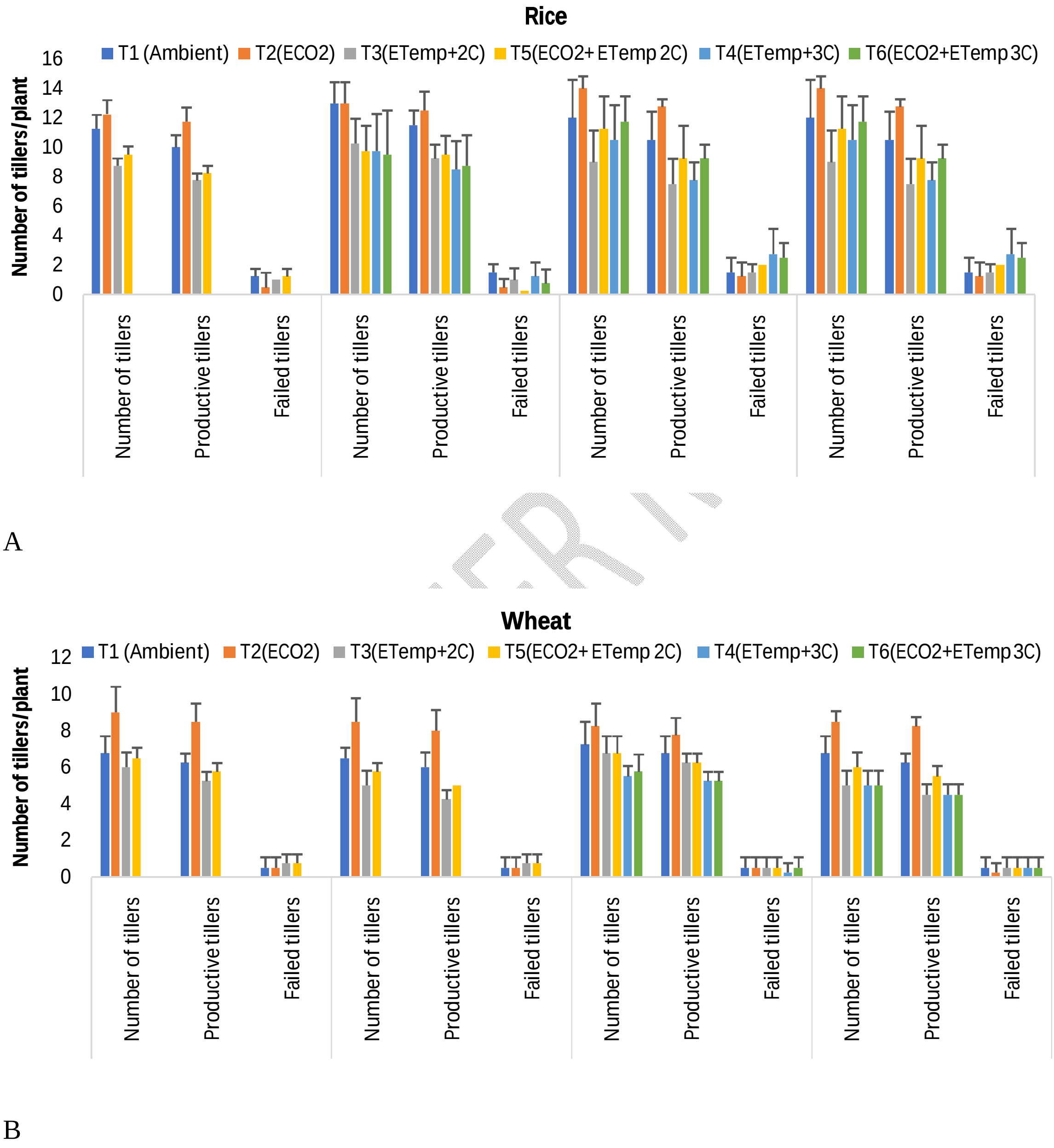
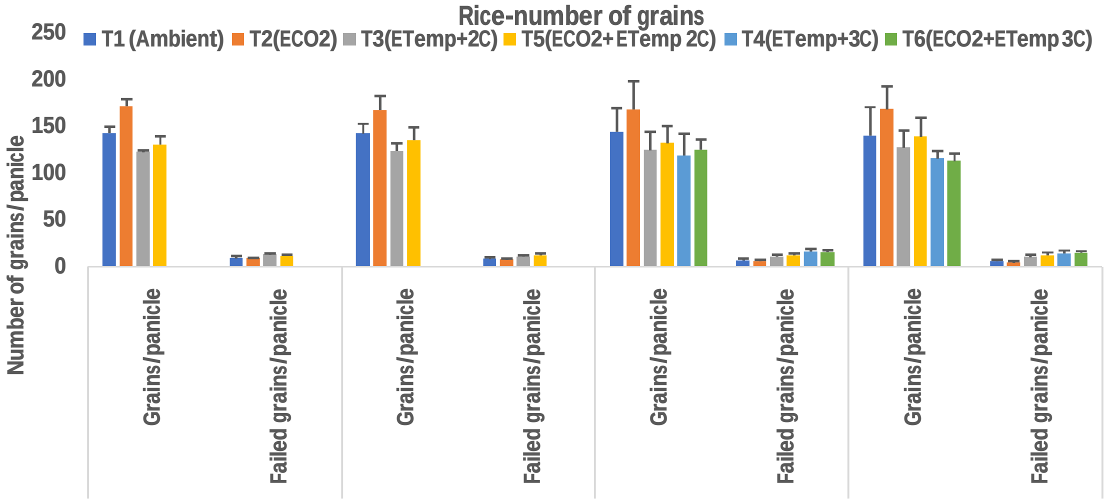


