Climatic Change (2020) 163:253–266
https://doi.org/10.1007/s10584-020-02855-7

Climate change impacts and adaptations for wheat employing multiple climate and crop models in Pakistan

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Received: 19 August 2017 / Accepted: 30 August 2020 /Published online: 3 October 2020

Abstract
Comparing outputs of multiple climate and crop models is an option to assess the uncertainty in simulations in a changing climate. The use of multiple wheat models under five plausible future simulated climatic conditions is rarely found in literature. CERES-Wheat, DSSAT-Nwheat, CROPSIM-Wheat, and APSIM-Wheat models were calibrated with observed data form eleven sowing dates (15 October to 15 March) of irrigated wheat trails at Faisalabad, Pakistan, to explore close to real climate changing impacts and adaptations. Twenty-nine GCM of CMIP5 were used to generate future climate scenarios during 2040–2069 under RCP 8.5. These scenarios were categorized among five climatic conditions (Cool/Wet, Cool/Dry, Hot/Wet, Hot/Dry, Middle) on the basis of monthly changes in temperature and rainfall of wheat season using a stretched distribution approach (STA). The five GCM at Faisalabad and Layyah were selected and used in the wheat multimodels set to CO_2 571 ppm. In the future, the temperature of both locations will elevate 2–3 °C under the five climatic conditions, although Faisalabad will

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be drier and Layyah will be wetter as compared with baseline conditions. Climate change impacts were quantified on wheat sown on different dates, including 1 November, 15 November, and 30 November which showed average reduction at semiarid and arid environment by 23.5%, 19.8%, and 31%, respectively. Agronomic and breeding options offset the climate change impacts and also increased simulated yield about 20% in all climatic conditions. The number of GCMs was considerably different in each quadrate of STA, showing the uncertainty in possible future climatic conditions of both locations. Uncertainty among wheat models was higher at Layyah as compared with Faisalabad. Under Hot/Dry and Hot/Wet climatic conditions, wheat models were the most uncertain to simulate impacts and adaptations. DSSAT-Nwheat and APSIM-Wheat were the most and least sensitive to changing temperature among years and climatic conditions, respectively.

Keywords Planting dates · Multimodels · Climate change · Adaptations · GCMs · Stretched distribution approach

1 Introduction

Climate models have predicted a mean increase in temperature by 1–3.7 °C and a greater likelihood of higher frequency of heat waves and changing patterns of precipitation over most land areas by the mid to late twenty-first century (IPCC 2013). Pakistan is expected to be one of the countries most affected by climate change in South Asia (Stocker et al. 2013; Ullah et al. 2016). The day temperature of Pakistan has been increasing significantly in the months of March, April, and May, and the night temperature is elevating in the month of March, which is during a grain filling stage of wheat (Iqbal et al. 2015). The semiarid environment of Pakistan is expected to warm by 2 to 3 °C during midcentury under representative concentration pathway (RCP) 8.5 from five General Circulation Models (Ahmad et al. 2015).

Agricultural production systems are vulnerable because they are directly exposed to the changing climate, and risks are multiplying with recent unprecedented weather events (Thornton et al. 2010). With negative impacts of climate change on other crops, wheat is under threat with increasing temperature and changing rainfall pattern and intensity. Sultana et al. (2009) predicted 6% reduction in grain yield in semiarid and arid environments of Pakistan with rise of 1 °C temperature, while Ahmad et al. (2015) reported that a 2 °C rise in temperature may cause 15.2% reduction in yield of irrigated wheat in semiarid environment during midcentury 2040–2069.

Studies on climate change are limited in Pakistan especially in the arid environment (Ullah et al. 2016). Wheat is a staple food globally and has not been studied thoroughly in the era of climate change. Studies on climate change impacts on wheat through multiple crop and climate models are very limited especially in Pakistan with comprehensive methodology. Exploring the impacts of climate change on wheat is a way forward to develop agronomic and breeding adaptation options to boost wheat yield. For example, Ahmad et al. (2015) suggested early sowing of wheat in the semiarid environment of Pakistan with changing climate. In our studies, all possible climate scenarios have been explored for the future, and crop models have been calibrated for different wheat varieties sown on eleven dates 15 October to 15 March, representing changing temperatures from low to high.

To quantify the uncertainty and increase the reliability of model results, a multimodel ensemble is a better option to quantify the impacts of climate change (Martre et al. 2015) and develop adaptations (Ewert 2012). The significant objectives of this study are (1) to quantify climate change impacts on irrigated wheat in arid and semiarid environments through crop simulation modeling during 2040–2069; (2) to assess uncertainties in simulations of four wheat models and five GCMs; and (3) to evaluate adaptation options for wheat to minimize the climate change effects on wheat.

2 Materials and methods

2.1 Generation of baseline climatic data (1980–2010)

The baseline period (1980–2010) historical daily weather data of Faisalabad were available, while baseline data of Layyah were simulated. The simulated baseline data and changes in monthly climatology of Layyah were determined between WorldClim data and observed data from the nearest meteorological observatory. WorldClim contains high-resolution global climate grids of approximately 1 km^2 (Hijmans et al. 2005). Missing data were filled by gap-filling bias adjustment, described in Agricultural Model Intercomparison and Improvement Project (AgMIP) Guide for Regional Integrated Assessments Handbook of Methods and Procedures Version 5.0 (Rosenzweig et al. 2013). Differences in monthly climatology were calculated between WorldClim dataset. This set of activity produces a continuous, complete, and physically consistent daily climate series for the two districts from 1980 to 2010.

