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Research Paper

Simulation of bio-physical parameters and yield of wheat under projected climate during mid-century

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ABSTRACT

The experiment was conducted at the research farm of Punjab Agricultural University, Ludhiana, during the *rabi* seasons of 2021-22 and 2022-23 to simulate biophysical parameters viz leaf area index (LAI), biomass, and yield for the mid-century (2040–2069) under SSP2-4.5 and SSP5-8.5 climate scenarios using validated CERES-wheat model. The duration of wheat was projected to be shortened while biomass accumulation was projected to increase. The LAI showed a noticeable decrement during the grain-filling stage. Furthermore, the model simulated decrease in yield by 5.78% and 3.32% for SSP2-4.5 and SSP5-8.5 scenarios, respectively. Among the phenology as simulated using CERES wheat model, the grain-filling stage was identified as the most sensitive period for biophysical parameters under both the projected climate scenarios.

Keywords: Sensitivity analysis, Bio-physical parameters, Weather variables, wheat, CERES-wheat

Crop bio-physical parameters such as leaf area index and dry matter accumulation are major determinant of crop growth and productivity. Together, these parameters provide insights into the crop's health, growth dynamics, and yield potential, making them essential for monitoring crop performance, optimizing agronomic practices, and improving resource use efficiency (Reisi *et al.,* 2020). According to IPCC AR6 report, temperature is forecasted to peak by 1.5 °C or above, before 2025 (IPCC, 2023). The climate change projection predicted decline in agricultural production. Kumar *et al.,* (2014) found that the projected climate would decrease the yield in the range of 6-23% by 2050 and 15-25% by 2080. During 2080-2100, the wheat yield is expected to decline by 0.2 to 0.8 tha^{-1} in western regions (Alsafadi *et al.,* 2023). Daloz *et al.,* (2021) also reported a decline of 1-8% loss of wheat yield in Indo-Gangetic plains. The present study has been planned to simulate the biophysical parameters and yield of wheat under projected climate using validated CERES-wheat model.

MATERIAL AND METHODS

Experimental details

The experiments were conducted during *rabi* seasons of 2021-22 and 2022-23 at research farm of Punjab Agricultural University, Ludhiana (30.90 °N, 75.85 °E) with wheat crop sown on three dates of sowing (27th October, 17th November and 8th December) with four irrigations and two nitrogen levels. The CERES-wheat model was calibrated and validated using field experimental data, weather data (maximum and minimum temperatures, rainfall, and sunshine hours) and soil data of the experimental site.

Projected scenarios

Two levels of air temperature (°C) and precipitation (mm) for mid-century (2040-2069) were taken from Krishnan *et al.,* (2020), where they simulated change in the two weather parameters relative to 1850-1900 using Coupled Model Intercomparison Project Phase 6 (CMIP6) models for Indian region under two SSP scenarios (SSP2-4.5 and SSP5-8.5). Similarly, the two levels of CO_2 projections (ppm) were obtained from the projections derived from socio-economically explicit Integrated Assessment Models (IAMs) under the SSP framework (Table 1). The projected scenarios using CMIP6 model has been sourced from Earth System Grid Federation (ESGF).

CERES-wheat model was used to make the simulations

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Table 1: Description of projected weather variables under SSP2-4.5 and SSP5-8.5 scenarios for mid century (2040-2069)

Weather variables	SSP2-4.5	SSP5- 8.5
Air temperature **(°C)**	2.37 (1.67 to 3.16)	3.04 (1.92 to 4.53)
Precipitation (mm day^{-1})	0.33 (−0.36 to 1.38)	0.49 (−0.20 to 0.96)
CO_2 (ppm)	509.2	567.2

Table 3: Number of days taken in attaining different phenological stages under SSP2-4.5 and SSP5-8.5

Phenological stages	Base line year (2022-23)	SSP2-4.5	SSP5-8.5
Germination	1	1	1
Emergence	3	3	3
Terminal spikelet	73	70	69
End of vegetative stage	86	83	82
End of ear growth	97	94	93
Beginning of grain filling	107	103	102
End of grain filling	140	135	133

under projected climate with elevated air temperature, precipitation and carbon-dioxide under two SSP scenarios. The model outputs in terms of phenology (germination, emergence, terminal spikelet, end of vegetative stage, end of ear formation, beginning of grain filling, end of grain filling and harvest), daily dry matter accumulation, leaf area index, and grain yield were generated and the outcomes were compared and analysed for the impacts of projected climate on wheat production for mid century.

