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It may be cited using the following DOI

DOI: 10.20937/ATM.52751
Acceptance date: 27 January 2020

The published manuscript will replace this preliminary version at the above DOI.

Atmósfera is a quarterly journal published by the Universidad Nacional Autónoma de México (UNAM) through its Centro de Ciencias de la Atmósfera in Mexico City, Mexico. ISSN 2395-8812. https://www.revistascca.unam.mx/atm
Implications of 1.5 and 2.0°C additional warming for wheat yield using a gridded modeling approach

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Highlights

• The CERES-Wheat model was calibrated well with experimental data set

• Mean temperature of 0.5°C -1.5°C will increase under HAPPI scenarios

• Wheat yield will decline by 3-5% in Punjab, while 13-18% in Sindh provinces under HAPPI scenarios

• Wheat yield will increase by 13% in Khyber Pakhtunkhwa, while 9-15% in Baluchistan under HAPPI scenarios

Abstract

The goal of limiting the increasing global mean temperature below 2.0°C and possibly to 1.5°C, was decided in Paris Agreement in 2015. It is therefore important to understand the climate risk and impacts associated with 1.5°C and 2.0°C additional warming scenarios. The current study investigates the impacts of 1.5°C and 2.0°C additional warming on wheat yield in Pakistan using a gridded modeling approach. The generated climate data by four GCMs under 1.5°C and 2.0°C were acquired from the Half a degree Additional warming, Prognosis and Projected Impacts (HAPPI) scenarios group. The CERES-Wheat model was calibrated and evaluated using the field data and then applied to the entire region of Pakistan. Model calibration results showed a close association between observed and simulated wheat yield with an error ranging from 0.52 to 1.36%. Climate change projections indicated that the mean temperature is expected to rise by 0.46°C in 1.5°C and 1.44°C in 2.0°C additional warming scenarios in the GCMs. The spatial variations of precipitation ranges from -22.4 to 42.6% and 4.6 to 34.1% under 1.5°C and 2.0°C HAPPI scenarios, respectively. Higher precipitation was recorded in northern Pakistan as compared to central and southern Pakistan. The projected changes in temperature and precipitation will decrease the wheat yield by 3.2% and 4.7% in Punjab, 17.8% and 13.8% in Sindh province under 1.5°C and 2.0°C additional warming, respectively. However, the wheat yield will increase by 4.7% and 13% in KP, 9.4% and 15.3% in Baluchistan under 1.5°C and 2.0°C additional warming, respectively.

Keywords: Gridded modeling, HAPPI scenarios, Climate impacts, Wheat, Pakistan
1. Introduction

Climate change is threatening agriculture and food security globally (Lipper et al., 2014; Lobell and Gourdji, 2012; Moorhead, 2009). Variations in temperature and uneven distribution of precipitation, negatively impact the crop production (Ahmed et al., 2018; Asseng et al., 2015a; Rahman et al., 2018; Ullah et al., 2019a). Future climate projections indicate that the global surface temperature is expected to increase by 0.8°C to 1.2°C between 2030 to 2052, resulting in decrease in agriculture productivity (IPCC, 2013). Paris Agreement in 2015 sets a goal to constrain the global warming by 2.0°C and pursue efforts to limit the rise in temperature by 1.5°C (Rogelj et al., 2016). So, there is an urgent need to explicitly evaluate the spatial climate change variations and impact at country scale under 1.5°C and 2.0°C additional warming, which will provide the requisite scientific information to the policy makers to develop the adaptation and mitigation strategies.

Wheat is one of the domesticated and widely grown staple food in many developing countries including Pakistan (FAO, 2017). Wheat contributes 9.6% in value addition and 1.9% in Gross Domestic Product (GDP) of Pakistan. Wheat is cultivated on an area of 9.05 million hectare with a total production of 25.7 million tones (Government of Pakistan, 2017). Wheat production in Pakistan is high; an increase unusual climatic conditions such as heat waves, uncertain precipitation and drought have caused the reduction in wheat yield (Ali et al., 2017). Thus, assessing the impact of warming levels of ≤ 2.0°C above pre-industrial level, including the benefits of CO₂ fertilization on wheat productivity is quite timely for ensuring global food security (Rosenzweig et al., 2014).

Climate change projections showed that temperature is expected to rise by 2.8°C by the middle of century, resulting in 15% reduction in wheat yield (Chaudhry, 2017). However, Chaudhry (2017) used Coupled Model Intercomparison Project Phase 5 (CMIP5) only and no spatiotemporal variability was studied. The reduction in wheat yield due to higher temperature could be due to shorting of growing period (Asseng et al., 2011; Hernandez-Ochoa et al., 2018; Ahmed et al. 2019a). Rise in temperature will reduce the growing season length by accelerating the phenological development, resulting in wheat yield decrease (Asseng et al., 2015a; Lobell and Ortiz-Monasterio 2007; Ullah et al. 2019b). High temperature reduces the grain filling duration of the crop, however, cooler temperature at grain filling stage could result in high yield due to delay...
in maturity (Asseng et al., 2015a). Temperature stress reduces the number of grain and grain size, which leads to a decrease in yield (Dias and Lidon, 2009).