2.2 Generation of future climate projections

Climate change projections for the region were generated using five GCMs at Faisalabad (CESM1-BGC, inmcm4, IPSL-CM5A-MR, CMCC-CMS, and NorESM1-M) and Layyah (bcc-csm1-1, inmcm4, CanESM2, CMCC-CMS, and ACCESS1-0) to represent the uncertainty in projected temperature and rainfall changes based on five possible climate characteristics (Cool/Wet, Cool/Dry, Hot/Wet, Hot/Dry, and Middle), respectively (Taylor at al. 2012; Hudson et al. 2015). In this process, Fig. 1 presents the subset of GCMs for Faisalabad and Layyah by letter. Figure 2 shows the change in future temperatures (2040–2069) and change in rainfall from the baseline climate (1980–2010). The five GCMs for Faisalabad were CESM1-BGC, inmcm4, IPSL-CM5A-MR, CMCC-CMS, and NorESM1-M presented (Fig. 1a) with letters (f, l, n, w, and a) to represent the five possible climate conditions Cool/Wet, Cool/Dry, Hot/Wet, Hot/Dry, and Middle, respectively. At Layyah, five selected GCMs were (Fig. 1b) bcc-csm1-1 (b), inmcm4 (l), CanESM2 (d), CMCC-CMS (w), and ACCESS1-0 (a) to represent five possible climate conditions Cool/Wet, Cool/Dry, Hot/Wet, Hot/Dry, and Middle, respectively. The subset of GCMs was presented in Fig. 1 for Faisalabad (Fig. 1a) and Layyah (Fig. 1b) by letter on five possible climate characteristics (Cool/Wet, Cool/Dry, Hot/Wet, Hot/Dry, and Middle), respectively.

2.3 Multimodels and simulations analysis

Four wheat models such as CERES-Wheat, DSSAT-Nwheat, CROPSIM-Wheat, and APSIM-Wheat (Table 1) were used to quantify the climate change impacts on wheat and develop adaptation options for wheat (Table 2). These models were calibrated, parameterized, and evaluated with a long series of sowing dates grown under very low to high temperature to represent the climate change impacts on wheat of both locations.

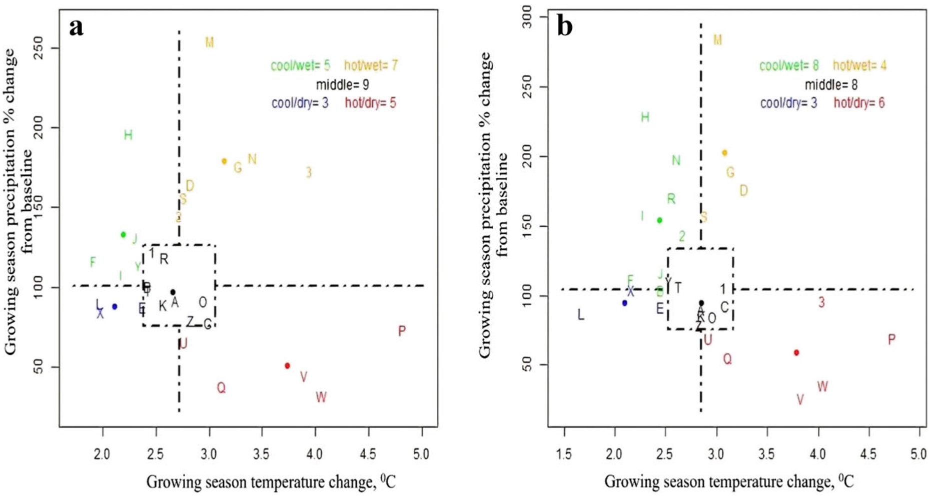

Fig. 1 Temperature (°C) and precipitation (%) change of future (2040–2069) from baseline climate (1980–2010) for (1) distribution of 29 General Circulation Models among five projected climatic conditions Cool/Wet, Hot/Wet, Cool/Dry, Hot/Dry, and Middle during November, December, January, February, March, and April (wheat season) under RCP8.5 at Faisalabad (**a**) and Layyah (**b**), Pakistan, and (2) selection of 5 representative GCMs from each climatic conditions quadrate

Results from simulations were analyzed as follows:

$$x_k = \bar{y}future, k - \bar{y}baseline, k$$

$$\mathrm{r_k} = \frac{\bar{\mathrm{y}}\mathrm{future,\ k} - \bar{\mathrm{y}}\mathrm{baseline,\ k}}{\bar{\mathrm{y}}\mathrm{baseline,\ k}} \times 100$$

$$\mathrm{r_a} = \frac{\bar{\mathrm{y}}\mathrm{future\ with\ adaptations,\ k} - \bar{\mathrm{y}}\mathrm{future\ without\ adaptations,\ k}}{\bar{\mathrm{y}}\mathrm{future\ without\ apadatations,\ k}} \times 100$$

where $x_k$is predicted yield change according to the model k, and $\bar{y}$ future, k is yield averaged over 30 years of baseline climate according to model k. r_a is relative grain yield change with adaptations as compared with without adaptations for future climate (2040–2069).