Figure 3. Effect of climate changing factors on tillers of rice (A) and wheat (B). Tillers were estimated as number of tillers, productive tillers and failed tillers. Rice and wheat were cultivated under Free Air CO_2 Enrichment (FACE) system with the different treatments. The

treatments were ambient (T1), elevated CO_2 600 ppm (T2), elevated temperature (+2°C) (T3), elevated CO_2 (600 ppm) +temperature (+2°C) (T5), elevated temperature (+3°C) (T4), elevated CO_2 (600 ppm)+elevated temperature (+3°C). Plant samples were collected at maturity stage of crop grown during different years. X axis represents different cropping years. Y axis represents number of tillers/plant. Each data point represents arithmetic mean and standard deviation as error bar of 4 replicated observations.



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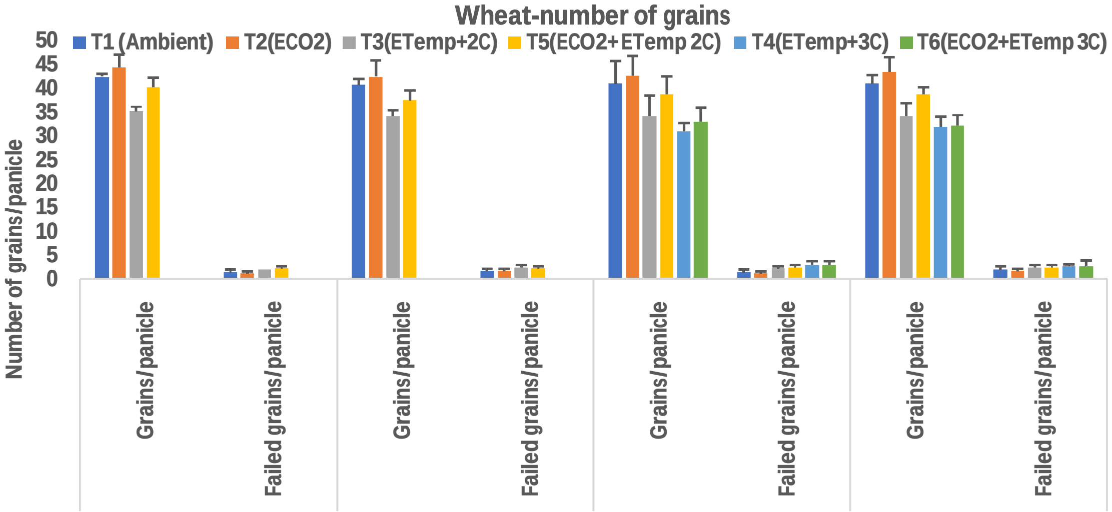