In recent past, crop simulation models are generally employed to estimate crop performance under climate change (Eitzinger et al., 2004; Harrison et al., 2000; Hoogenboom et al., 2006). Crop models such as Decision Support System for Agro-technology Transfer (DSSAT) predict the development, growth and yield of crops through mathematical equations as a function of crop genetics, management practices, soil and weather conditions (Hoogenboom, 2000). Crop models have been used under gridded modeling approach, which provided an accurate information in decision management and climate impacts at regional scale under spatially heterogenous conditions (Holzworth et al. 2015; Müller et al. 2017; Vanli et al. 2019). The detailed insight and risks in agriculture sector for Pakistan under Half a degree Additional warming, Prognosis and Projected Impacts (HAPPI) scenarios (Mitchell et al., 2017), remained unstudied so far.

Various studies were conducted on climate change impact assessment in agriculture sector. For example, Ahmad et al. (2015) used the General Circulation Models (GCMs)’ data and found that due to rise of 2.8°C temperature, the wheat yield will decrease by 15% in Punjab. Sadozai et al. (2019) reported that wheat yield will decrease by 6% due to rise in temperature of 1°C in Khyber Pakhtunkhwa (KP), Pakistan. They also noticed that wheat yield will decrease by 11% due to rise of 1°C in Sindh, Pakistan. The Crop Environment Resource Synthesis (CERES)-Wheat model was also used for climate change studies. Previous studies assessed the climate impacts on a specific location, however, spatial pattern of changes in wheat yield over the entire region of Pakistan under 1.5°C and 2.0°C additional warming scenarios are not yet studied, as mentioned earlier.

It is also documented that 1.5°C and 2.0°C additional warming will affect negatively the Sub-Saharan agriculture countries (King and Harrington, 2018; Wilfried et al., 2018). Thus, the current study is planned to use gridded simulations for evaluation of the impacts of 1.5°C and 2.0°C additional warming on wheat yield and development of ensuing empirical models for arid, semi-arid and humid climates in Pakistan. The information on spatial changes in wheat yield under additional warming scenarios will be useful for policy makers and will provide the scientific basis for the development of adaptation strategies. The developed empirical models in this study could be used by researchers and academia to quantify the impact of changes in temperatures and
precipitation on wheat yield under various environmental conditions. In general the developed methodology could be used for regional integrated assessment of climate change as well.

2. Data and methodology

2.1. Description of study area

The study was conducted for data sparse region of Pakistan, located in subtropical zone of southern Asia. Climatic conditions of Pakistan are semiarid with hot summers and mild winters (Ahmad et al., 2018). The entire region of Pakistan was divided into 10 km × 10 km grids with a total 8188 grids to take into account the soil and climatic spatial heterogeneity.

2.2. HAPPI scenarios

Climate data of maximum temperature (Tmax), minimum temperature (Tmin), precipitation (Pr) and solar radiation were downloaded from the HAPPI project (2013). The generated data of HAPPI project describes how the climate might be different from the current one in the world that is 1.5°C and 2.0°C warmer than the pre-industrial conditions (Mitchell et al., 2017). The baseline period of HAPPI dataset is during 2006–2015, while projected climate period ranges between 2030 and 2040 (IPCC, 2018). The output of four GCMs under HAPPI scenarios were used to assess the climate impacts. The Community Atmosphere Model, version 4 (CAM4), contributed by the Federal Institute of Technology (ETH) Zurich with spatial resolution of 1.87° lat ×2.5° lon (Neale et al., 2010). The European Centre for Medium-Range Weather Forecasts, version 6 (ECHAM6), contributed by the Max Planck Institute for Meteorology, Hamburg, Germany with spatial resolution of 1.87° lat ×1.87° lon and it includes a modified version of the land component (Stevens et al., 2013). The Model for Interdisciplinary Research on Climate, version 5 (MIROC5), contributed by the National Institute for Environmental Studies, Tsukub, Japan with spatial resolution: 1.4° lat ×1.4° lon (Shiogama et al. 2014). The model Norwegian Earth System model, version 1 (NorESM1), contributed by the Norwegian Climate Center with spatial resolution of 0.94° lat ×1.25° lon. The NorESM1 is an ocean model, which includes an advanced module for aerosols and aerosol-cloud radiation interactions (Bentsen et al., 2013).

The GCMs were biased corrected by the methods described by Hempel et al. (2013) and Frieler et al. (2017). The climate data were generated from the ensemble simulations under various initial conditions. Climatic data of Pakistan were extracted from global climatic data and disaggregated to 10 km × 10 km grids. The annual mean ambient temperature (TAV) and annual
amplitude (AMP) were also calculated from the climate data. The CO₂ mixing ratio for the baseline period was 390 ppm, while it was 423 ppm (486 ppm) for 1.5°C (2.0°C) additional warming scenario, respectively (Mitchell et al., 2017).

2.3. Soil data

Soil properties data were acquired from ISRIC-World soil information (Hengl et al., 2014). Soil profile data of 0–5, 5–15, 15–30, 30–60 and 60–100 cm depths were taken at 1 km spatial resolution. The soil parameter includes, saturation percent (SP%), bulk density (g cm⁻³), cation exchange capacity (cmol kg⁻¹), organic carbon (%), and soil pH. The global soil data for each of the above parameters were aggregated to 10 km resolution. The drainage upper limit (field capacity) was calculated as 0.50×SP and lower limit (permanent wilting point) as 0.25×SP (Miller and Kissel, 2010).