3 Results

3.1 Climate change scenarios

Change in maximum and minimum temperature and rainfall showed an increase in mean temperature in the future (2040–2069) at both locations under all climatic conditions during the wheat season (Fig. 2). Decreasing trend form November to January of mean temperature and increasing trend from February to April are general past trends and in our future projections. Our results showed that maximum monthly mean temperature of wheat season was elevated 0–2.2 °C, 1.9–2.6 °C, 3.5–5.1 °C, 2.5–3.9 °C, and 1.9–3.1 °C under Cool/Dry, Cool/Wet, Hot/Dry, Hot/Wet, and Middle climatic conditions, respectively, for the future (2040–2069) as compared with baseline (1980–

Table 1 Brief description of four wheat models CERES-Wheat, DSSAT-Nwheat, APSIM-Wheat, and CROPSIM-Wheat

CERES-Wheat	DSSAT-Nwheat	APSIM-Wheat	CROPSIM-Wheat
Original CERES-Wheat (Ritchie et al. 1998) model as implemented in the Cropping System Model of DSSAT, using a common soil water, nitrogen, and organic carbon simulation	NWheat model as implemented in DSSAT recently. NWheat is a modification of the original CERES-Wheat model (Asseng et al. 2011)	The NWheat model as implemented in the Cropping System Model of APSIM using a common soil water, nitrogen, and organic carbon simulation	The CROPSIM-Wheat model as implemented in Cropping System Model of DSSAT using a common soil water, nitrogen, and organic carbon simulation. CROPSIM is a generic crop model that was originally based on CERES-Wheat

2010) at Faisalabad. Maximum temperature elevation of November, December, January, February, March, and April ranged 0–3.5 °C, 0.7–4.1 °C, 0.7–3.4 °C, 1.6–4.5 °C, 2–5.1 °C, and 2–4.8 °C, respectively, with projections of different climatic conditions. During March among different climatic conditions, the highest temperature (33.7 °C) and the lowest temperature (30.6 °C) were observed in Hot/Dry conditions. Overall dry conditions were predicted for the semiarid environment of Faisalabad, which received 14.4 mm during January, 17.05 mm during February, 33.64 mm during March, and 9.35 mm during April.

Layyah is classified as an arid environment. Future projections of Layyah showed that maximum and minimum temperature would increase with higher rainfall. Figure 2 d of Tmax showed that there would be an increase in temperature of all five future climate ranging (0–3.5 °C) as compared with baseline (27.5 °C). In case of December, Tmax was calculated in Hot/Dry conditions (4.1 °C) while minimum during Cool/Dry (0.7 °C) climatic conditions. January was predicted the coolest month of midcentury with temperature about 20.6 to 24.1 °C compared with the baseline temperature of 19.7 °C. In February, temperature again would start to rise and reach at 28.37 °C during Hot/Dry conditions, whereas it would be about 25.4 °C in Cool/Dry conditions. Temperature during baseline climate of February was 24.1 °C. In March, temperature would remain higher than February with temperature ranging from 29.6 to 32.6 °C under different climatic conditions, while baseline temperature was 27.3 °

Table 2 Agronomic and breeding adaptation options for wheat under future climate change 2040–2069 and baseline climate (1980–2010)

Adaptations	Specific practices	Increase (%/unit)
Agronomic adaptations	Soil fertility	8%
	Increase in urea	15%
	Early planting	10 days
	Planting density	8%
	Organic matter	10%
Breeding adaptations	CO_2 response curve	10%
	Heat/temperature tolerance	2 °C
	Radiation use efficiency	8–12%
	Grain weight	10%