RESULTS AND DISCUSSION

Validation of CERES-wheat model

The CERES-wheat model indicated better proximity between actual and simulated values of phenology and bio-physical parameters in terms of anthesis, maturity, dry matter as well as LAI having value of 96 and 97, 140 and 138, 7020 g/m^2 and 6573 g/m^2, 3.4 and 2.8 respectively (Table 2). Moreover in terms of statistical analysis, the model performed well as the R^2 was found 0.78 between the simulated and observed yield was 0.78. Similarly, the model was in good agreement with the observed yield with d.Stat. and RMSE values of 0.80 and 705 kg/ha respectively (Fig. 1). The model was able to simulate anthesis (d.Stat.: 0.86, RMSE: 5.48) and maturity (d.Stat.: 0.98, RMSE:3.31) of wheat satisfactorily (Table 2).

Effect of projected climate on phenology of wheat

The simulated various phenological stages of wheat under the SSP2-4.5 and SSP5-8.5 scenarios for mid-century (2040-2069) along with the baseline year (2022-23) are presented in Table 3. Results indicated that the crop durations are expected to be shortened by 5 days under SSP2-4.5 to 7 days under SSP5-8.5. End

Table 2: Relationship between observed and model simulated phenology, dry matter and LAI

Variable Name	Observed	Simulated	r-Square	RMSE	d-Stat.
Anthesis day	96	97	0.84	5.48	0.86
Maturity day	140	138	0.95	3.31	0.98
Dry matter	7020	6573	0.67	900	0.87
LAI	3.4	2.8	0.75	1.3	0.66

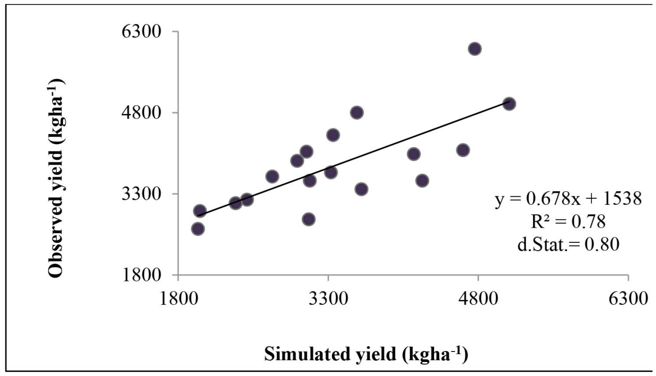

Fig. 1: Simulated and observed yield of wheat

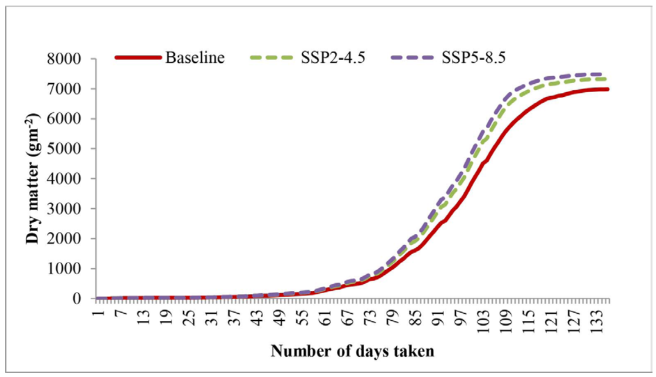

Fig. 2: Variation in dry matter under SSP2-4.5 and SSP5-8.5 with respect to base line year 2022-23

of vegetative stage is expected to be shortened by 3 to 4 days. The projected climate scenarios under SSP2-4.5 and SSP5-8.5 indicate an overall acceleration in the attainment of key phenological stages compared to the baseline year (2022-23). These shifts indicate that rising temperatures under climate change will accelerate crop development, potentially reducing the duration available for biomass accumulation and grain filling, which could impact final yields.

Effect of projected climate on dry matter accumulation

Fig. 2 illustrates the dry matter accumulation (gm^{-2}) over time (days) under three different scenarios. Initially, all three scenarios exhibit similar trends with minimal dry matter accumulation until around day 60. After this point, the growth rate accelerates, showing a significant increase in dry matter. Between days 80 and 110, a noticeable divergence occurs. SSP5-8.5 exhibited the highest dry matter accumulation throughout the later stages, followed closely by SSP2-4.5. By the end of the growing

Table 4: Grain yield obtained under projected climate scenarios SSP2-4.5 and SSP5-8.5

Climate scenarios	Projected yield (kg ha^{-1})	Deviation from baseline (%)
Base line	5109	-
SSP2-4.5	4830	-5.78
SSP5-8.5	4945	-3.32