The soil profile data of 0–5 cm depth is displayed in Fig. 1, which indicated that more available water and organic carbon were found in north Pakistan while less in central and southern Pakistan. Higher bulk density and soil pH were observed in central and southern Pakistan, while less in northern Pakistan. Higher percentage of silt and clay in soil were recorded in Indus basin irrigation system.

2.4. Model calibration and evaluation

The CERES-Wheat model under the shell of DSSAT was calibrated and evaluated using the field data. The experiment was conducted at Ayub Agriculture Research Institute, Faisalabad during the Rabi season of 2016–17 and 2017–18.

Response of three wheat cultivars (Faisalabad-2008, Lasani-2008 and Sehar-2006) were evaluated under four different levels of nitrogen (0, 50, 100 and 200 kg ha⁻¹). The genetic coefficients of model were adjusted at non-stressed treatment of 100 kg N ha⁻¹ for three cultivars using Generalized Likelihood Uncertainty Estimation (GLUE); as used by Ahmed et al. (2018). After calibration, model was evaluated using experimental data for the year 2017–18.

2.5. Impact assessment of 1.5°C and 2.0°C additional warming scenarios using gridded approach

The calibrated CERES-Wheat model was used for gridded climate analysis. The recommended crop management practices and fertilizers such as Nitrogen (N), Phosphorus (P) and
Potassium (K) by the Govt. of Pakistan were used as management for model. The management practices were divided into irrigated (4 irrigations of 75 mm), rainfed (no irrigation) and partially irrigated (2 irrigation of 75 mm) categories as shown in Table I. The spatial analysis was carried out in model to estimate the impact of 1.5°C and 2.0°C additional warming under HAPPI scenarios. The output yield of each grid was displayed via geo-spatial maps for Pakistan. The detail methodology is presented in Fig. 2.

The impacts of climate change on yield were computed by the difference of yield with 1.5°C and 2.0°C additional warming from baseline yield as described in Eq. (1).

\[ Y_c = \frac{Y_f - Y_b}{Y_b} \times 100 \]  

where, \( Y_c \) was the percent change in yield, \( Y_f \) was the future simulated yield, while \( Y_b \) the baseline simulated yield.

Multiple linear yield estimation empirical models were developed by utilizing the climate variables for arid, semi-arid and humid areas of Pakistan. Temperature, precipitation and yield differences were computed for the baseline and future period of each GCM and the Least Absolute Shrinkage and Selection Operator (LASSO) regression was employed to develop the empirical model. About 70% data was used for the development of model, whereas 30% for validation, following Kohavi (1995).

3. Results

3.1. Estimated genetic coefficient of CERES-Wheat model

The estimated genetic coefficients of wheat cultivars during model calibration are displayed in Table II. The coefficients P1V and P1D are related to phenology when moisture is a non-limiting factor for germination and the rate of crop development depends upon the temperature. The values of vernalization (P1V) were set to 9–0 days for spring wheat cultivars. The photoperiod requirement (P1D) were similar for Lasani-2008 and Sehar-2006, while lower for Faisalabad-2008. A large thermal time of 430°C day\(^{-1}\) at grain filling (P5) was estimated for Faisalabad-2008 and Sehar-2006 as compared to that for Lasani-2006.

The G1 and G2 coefficients are related to yield traits and showed a compensatory affect since increasing G1 results in decreasing of G2. The G3 is related to plant height and biomass
production and did not showed any difference among wheat cultivars. The PHINT is the Phyllochroin interval that showed the appearance of leaves on stem and is temperature dependent. The wheat cultivars did not show any difference during the vegetative stage.

3.2. Calibration and evaluation of CERES-Wheat model

The CERES-Wheat model was calibrated using the field observations on phenology, growth and yield attributes (Table III). A close agreement was observed in simulation of anthesis and maturity days. Model simulated the anthesis with no difference between simulated and field observation for Faislabad-2008 and Sehar-2006, whereas only one day difference was observed for Lasani-2008. The simulated maturity days were close to observed values for Lasani-2008 and Sehar-2006, however, model showed two days early maturity for Faisalabad-2008 (Table III). Model over simulated the leaf area index maximum \((\text{LAI}_{\text{max}})\) for all cultivars with an error ranging from 5.76 to 9.25%.

The wheat yield was also simulated well by the model, a close match was found between simulated and observed values with an error ranging from 0.52 to 1.36%. A close fit was also recorded in simulation of biological yield for Faislabad-2008 and Sehar-2006, while model over simulated the biomass for Lasani-2008 with an error of 6.94%.

Evaluation results indicated that the performance of model was reasonably well as shown in Table IV. Model simulated the anthesis days well at different levels of nitrogen for three cultivars of wheat. Nevertheless, a 4 days difference was recorded with the field observation at which zero nitrogen was applied for Sehar-2006. The simulation of maturity days was good by model, however, a 2–3 days difference was recorded relative to the observed values at high dose of 200 kg N ha\(^{-1}\). The LAI simulation was satisfactory, but higher error was recorded at zero and 200 kg N ha\(^{-1}\). Model showed a close match in simulation of grain with observed one at various doses of nitrogen and cultivars with an error ranging from 0.59 to 11.60%. In case of biological simulation, model overestimated the biomass at zero nitrogen, which could be due to presence of initial nitrogen.