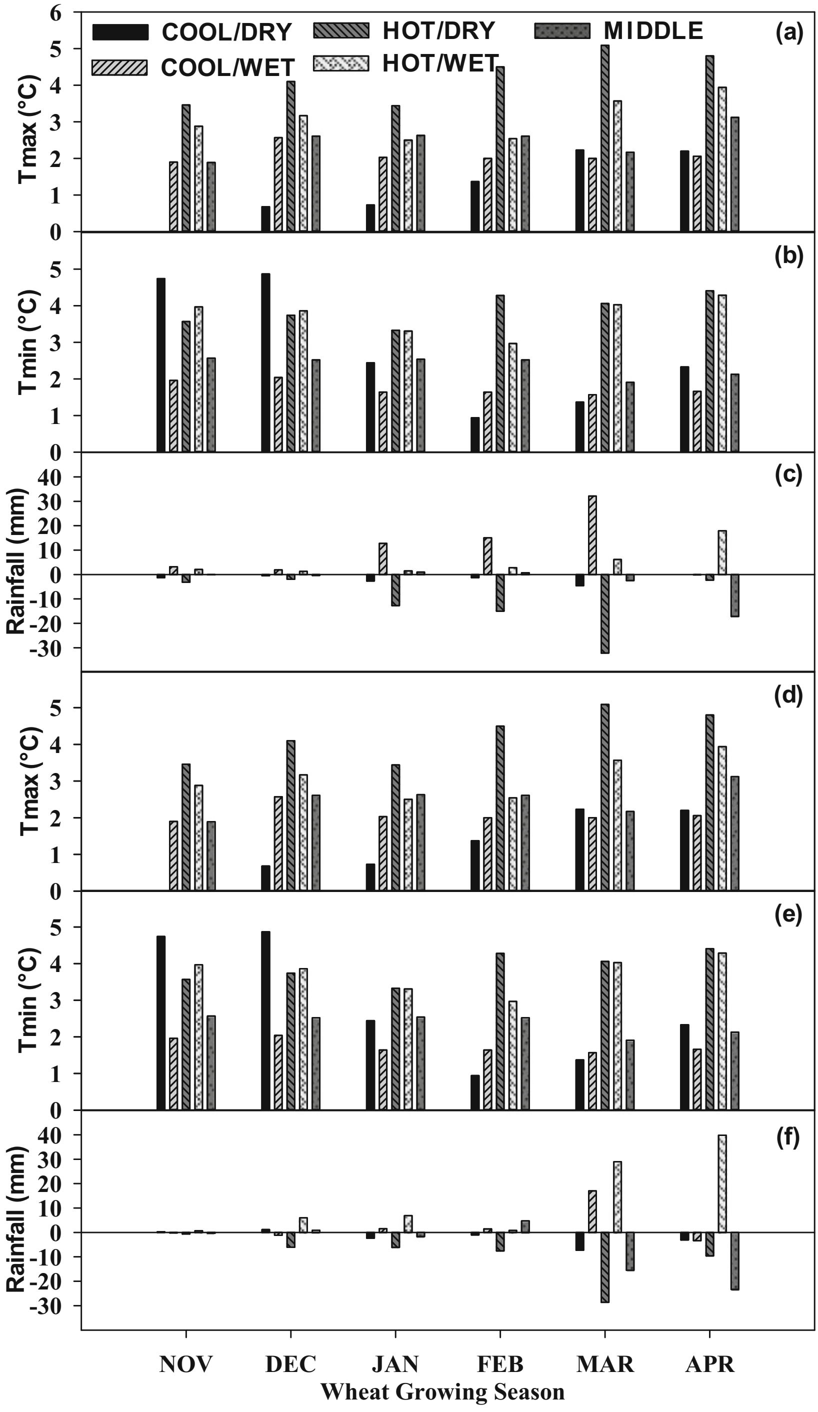

Fig. 2 Change in monthly Tmax (°C), Tmin (°C), and precipitation (mm) of future (2040–2069) from baseline (1980–2010) at Faisalabad (**a**, **b**, **c**) and Layyah (**d**, **e**, **f**), respectively, for climatic conditions Cool/Dry, Hot/Dry, Cool/Wet, Hot/Wet, and Middle under RCP8.5

C. During April, temperature would be 39.4 °C in Hot/Dry conditions, while baseline temperate was 34.6 °C.

Future rainfall for Layyah would be higher as compared with Faisalabad as shown in Fig. 2 c and f. Faisalabad is classified as a semiarid climate and Layyah as an arid climate; however, future projections (2040–2069) showed higher rainfall at Layyah than at Faisalabad, that is, a switch in their classification (Fig. 2).

3.2 Climate change impacts

3.2.1 Early sown wheat

Wheat planted around the first week of November is considered early-planted wheat. Simulated grain yield of four models over 30 years for early-planted wheat varied among locations and future climatic conditions as shown in Fig. 3 a and b for Faisalabad and Layyah, respectively. At Faisalabad, variation among climatic conditions was higher as compared with Layyah. Maximum yield of wheat was reduced owing to Hot/Dry conditions (27.5%) followed by Hot/Wet (15%) conditions, while Middle climatic conditions also caused 10% grain yield reduction. Four models simulated grain yield under Cool/Wet and Cool/Dry climate closer to baseline, which would not be a big threat to wheat in the future. In arid conditions of Layyah, maximum yield reduction was observed under Hot/Dry (17%) climatic conditions followed by Middle climatic scenarios (6%). In contrast to projections of Faisalabad, chances of yield reduction were lesser during Hot/Wet conditions at Layyah, with more reduction due to Cool/Wet conditions. Interestingly, simulated wheat yield showed higher production during Cool/Dry conditions at arid environment of Layyah.

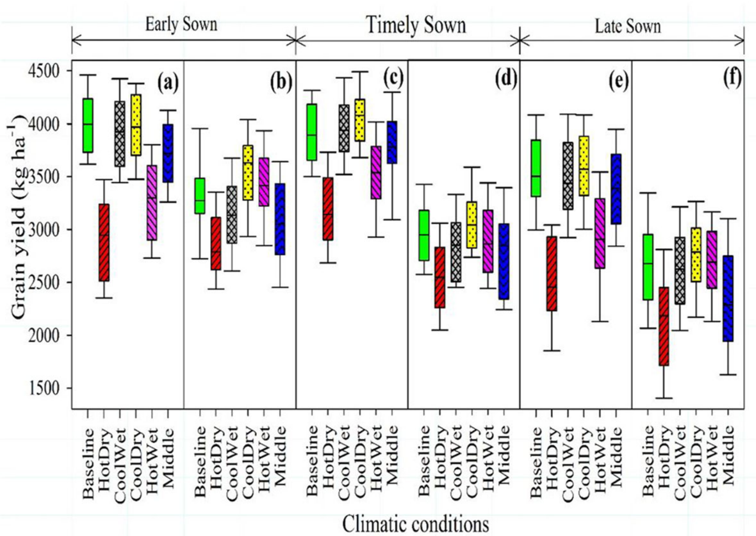

Fig. 3 Impact of projected climatic conditions (Hot/Dry, Cool/Wet, Cool/Dry, Hot/Wet, and Middle) of midcentury (2040–2069) and baseline climate (1980–2010) on grain yield of early, timely, and late sown wheat at Faisalabad (**a**, **c**, **d**) and Layyah (**b**, **d**, **f**) under RCP8.5