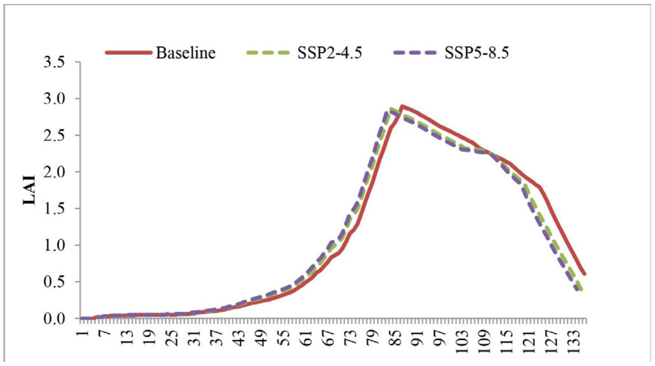

Fig. 3: Variation in LAI under SSP2-4.5 and SSP5-8.5with respect to base line year 2022-23

period, both SSP2-4.5 (7321.33 g/m²) and SSP5-8.5 (7479.17 g/m²) scenarios resulted in higher dry matter values compared to the baseline, with SSP5-8.5 demonstrating the most pronounced increase (Fig. 2). Moreover, significant changes in dry matter accumulation began after 86 days, marking the end of the vegetative stage. Zheng *et al.,* (2017) also indicated an increase in temperature by 1.1°C enhanced the grain dry matter partition ratio and the contribution of dry matter translocation by 5.6% and 68.6%, respectively. While, future climate projections suggested a positive impact on the grain-filling stage, with minimal effects during the vegetative stage and a diminishing positive impact after grain filling. This suggests that elevated temperature and CO_2 concentrations in the future climate scenarios (especially SSP5-8.5) may enhance crop growth and dry matter accumulation, potentially due to increased photosynthesis and biomass production (Mukherjee *et al.,* 2024). However, the extent of this benefit would also depend on other growth-limiting factors such as water availability and nutrient status.

Effect of projected climate on Leaf area index

The model result indicated similar trend for both the projected climate scenarios over baseline. The simulated leaf area index (LAI) was found to decrease during the grain-filling stage, with a greater reduction under the SSP5-8.5 scenario compared to SSP2-4.5. On the other hand, an overestimation was observed for both projected climate scenarios up until the end of the vegetative stages, with the maximum LAI reaching 2.86 at 84 days and 2.84 at 83 days under the two scenarios, respectively. However, after this point (during the reproductive stages), an underestimation occurred, following the trend of the baseline (Fig. 3). This indicates that higher magnitude of weather variables, particularly rising temperatures have negative impact on LAI beyond the vegetative phase. While climate projections showed an increase in LAI during the vegetative stage, a sharp decline was observed afterward. Similar to dry matter, changes in LAI began around the end of the vegetative stage, approximately 86 days after sowing. In the end, future climate projections indicated a negative impact on the grain-filling and post-grain-filling stages but a positive effect during the vegetative stage. A study by Ramezani *et al.,* (2020) found that in deciduous forests and shrubs, increased CO_2 levels combined with higher temperatures and precipitation led to an increase in LAI. This discrepancy may be attributed to the nitrogen availability differences between these vegetation types (Psibisauskiene *et al.,* 2012).

Effect of projected climate on grain yield

The simulated yields were projected to decrease by 5.78 % and 3.32 % under SSP2-4.5 and SSP5-8.5 scenarios in comparison to baseline yield of 5109 kg ha^{-1} (Table 4). Among the projected climate scenarios, the decrease in yield was found higher under SSP5-8.5 scenario due to higher magnitude than SSP2-4.5. When temperature, precipitation and CO_2 concentration are increased together, they prolong the length of growing season and maturity date, which ultimately can cause wheat yield to decline (Pal *et al.,* 2014). A study by Zheng *et al.,* (2017) reported that the post anthesis warming with results in lower grain yield (8.1%).

CONCLUSION

This study revealed that the duration of wheat was projected to be shortened during mid-century period under climate scenarios SSP2-4.5 and SSP5-8.5 compared to the baseline. Dry matter accumulation increased consistently throughout the crop growth period under both SSP scenarios. In contrast, the leaf area index (LAI) increased until the end of the vegetative stage but declined during the reproductive stage. The grain yield was projected to decrease under two climate scenarios. The grain-filling stage was identified as the most critical period influencing biophysical parameters under projected climate conditions.

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Data availability: The crop experimental data was obtained from the field experiment.

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