3.3. Climate change projections under HAPPI scenarios
Projected winter temperature and precipitation in all GCMs under HAPPI scenarios displayed different patterns over the entire region of Pakistan (Fig. 3 to Fig. 5). The spatial pattern of warming is similar under 1.5°C and 2.0°C additional warming scenarios, the magnitude of warming is higher over the entire region of Pakistan under 2.0°C additional warming scenario. Spatial pattern of Tmax and Tmin revealed a lesser increase in northern Pakistan, while a more increase is projected in central and southern Pakistan (Fig. 3 and Fig. 4). The CAM4 showed a higher increase in Tmax and Tmin in Pakistan, whereas ECHM6 showed a less increase in Tmax and Tmin over the entire region especially in KP and Gilgit Baltistan. The NorESM1 displayed more increase in Tmax in Punjab (Fig. 3), with less increase in Tmin (Fig. 4). The Tmax ensemble mean showed an increase over the entire region of Pakistan under 1.5°C additional warming, whereas greater increase was observed in Punjab under 2°C additional warming (Fig. 3). The Tmin ensemble mean showed a greater increase in Gilgit-Baltistan in 1.5°C and 2.0°C additional warming scenarios (Fig. 4).

Precipitation trend showed an increase under 1.5°C and 2.0°C additional warming scenarios. The change in spatial pattern of precipitation was also similar in both 1.5°C and 2.0°C additional warming scenarios in Pakistan. Higher precipitation was recorded in KP and Gilgit-Baltistan, whereas lower in Punjab, Sindh and Baluchistan (Fig. 5). Wheat is a winter (rabi) crop sown in November-December and harvested in March-April and the crop fully relies on irrigation because of low precipitation during winter. Increased rainfall during critical stages (crown root initiation, flowering, and physiological maturity) enhances the yield (Mudasser et al. 2001; Ahmad et al. 2019b). Thus, high precipitation in KP and Gilgit-Baltistan as shown in Fig. 5, enhanced the yield, while less precipitation in lower in Punjab, Sindh and Baluchistan caused the reduction in yield.

Furthermore, HAPPI scenarios indicated that Tmax (Tmin) will increase by 2.60°C (0.66°C) under 1.5°C warming scenario, whereas Tmax (Tmin) will increase by 1.45°C (1.44°C) under 2.0°C warming scenario in Pakistan (Table V). The ensemble means showed that the Tmax will increase by 0.85°C, Tmin will increase by 1.05°C and precipitation by 204 mm under 1.5°C and 2.0°C additional warming during 2030-2040 (Table V). Thus, higher temperatures, coupled with less precipitation caused the reduction in wheat yield, because higher temperatures increase levels of water stress in plant cells, crop water requirement, and respiration.
3.4: Impact of 1.5°C and 2.0°C additional warming on wheat yield

The impacts of 1.5°C and 2.0°C additional warming scenarios include both positive as well as negative relative change in wheat yield in different districts of Pakistan (Fig. 6 and Fig. 7). The spatial pattern of yield showed that a higher yield was recorded in KP, Punjab and Sindh provinces, while less yield in Baluchistan and Gilgit Baltistan in all GCMs under 1.5°C and 2.0°C additional warming scenarios (Fig. 6). A maximum wheat yield of 2500–3000 kg ha⁻¹ was recorded in KP, Punjab and Sindh. The high yield was due to good quality soil and availability of water due to presence of Indus and Kabul rivers. The productive zone for wheat cultivation is near to Indus and Kabul rivers in current conditions and under 1.5°C and 2.0°C additional warming scenarios. The new potential areas are emerging for wheat cultivation in Gilgit Baltistan, KP and Baluchistan under 1.5°C and 2.0°C additional warming scenarios (Fig. 6).

The spatial pattern of changes in wheat yield (%) at district level showed a similar trend in both 1.5°C and 2.0°C additional warming scenarios, with a higher increase in yield was found in 2.0°C warming scenario (Fig. 7). A reduction in yield was recorded in Punjab, Sindh and few districts in Baluchistan, whereas the areas in KP, Baluchistan and Gilgit Baltistan showed an increase in yield under both 1.5°C and 2.0°C additional warming scenarios as compared to baseline. A high reduction in yield was recorded in CAM4 and MICRO5. The CAM4 showed a decrease in yield in Baluchistan and in few areas in KP under 1.5°C warming scenarios, whereas MIROC5 showed a decrease in yield in Baluchistan under both 1.5°C and 2.0°C additional warming scenarios (Fig. 7). The ECHAM6 and NorESM1 displayed a decrease in yield in Punjab and an increase in yield in KP, Baluchistan and in Gilgit Baltistan (Fig. 7).

The yield will decrease by 3.25% and 4.75% in Punjab, while 17.8% and 13.8% in Sindh under 1.5°C and 2.0°C warming scenarios, respectively. However, the yield will increase by 13% in KP, while an increase of 9.4% and 15.3% in Baluchistan under 1.5°C and 2.0°C additional warming scenarios is projected. The Gilgit Baltistan showed an increased in yield of 10.6% under 1.5°C and 98% in 2.0°C warming scenarios. The higher increase in yield at Gilgit Baltistan was due to suitability of new areas for wheat production due to additional warming of 1.5°C and 2.0°C as shown in Table VI.