3.2.2 Timely sown wheat

Wheat sowed around the 15 November is considered timely sown. Future outputs of models for timely planting date also showed that wheat would be least affected if planted around 15 November (Fig. 3 c and d). Simulated yield of crop models had the same trend at timely planting dates as in early planting dates, but the reduction rate of timely planting date was lesser to early planting date. Maximum yield reduction was observed under Hot/Dry conditions (19.23%) followed by Hot/Wet conditions (9.61%) in comparison with baseline climate (3900 kg ha^{-1}). Variation in simulations of four crop models was decreased at timely planting date, which showed low uncertainty in outputs of models. At Layyah, baseline yield was 2930 kg ha^{-1} as compared with early planting dates (3250 kg ha^{-1}). In future climatic conditions, Hot/Dry conditions would cause 15.35% reduction in grain yield. Interestingly, variation among models was more in timely planting date as compared with early planting date at Layyah. The results of early and timely sown wheat show that wheat should be sown around 1 November at Layyah for maximum production under baseline, current, and future climate.

3.2.3 Late sown wheat

Late sown wheat (30 November) faces problem of high temperature which causes substantial reduction in yield. Simulated baseline yields of Faisalabad (Fig. 3e) and Layyah (Fig. 3f) were 3500 kg ha^{-1} and 2700 kg ha^{-1}, respectively, as usually observed in farmers' fields and experiments. Models simulated that yield would be reduced to 2500 kg ha^{-1} (28.57%) under Hot/Dry followed by Hot/Wet (18.57%) climatic conditions of Faisalabad as shown in Fig. 3e, while Cool/Dry climatic conditions showed probabilities of yield increase. Cool/Wet and Middle climatic conditions also caused reduction in grain yield. Delay in the sowing of wheat increased uncertainty in simulations of

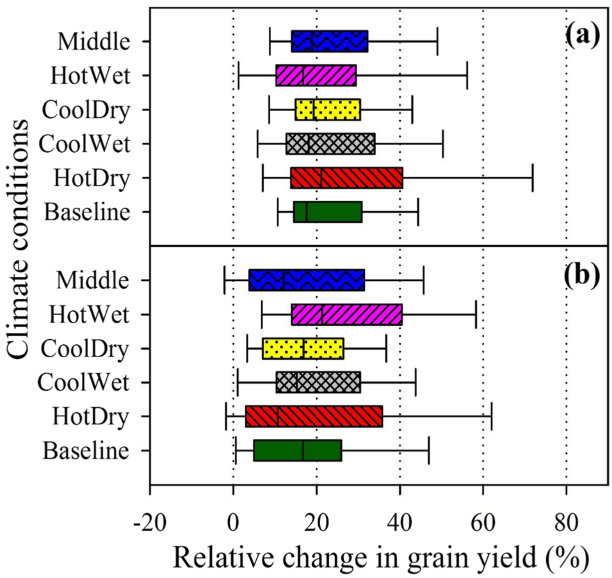

Fig. 4 Relative change in simulated grain yield (%) of all models with agronomic and breeding adaptations to without adaption under baseline (1980–2010) and future (2040–2069) climatic conditions of Faisalabad (**a**) and Layyah (**b**)

multimodels. In the case of Layyah, Hot/Dry conditions caused maximum yield reduction (18.50%) as compared with the baseline, followed by Middle climatic conditions (14.81%). Uncertainty in models was increased with delay in planting as shown in Fig. 3.

In future climatic conditions, yield would be reduced except Cool/Dry conditions at both locations, whiles reduction rate would be maximum in wheat yield planted on 30 November as compared with planting of 15 November and 1 November. In current climate as shown by baseline data, wheat should be planted around 15 November at Faisalabad and 1 November at Layyah.

3.3 Climate change adaptations

The grain yield was higher with agronomic and breeding adaptations (ideotype) than without adaptations under future climate (Fig. 4). Comparing the simulated yield of Faisalabad indicated maximum increase in Hot/Dry (> 20%) conditions and minimum increase during Hot/Wet climatic conditions (< 20%), while 20% increase was noticed in all other climatic conditions. In hotter climatic conditions, the uncertainty was higher in simulations of models such as Hot/Dry (5–72%) and Hot/Wet (0–58%).

In the case of Layyah, the trend of crop models for different climatic conditions was similar to Faisalabad. However, the median relative increase showed that maximum relative grain yield (> 20%) was increased during Hot/Wet conditions, while minimum increase (< 15%) was obtained during Hot/Dry conditions at Layyah. At Layyah, the same trend was found as in Faisalabad, while the percent increase in relative yield had more uncertainty in simulations.