B

Figure 4. Effect of climate changing factors on number of grains and failed grains per panicle in rice (A) and wheat (B). Rice and wheat were cultivated under Free Air CO_2 Enrichment (FACE) system with the different treatments. The treatments were ambient (T1), elevated CO_2 600 ppm (T2), elevated temperature (+2°C) (T3), elevated CO_2 (600 ppm) +temperature (+2°C) (T5), elevated temperature (+3°C) (T4), elevated CO_2 (600 ppm) + elevated temperature (+3°C). Plant samples were collected at maturity stage of crops grown at different years. Parameters were number of grains and failed grains per panicle. X axis represents different cropping years. Y axis represents grains per panicle. Each data point represents arithmetic mean and standard deviation as error bar of 4 replicated observations.

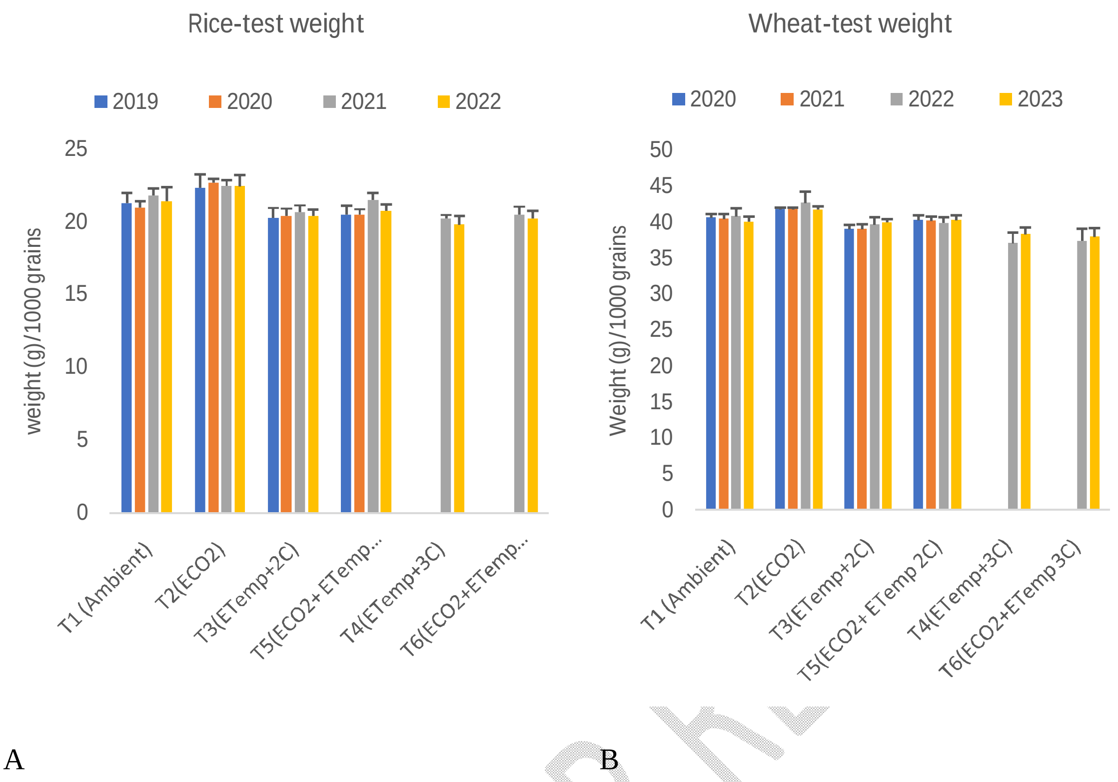

Figure 5. Effect of climate changing factors on test weight of rice (A) and wheat (B). Rice and wheat were cultivated under Free Air CO_2 Enrichment (FACE) system with the different treatments. The treatments were ambient (T1), elevated CO_2 600 ppm (T2), elevated temperature (+2°C) (T3), elevated CO_2 (600 ppm) +temperature (+2°C) (T5), elevated temperature (+3°C) (T4), elevated CO_2 (600 ppm) + elevated temperature (+3°C). Grain samples were collected after harvesting of crop from each treatment and test weight estimated as weight(g)/1000 grains. Crops were grown during different years. X axis represents different treatments. Y axis represents test weight. Each data point represents arithmetic mean and standard deviation as error bar of 4 replicated observations.