The climate change impacts showed a reduction in yield of 3.2% and 4.7% in Punjab, 17.8% and 13.8% in Sindh province, under 1.5°C and 2.0°C additional warming scenarios,
respectively. However, the yield increases by 4.7% and 13% in KP, 9.4% and 15.3% in Baluchistan under 1.5°C and 2.0°C additional warming scenarios respectively. The reduction in yield was calculated using Eq. (1). The Gilgit Baltistan showed a greater increase in yield of 10.6% and 98% in both 1.5°C and 2.0°C additional warming (Table VI). The greater increased in yield under 2.0°C additional warming could be due to emergence of new areas for wheat production.

The GCMs indicated an uncertainty in evaluating the climate change impacts. The country average showed a higher reduction in yield of 11.7% in CAM4 and 9.8% in MIROC5 was recorded under 1.5°C additional warming, whereas yield increases in all GCMs under 2.0°C additional warming (Table VI and Fig. 8). A greater increase in yield was recorded in NorESM1 under both additional warming scenarios. The CAM4 and MIROC5 have more interquartile ranges as compared to ECHAM6 and NorESM1 (Fig. 8). Considering the values less then 25th percentile or more then 75th percentile as outliers; the ECHAM6 under 1.5°C (Fig. 8a) and MIROC5 under 2.0°C displayed more outliers (Fig. 8b).

3.5. Development of empirical model for yield estimation

Yield estimating empirical models were developed for arid (annual precipitation less than 300 mm), semi-arid (300–1000) and humid (>1000) environment using LASSO regression (Table VII). The differences of Tmax, Tmin, precipitation and yields were calculated using the future GCMs relative to baseline, with 70% of gridded data of all GCMs were used to develop the model and 30% were used to test the model. The results indicated that all climate variables significantly contributed in the development of model, except for Tmin for arid environment and precipitation for humid environment (Table VII).

The developed empirical based models for estimating the wheat yield for arid \(Y_a\), semi-arid \(Y_{sa}\) and humid \(Y_h\) environments are given in Eq. (4), Eq. (5) and Eq. (6), respectively:

\[
Y_a = -42.31 - 22.90 \times T_{max} + 8.02 \times T_{min} + 0.10 \times Pr
\]  

(2)

\[
Y_{sa} = 12.0 - 119.0 \times T_{max} + 73.14 \times T_{min} + 0.47 \times Pr
\]  

(3)

\[
Y_h = 106.0 - 264.90 \times T_{max} + 288.20 \times T_{min} + 0.005 \times Pr
\]  

(4)
Here \( Y \) is in kg ha\(^{-1} \), \( Tmax \) and \( Tmin \) are in °C and \( P \) is in mm. The results indicate that due to rise of 1°C \( Tmax \) the yield will be decreased by 22.9 kg ha\(^{-1} \) in arid, 119 kg ha\(^{-1} \) in semi-arid and 264 kg ha\(^{-1} \) in humid environment. While 1°C rise of \( Tmin \) increased the yield by 8 kg ha\(^{-1} \) in arid, 73 kg ha\(^{-1} \) in semi-arid and 288 kg ha\(^{-1} \) in humid environment.

The performance of developed empirical model for arid environmental was good since it indicated the RMSE of 102.9 kg ha\(^{-1} \), with \( R^2 \) of 0.71. The results for semi-arid environments were also good with RMSE values of 128.2 kg ha\(^{-1} \) and \( R^2 \) of 0.74. The developed model for humid environment also showed RMSE of 147.5 kg ha\(^{-1} \) and \( R^2 \) of 0.68. The developed models will be useful for stakeholders such as policy makers, researchers, farmers and academia in estimation of yield in changing climate conditions. The yield change (kg ha\(^{-1} \)) can be estimated by knowing the change in temperatures and precipitation. The impact of unit change in \( Tmax \), \( Tmin \) and precipitation on wheat yield can be calculated for arid, semi-arid and humid environments by using the developed empirical models, shown in Eq. (2), Eq. (3), and Eq. (4), respectively.

4. Discussion

The calibration of CERES-Wheat model indicated good to fair predictions of phenology, growth and yield of wheat cultivars (Table III). Phenology of wheat has a strong influence on development and grain yield of the crop (Ceglar et al., 2011). The precise estimation of phenological events is the first priority to calibrate crop mode, because it captures all genotypic variations which affect the leaf area development, biomass production and grain yield (Robertson et al., 2002). In CERES-Wheat model, flowering and maturity dates were controlled by parameters like P1V, P1D, P5 and PHINT (Andarzian et al., 2008). In the current study, a close agreement was found between predicted and observed days to anthesis and maturity as indicated by different validation scores (Table III and Table IV).