Adaptations were effective in all climatic conditions from Cool/Wet to Hot/Dry in all four models at both locations. Combined application of all adaptations (agronomic and breeding) was effective to adapt all climatic conditions. Crop model simulations were more uncertain at hotter conditions as compared with cooler conditions. More variation was observed at high percentage increase of yield as compared with lower percentage increase of yield.

3.4 Uncertainties in climate change impacts and adaptations

Climate change impacts varied with the crop model climatic conditions and locations (Fig. 5). Climatic conditions were a major source of uncertainty, followed by location. All four models showed different trends to all climatic conditions at Faisalabad (Fig. 5a–f) and Layyah (Fig. 5 g, h, I, j, k and l). All models simulated maximum yield reduction under Hot/Dry climatic conditions and minimum under Cool/Wet climatic conditions except DSSAT-Nwheat. Wheat models are sensitive to these climatic conditions in the same way, but the sensitivity level of models was not the same. For example, all four wheat models showed maximum reduction in grain yield during Hot/Dry conditions, but reduction percentage was different among models. APSIM-Wheat and CERES-Wheat showed minimum and maximum uncertainty in simulated grain yield during Hot/Dry and Hot/Wet climatic conditions, respectively.

In Fig. 6, APSIM-Wheat showed the increasing trend in grain yield under Cool/Dry climatic conditions at Faisalabad. DSSAT-Nwheat simulations showed variation among simulation of different climatic conditions with same trend of APSIM-Wheat, while range of data was wider in Hot/Dry and Hot/Wet climatic conditions. Simulations of CERES-Wheat model were also uncertain at hotter conditions as compared with cooler conditions, while CROPSIM-Wheat showed higher agreement in simulation at hotter climates as compared with cooler climates as in other models. Layyah is currently facing arid conditions. Among the four

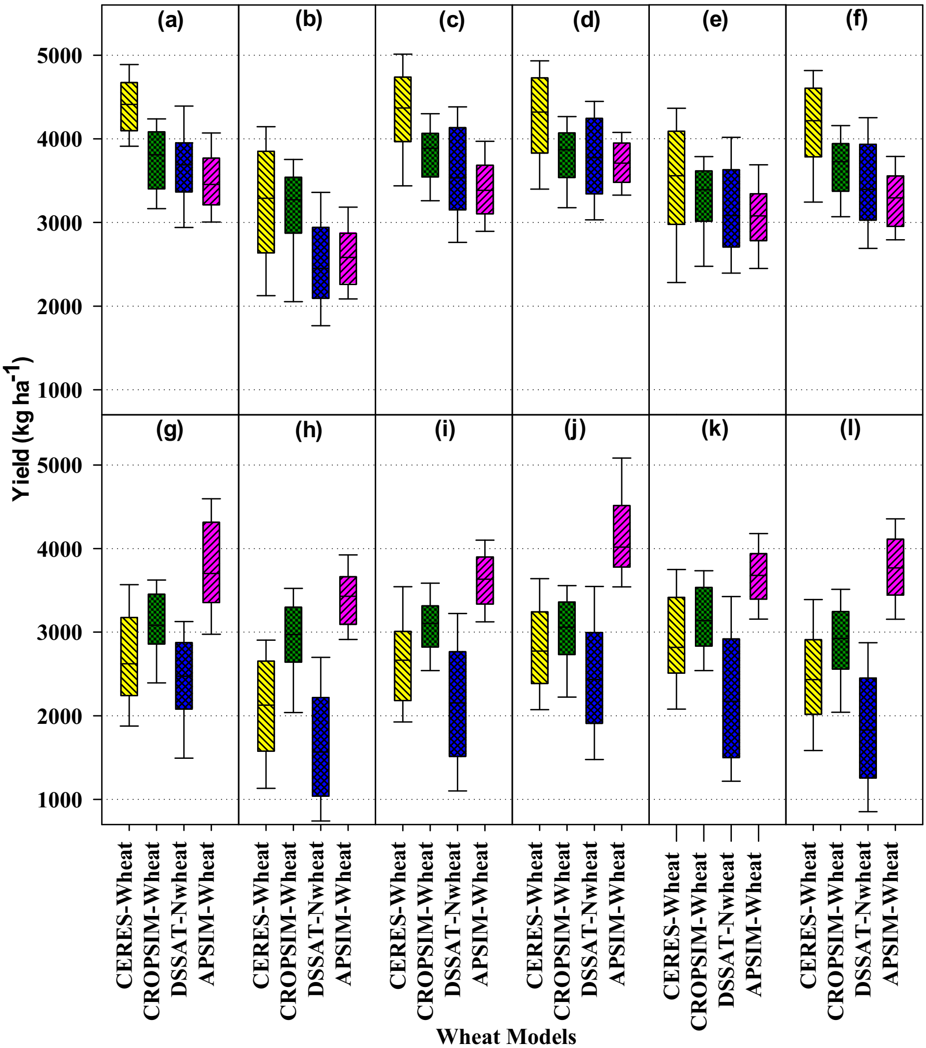

Fig. 5 Uncertainty among wheat models (CERES-Wheat, CROPSIM-Wheat, DSSAT-Nwheat, APSIM-Wheat) with climatic conditions, baseline, Hot/Dry, Cool/Wet, Cool/Dry, Hot/Wet, and Middle in **a**, **b**, **c**, **d**, **e**, and **f** at Faisalabad and **g**, **h**, **i**, **j**, **k**, and **l** at Layyah, respectively

wheat models and five climatic conditions, more uncertainty was found as compared with Faisalabad. Nwheat was more sensitive to different climatic conditions as compared with other models, while CROPSIM-model was the least responsive to all climatic conditions. Uncertainty in the simulations of single climatic conditions (e.g., Hot/Dry) was the maximum in the CERES-Wheat while the minimum in APSIM-Wheat.