In CERES-Wheat model, \( G1 \), \( G2 \) and \( G3 \) were the parameters controlling grain yield, therefore precise adjustment of these parameters is important. The results of simulations showed that the yield remained close to the observed values among all cultivars as confirmed by the validation skill scores (Table III and Table IV). Related coefficients represented by \( G1 \) (grain number) and \( G2 \) (grain size) showed the compensatory affect in all cultivars (Table II). It could be due to the fact that as number of grain increases, the assimilates available for grain filling decreases; the grain weight is reduced due to higher competition (Maldonado-Ibarra et al., 2015).
Climate change projections showed a higher increase in temperature in Punjab, Sindh and Baluchistan, while a lower increase in KP and Gilgit Baltistan provinces in Pakistan (Fig. 3). The northern Pakistan (KP and Gilgit Baltistan) is at high altitude, which has cold mountains and frigid areas, thus a less increase in temperature and more precipitation was projected in climate change scenarios. However, Punjab, Sindh and Baluchistan are the middle and low altitude areas at which a greater increase in temperature was projected. A higher precipitation was projected in 2.0°C additional warming scenario as compared to 1.5°C additional warming scenarios (Fig. 3). It could be due to fact that high temperature could cause the higher evaporation and more water is available for precipitation (Trenberth, 2011).

Projected rise in temperature and changing precipitation patterns under 1.5°C and 2.0°C additional warming scenarios showed a decrease in yield at Punjab and Sindh, while an increase in KP, Baluchistan and Gilgit Baltistan is predicted (Table VI). The Punjab and Sindh are the hotter areas as compared to northern Pakistan, thus additional warming of 1.5°C and 2.0°C and a decrease in precipitation pattern resulted in a yield decrease (Fig. 4). The decrease in yield was due to reduction in growing period of crop with an increase in temperature. Another reason could be that higher temperature decrease the number of tillers, grain size and weight, resulting in a decrease in yield (Wheeler et al., 1996; Ahmad et al. 2018a). Temperature greater than 32°C reduces the grain filling duration that limit the time for development of grains for wheat (Asseng et al., 2015b). The yield increased in few areas; it could be due to availability of favorable temperature for wheat production and the warmer environment that is close to the optimal temperature for photosynthesis. Normally in northern Pakistan, temperature is very low and unfavorable for successful crop production. Thus, a combination of increased temperatures, changing patterns of precipitation and CO₂ fertilization affects will offer a suitable growth environment for successful wheat production in northern Pakistan.

The multiple linear regression empirical models were developed for yield estimation from climate variables for arid, semi-arid and humid environments separately using LASSO regression (Table VII). The LASSO employs machine learning approach which is used to develop the models. It is widely used by researchers for training and testing of linear models (Hans, 2009; Meier et al., 2008; Reid et al., 2016). The developed regression equations reflect the linear combination of Tmax, Tmin and Pr, and will be useful for stakeholders such as researchers, farmers
to estimate the variation in yield due to changes in temperature and precipitation. The yield variation will provide the scientific basis for the development of adaptation strategies offsetting the impacts of climate change.

In the current study, there were extreme changes in yield (above 75th percentile and below 25th percentile) in all GCMs as displayed in Fig. 8. The extreme increase in yield could be due to addition of new areas for wheat production due to favorable environment of 1.5°C and 2.0°C additional warming scenarios including the changing pattern of precipitation. The extreme reduction in yield could be extinction of few areas for wheat production due to unsuitable condition by additional warming of 1.5°C and 2.0°C and changes in precipitation. Overall benefits from climate change are larger than yield losses. Thus, it could be expected that 1.5°C and 2.0°C additional warming would bring more opportunity than a risk for crop production and food supply in Pakistan.

5. Conclusions

The study was conducted to investigates the climate risk and impacts associated with 1.5°C and 2.0°C additional warming scenarios on wheat yield in Pakistan using a gridded modeling approach. The salient features of this study are as follows:

- The CERES-Wheat model was calibrated using experimental data set, which showed a good agreement between observed and simulated values of wheat yield with an error ranging between 0.52 and 1.36%.
- Spatial distribution patterns showed a higher increased in Tmax, Tmin and a lower precipitation in Punjab and Sind as compared to KP, Baluchistan and Gilgit Baltistan provinces of Pakistan under 1.5°C and 2.0°C additional warming scenarios.
- Climate change projections showed that mean temperature is expected to rise by 0.46°C in 1.5°C additional warming scenario and 1.44°C in 2.0°C additional warming scenario in Pakistan.
- The projected changes in temperature and precipitation will decrease the yield by 3.2% and 4.7% in Punjab, while 17.8% and 13.8% in Sindh provinces under 1.5°C and 2.0°C additional warming scenarios, respectively.
- Wheat yield will increase by 13% in Khyber Pakhtunkhwa, while 9.4% and 15.3% in Baluchistan under 1.5°C and 2.0°C additional warming scenarios, respectively. Thus,
creating an opportunity to identify the new areas for wheat production for ensuring food security in Pakistan

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Table I. The Govt. of Pakistan recommended management practices for wheat production in each grid.

| Management Practices | No. of Irrigations | Irrigation quantity (mm) | Sowing date | NPK applied (kg ha\(^{-1}\)) | Seed rate (kg ha\(^{-1}\)) | Total Grids |
|----------------------|--------------------|--------------------------|-------------|-----------------------------|-----------------------------|-------------|
| Irrigated            | 4                  | 60-60-75-75              | 20 Nov      | 65+65:114:62                | 125                         | 1994        |
| Partially irrigated  | 2                  | 60-60-0-0                | 01 Nov      | 65+65:114:62                | 100                         | 422         |
| Rainfed              |                    | Rainfed                  | 01 Nov      | 65:114:62                   | 100                         | 5772        |
Table II. Adjusted genetic coefficients of CERES-Wheat for three cultivars of wheat.

| Cultivars        | P1V | P1D | P5  | G1  | G2  | G3  | PHINT |
|------------------|-----|-----|-----|-----|-----|-----|-------|
| Faisalabad-2008  | 9   | 47  | 429 | 35  | 20  | 2.8 | 100   |
| Lasani-2008      | 10  | 50  | 402 | 31  | 21  | 2.8 | 102   |
| Sehar-2006       | 10  | 49  | 420 | 34  | 20  | 2.8 | 100   |

P1V: vernalization days, P1D: Photoperiodic sensitivity, P5: Grain filling duration (°C day⁻¹), G1: Grain number (# g⁻¹), G2: Grain size (mg), G3: Non-stress tillers, PHINT: Subsequent leaf tip interval (°C day⁻¹)
Table III. Calibration of CERES-Wheat model at 100 kg N ha\(^{-1}\) for various wheat cultivars for the year 2016-17.

| Parameters                  | Faisalabad-2008 |                               | Lasani-2008 |                               | Sehar-2006 |                               |
|-----------------------------|------------------|--------------------------------|--------------|--------------------------------|-------------|---------------------------------|
|                             | Obs. | Sim. | %Error | Obs. | Sim. | %Error | Obs. | Sim. | %Error |
| Days to anthesis            | 106   | 106  | 0.00    | 109  | 108  | -0.91  | 108  | 108  | 0.00    |
| Days to maturity            | 136   | 134  | -1.47   | 137  | 135  | -1.45  | 135  | 135  | 0.00    |
| LAI\(_{max}\)               | 5.20  | 5.50  | 5.76    | 5.20 | 5.60 | 7.69    | 5.40 | 5.90 | 9.25    |
| Wheat yield (kg ha\(^{-1}\)) | 4485 | 4546 | 1.36    | 4147 | 4145 | -0.04  | 4504 | 4527 | 0.51    |
| Biological yield (kg ha\(^{-1}\)) | 12133 | 12445 | 2.57 | 11973 | 12804 | 6.94 | 12375 | 12431 | 0.45    |
| Cultivars Name | Nitrogen Levels (kg ha\(^{-1}\)) | Days to Anthesis | Days to Maturity | LAI Maximum | Wheat Yield | Biological Yield |
|---------------|---------------------------------|------------------|------------------|-------------|-------------|------------------|
|               | 2016-17 | 2017-18 | 2016-17 | 2017-18 | 2016-17 | 2017-18 | 2016-17 | 2017-18 | 2016-17 | 2017-18 |
| Faisalabad-2008 | 0       | 0.95    | 0.93    | -0.74   | 0.00    | -11.1  | 0.00    | 2.90    | 8.53    | -0.77   | 2.42    |
|                | 50      | 0.00    | 0.00    | -1.48   | 0.74    | 3.12   | 7.41    | 6.37    | 7.95    | 2.69    | 4.19    |
|                | 100     | 0.00    | 1.87    | -1.47   | 0.74    | 5.76   | 10.00   | 1.36    | 6.72    | 2.57    | 11.25   |
|                | 200     | -0.93   | 0.00    | -2.13   | 1.47    | 3.33   | 10.87   | 0.19    | 1.94    | 6.08    | 1.39    |
| Lasani-2008   | 0       | 0.00    | 0.00    | 0.00    | 0.75    | 11.1   | 0.00    | 5.83    | 10.56   | 6.08    | 12.35   |
|                | 50      | 0.00    | 0.00    | -1.46   | 0.00    | 9.68   | 3.85    | 0.59    | 4.91    | 6.21    | 9.58    |
|                | 100     | -0.91   | 0.90    | -1.45   | 0.00    | 7.69   | 6.67    | -0.04   | 11.60   | 6.94    | 2.29    |
|                | 200     | -0.92   | 0.90    | -2.17   | 0.74    | 5.00   | 10.64   | -4.82   | 10.25   | 8.41    | 1.56    |
| Sehar-2006    | 0       | 0.93    | 3.77    | 2.22    | 2.19    | 0.00   | 0.00    | -4.49   | 1.82    | -6.01   | 0.24    |
|                | 50      | 0.93    | 1.85    | 2.22    | 2.19    | 2.94   | 8.74    | -1.11   | 8.20    | -4.62   | 4.61    |
|                | 100     | 0.00    | 1.85    | 0.00    | 2.90    | 9.25   | 3.33    | 0.51    | 5.56    | 0.45    | 10.37   |
|                | 200     | -0.92   | 0.92    | -1.43   | 2.90    | 4.62   | 10.20   | 0.24    | 6.09    | 4.10    | 5.95    |
Table V. Changes in temperatures and accumulated precipitation in winter season for all GCMs under 1.5°C and 2.0°C additional warming scenarios for Pakistan.