APSIM-Wheat showed that yield would change (− 20 to + 20%) under reference line in Hot/Dry climatic conditions, whereas Cool/Dry climatic conditions showed that yield would change in future (− 2 to + 30%) over the reference line. Nwheat showed highest uncertainty at Hot/Dry conditions ranging − 60 to + 2%, and agreement of simulations was the maximum

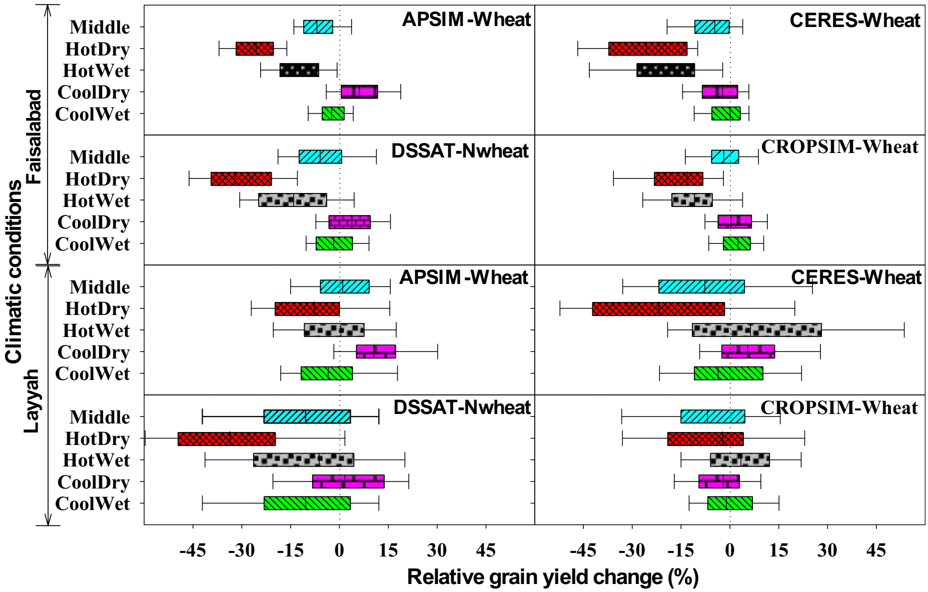

Fig. 6 Relative simulated grain yield change (%) with adaptations under different climatic conditions from baseline climate of APSIM-Wheat, CERES-Wheat, DSSAT-Nwheat, and CROPSIM-Wheat at Faisalabad and Layyah during midcentury 2040–2069

under Cool/Dry climatic conditions. CERES-Wheat was the most uncertain and showed higher chances of yield increase as compared with other crop models under Hot/Wet climatic conditions. CROPSIM-Wheat showed a decreasing trend (medians lower than reference line) of yield under all climatic conditions except Hot/Wet climate.

4 Discussion

Projections of climate and crops models for future are inherently uncertain due to the complexity of agro-ecosystem and uncertainty in driving factors. Using multiple GCMs and wheat models is the most reliable approach to simulate the future climate and wheat production.

4.1 Climate change scenarios

Distribution of 29 GCMs in five quadrate Hot/Wet, Hot/Dry, Cool/Wet, Cool/Dry, and Middle according to change in temperature and rainfall gave a comprehensive understanding of GCMs output and future climate. Hot/Wet, Hot/Dry, Cool/Wet, Cool/Dry, and Middle climatic conditions were possibly predicted by seven, five, five, three, and nine at Faisalabad and four, six, eight, three, and eight GCMs at Layyah, respectively (Fig. 1). A different number of models was distributed among five climatic conditions, which showed a variation among 29 GCMs in prediction of future climate. Furthermore, the possibility of a different climatic condition occurring also changes due to a different number of models in every quadrate (Fig.

1). Maximum nine GCMs were agreed to predict Middle climatic conditions followed by Hot/Wet (7 GCMs) and minimum (3 GCMs) under Cool/Dry climatic conditions at Faisalabad. The highest number of GCMs showed the highest chances of prevailing Middle climatic conditions while the least chances of Cool/Dry climatic conditions at Faisalabad. At Layyah, Cool/Wet and Middle climatic conditions were on par to occur in the future, while Cool/Dry climatic conditions are least expected in the future. Finally, selecting a representative GCM for each climatic condition increased the reliability of results for simulating future possible conditions.

4.2 Climate change impacts

Among five climatic conditions, Hot/Dry conditions caused maximum reduction in the production of grain yield due to its high temperature and dry conditions. Although our analysis was focused on irrigated wheat, future dry conditions with high temperature would increase the evapotranspiration losses of crop, increasing the demand for water for wheat crops. Furthermore, rising temperature under Hot/Dry conditions decreases crop total and grain filling duration, tillering potential, and causing sterility at anthesis stage.