| Scenarios | 1.5°C | 2.0°C |
|-----------|-------|-------|
|           | Tmax  | Tmin  | Precipitation | Tmax  | Tmin  | Precipitation |
|           | °C    | °C    | (mm)          | °C    | °C    | (mm)          |
| CAM4      | 1.22  | 1.00  | -290.4        | 1.95  | 1.89  | 59.07         |
| ECHAM6    | -0.13 | 0.22  | 583.7         | 1.06  | 1.34  | 466.9         |
| MIROC5    | -0.80 | 1.06  | 232.0         | 1.32  | 1.33  | 68.5          |
| NorESM1   | 0.76  | 0.35  | 357.2         | 1.48  | 1.21  | 157.2         |
| Ensemble Mean | 0.26  | 0.66  | 220.6         | 1.45  | 1.44  | 187.9         |
Table VI. Mean percent change in wheat yield in different GCMs under 1.5°C and 2.0°C additional warming scenarios in all provinces of Pakistan.

| Scenarios          | Provinces/ GCMs | CAM4 | ECHAM6 | MIROC5 | NorESM1 | Ensemble Mean | CAM4 | ECHAM6 | MIROC5 | NorESM1 | Ensemble Mean |
|--------------------|-----------------|------|--------|--------|---------|--------------|------|--------|--------|---------|--------------|
|                    | Punjab          | -1.56 | -8.57  | -6.63  | 3.75    | -3.25        | -5.15| -9.21  | -7.13  | 2.51    | -4.75        |
|                    | Sindh           | -10.89| -5.58  | -63.55 | 8.90    | -17.78       | -13.26| -5.61  | -23.57 | -12.77  | -13.80       |
|                    | KP              | -14.65| 11.89  | 7.91   | 13.85   | 4.75         | 3.57 | 22.37  | 2.50   | 23.94   | 13.09        |
|                    | Baluchistan     | -24.46| 35.86  | -12.10 | 38.28   | 9.40         | 31.04| 42.17  | -22.00 | 10.02   | 15.31        |
|                    | Gilgit Baltistan| -6.96 | -0.91  | 25.22  | 25.31   | 10.66        | 53.24| 59.53  | 123.39 | 156.99  | 98.29        |
|                    | Country Average | -11.70| 6.54   | -9.83  | 18.02   | 0.76         | 13.89| 21.85  | 14.64  | 36.14   | 21.63        |
Table VII. Development of empirical yield estimation models for arid, semi-arid and humid environmental conditions under changing climate.

| Co-efficient  | Estimate | Std. Error | t value | P(>|t|) |
|---------------|----------|------------|---------|---------|
| Arid (Precipitation < 300 mm) | | | | |
| Intercept     | -42.31   | 3.93       | -10.74  | 0.00 *  |
| Tmax          | -22.90   | 3.66       | -6.25   | 0.00 *  |
| Tmin          | 8.02     | 3.35       | 2.39    | 0.01 *  |
| Precipitation | 0.40     | 0.01       | 40.48   | 0.00 *  |

Semi-arid (Precipitation 300-1000 mm)

| Co-efficient  | Estimate | Std. Error | t value | P(>|t|) |
|---------------|----------|------------|---------|---------|
| Intercept     | 12.0     | 2.79       | 4.30    | 0.00 *  |
| Tmax          | -119.0   | 2.87       | -41.43  | 0.00 *  |
| Tmin          | 73.14    | 2.86       | 25.58   | 0.00 *  |
| Precipitation | 0.47     | 0.00       | 95.63   | 0.00 *  |

Humid (precipitation >1000 mm)

| Co-efficient  | Estimate | Std. Error | t value | P(>|t|) |
|---------------|----------|------------|---------|---------|
| Intercept     | 106.60   | 6.20       | 17.18   | 0.00 *  |
| Tmax          | -264.90  | 7.78       | -34.04  | 0.00 *  |
| Tmin          | 288.20   | 8.50       | 33.91   | 0.00 *  |
| Precipitation | 0.005    | 0.01       | 0.93    | 0.25    |

Note: The asterisk (*) indicates the probability level of 0.05.
Fig. 1. Spatial distribution of soil properties in Pakistan.
Fig. 2. Methodology for assessing the impact of 1.5°C and 2.0°C additional warming on wheat yield.
Fig. 3. Changes in Tmax of winter season from baseline under 1.5°C (top row panels) and 2.0°C (bottom row panels) additional warming scenarios in Pakistan.
Fig. 4. Changes in Tmin of winter season from baseline under 1.5°C (top row panels) and 2.0°C (bottom row panels) additional warming in Pakistan.
Fig. 5. Changes in precipitation of winter season from baseline under 1.5°C (top row panels) and 2.0°C (bottom row panels) additional warming scenarios in Pakistan.
Fig. 6. Spatial pattern of mean wheat yield in different GCMs under baseline (top row panels), 1.5°C (middle row panels) and 2.0°C (bottom row panels) additional warming scenarios in Pakistan.
Fig. 7. Mean percent change of wheat yield in different GCMs relative to baseline under 1.5°C (top row panels) and 2.0°C (bottom row panels) additional warming scenarios in Pakistan at district level.
Fig. 8. Change in wheat yield (%) in different GCMs under (a) 1.5°C and (b) 2.0°C additional warming in Pakistan.