Comparing climate change impacts on early, timely, and late-planted wheat showed that maximum grain yield of late-planted (40%) wheat would be reduced followed by early planting (33%) and minimum in timely planting (23%) at Faisalabad. At Layyah, reduction of grain yield would be 14%, 15%, and 22% at early, timely, and late planting, respectively. Increasing rainfall and current lower baseline yield at Layyah in the future might be the reason for lower reduction as compared with Faisalabad. The main reason of reduction in yield is always high temperature, which shortens the duration of grain filling (Rezaei et al. 2015). Early-planted wheat has longer duration as compared with late-planted wheat, which provides more tillering opportunity, high number of grains, and longer grain filling duration. Ahmad et al. (2015) reported that climate change will reduce the wheat yield by 15.2% in midcentury scenarios, while Sultana et al. (2009) predicted 6–9% in reduction of wheat yield in arid and semiarid environments. Results of our study showed higher reduction in yield than previous studies. This difference might be because of the methodology of using wheat multimodels. Although models are useful in simulating climate change impacts, using single climatic conditions for future and a single crop model is not considered a wise decision. Our study focused on two sites using five different possible climatic conditions, and we used four crop models with three cultivars of wheat to quantify the climate change impacts on three planting windows of wheat. This study explored the future climate for wheat very well with less uncertainty in simulated results as compared with the previous studies.

4.3 Climate change adaptations

In our study, agronomic and genetic options were combined to evaluate their impacts on wheat yield under future climate. Suggested adaptations proved useful to offset climate change impacts and boost the wheat yield from 15 to 20% in both arid and semiarid environments. Wheat yield is a product of environment × genetic × management (Howden et al. 2007; Craufurd et al. 2013). We must search the best options of genetic (breeding) and management (agronomic) for the best fit with the environment for higher wheat yield. The combinations of different adaptations were useful for all climatic conditions (e.g., Hot/Dry, Cool/Dry, Hot/Wet, Cool/Wet, and Middle), owing to effectiveness of diverse adaptation options. Sultana et al. (2009) proposed shifting the planting window to compensate climate change impacts. Ahmad et al. (2015) suggested to increase nitrogen and plant population, decrease water use, and shift planting windows to early November to suit different climatic conditions and enhance wheat production for the future changing climate. Yield was comparatively more enhanced in our studies because of genetic adaptations, which are equally effective in diverse climatic conditions from Hot/Dry to Cool/Wet. Overall, adaptations were very reliable in all climatic conditions except Hot/Dry and Hot/Wet climatic conditions, which showed a lot of variation in simulated yield. The crux of the discussion is that adaptations proved highly important to boost wheat production in future climate due to their diversity in nature.

4.4 Uncertainties in climate change impacts and adaptations

Crop yield simulations are uncertain under future climatic scenarios in their predictions (Godfray et al. 2010; Asseng et al. 2013). Multiple models are recommended to minimize the uncertainty in crop simulations models (Asseng et al. 2013; Martre et al. 2015; Hussain et al. 2018). Quantification of uncertainty in climate change impacts and adaptations are necessary to check the reliability level of simulation results (Asseng et al. 2013). It is impossible to quantify the level of reliability without using a multimodel approach for future climate. Two models may coincide and provide unrealistic results, while increasing the number of models increases reliability of results. Asseng et al. (2013) recommended the application of a different number of models at changing warming levels to get reliable results of future climate change impacts. The same results were observed in a study under discussion during quantifications of climate change impacts that variation in model outputs was increased with Hot/Dry conditions as compared with Cool/Dry conditions. The performance of models changes with the changing climatic conditions because of the different function and structure of the models. Furthermore, sensitivity of wheat models differs under different climatic conditions such as Hot/Dry, Cool/Dry, and Middle climatic conditions. During evaluation of climate change adaptations for wheat, models showed higher variation in simulations under hotter climatic condition than cooler climatic conditions. For example, during simulation of baseline climate, the uncertainty in model simulations was lower than Middle climatic conditions due to hot conditions during Middle climate. During simulation of climate change impacts, APSIM-Wheat showed the opposite response to Middle climatic conditions due to difference in rainfall of both locations. Furthermore, the models' response to locations was also different due to different climatic and soil conditions of both locations.

5 Conclusions

In the future, the mean temperature is expected to increase 2–3 °C during midcentury, which warming will severely affect wheat yield and threaten food security. Grain yield of early (1 November), timely (15 November), and late sown (30 November) of irrigated wheat was decreased by 33%, 23%, and 40% in semiarid and 14%, 15%, and 22% in arid environment, respectively. Simulations were uncertain under Hot/Dry climatic conditions. Using multimodels to quantify the climate change impacts and adaptations is a more reliable approach and good technique to decrease uncertainty in simulations of models. Combined effects of agronomic and breeding adaptations are not only useful to offset climate change impacts but also boost grain yield about 20%.

Acknowledgments I thank the Agricultural Model Intercomparison and Improvement Project and its leaders C. Rosenzweig from NASA Goddard Institute for Space Studies and Columbia University (USA), J. Jones from University of Florida (USA) for suggesting this study.

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