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RESEARCH ARTICLE

Assessing climate change impacts on pearl millet under arid and semi-arid environments using CSM-CERES-Millet model

Asmat Ullah[1,2,3] · Ishfaq Ahmad[2] · Ashfaq Ahmad[2] · Tasneem Khaliq[2] · Umer Saeed[2] · M. Habib-ur-Rahman[4] · Jamshad Hussain[2] · Shafqat Ullah[5] · Gerrit Hoogenboom[3]

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Abstract

Climate change adversely affects food security all over the world, especially in developing countries where the increasing population is confronting food insecurity and malnutrition. Crop models can assist stakeholders for assessment of climate change in current and future agricultural production systems. The aim of this study was to use of system analysis approach through CSM-CERES-Millet model to quantify climate change and its impact on pearl millet under arid and semi-arid climatic conditions of Punjab, Pakistan. Calibration and evaluation of CERES-Millet were performed with the field observations for pearl millet hybrid 86M86. Mid-century (2040–2069) climate change scenarios for representative concentration pathway (RCP) 4.5 and RCP 8.5 were generated based on an ensemble of selected five general circulation models (GCMs). The model was calibrated with optimum treatment (15-cm plant spacing and 200 kg N ha^{-1}) using field observations on phenology, growth and grain yield. Thereafter, pearl millet cultivar was evaluated with remaining treatments of plant spacing and nitrogen during 2015 and 2016 in Faisalabad and Layyah. The CERES-Millet model was calibrated very well and predicted the grain yield with 1.14% error. Model valuation results showed that there was a close agreement between the observed and simulated values of grain yield with RMSE ranging from 172 to 193 kg ha^{-1}. The results of future climate scenarios revealed that there would be an increase in T_{min} (2.8 °C and 2.9 °C, respectively, for the semi-arid and arid environment) and T_{max} (2.5 °C and 2.7 °C, respectively, for the semi-arid and arid environment) under RCP4.5. For RCP8.5, there would be an increase of 4 °C in T_{min} for the semi-arid and arid environment and an increase of 3.7 °C and 3.9 °C in T_{max}, respectively, for the semi-arid and arid environment. The impacts of climate changes showed that pearl millet yield would be reduced by 7 to 10% under RCPs 4.5 and 8.5 in Faisalabad and 10 to 13% in Layyah under RCP 4.5 and 8.5 for mid-century. So, CSM-CERES-Millet is a useful tool in assessing the climate change impacts.

Keywords Climate change impact assessment · System analysis research · CSM-CERES-Millet

Introduction

Pearl millet crop is the main food source grown in arid and semi-arid parts of Africa and Asia. In Pakistan, it is categorized and minor crop besides wheat, rice, and maize as main crops (Ullah et al. 2017). It is mostly grown in the southern part of Punjab, where weather variability and poor soil health with low water-holding capacity are common characters of the area (Ahmed et al. 2018). The interest of the farming community with management options of the crop is conservative to cover the risks in crop failure (O'Leary et al. 2008).

The poor soil health and climate variability put intense pressure on land and even low plant density (Sanders et al. 1996; Ahmed et al. 2018). Decision-making has been long

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✉ Ishfaq Ahmad
ishfaq.ahmad@uaf.edu.pk; ishfaqkanjal@gmail.com

[1] Ayub Agricultural Research Institute, Faisalabad, Punjab, Pakistan

[2] Department of Agronomy, University of Agriculture, Faisalabad 38040, Pakistan

[3] Institute for Sustainable Food Systems, University of Florida, Gainesville, FL 32611-0570, USA

[4] Department of Agronomy, MNS-University of Agriculture, Multan, Punjab, Pakistan

[5] Pakistan Meteorology Department, Multan, Punjab, Pakistan

derived from great wealth of research to combat the issues of the area to boost the yield of major crops in Pakistan. However, constraints related to pearl millet are still impeding the development of millet farming community in agricultural production systems (Ullah et al. 2017). There is a dire need of such tools that support system analysis approach or decision-making. The Decision Support System for Agro-technology Transfer (DSSAT) is a complete system analysis approach for evaluating crop management factors (Fig. 1) (Tsuji et al. 1994; Hoogenboom 2000; Jones et al. 2003)

Climate change is a real threat to agriculture and food security (Kang et al. 2009; Godfray et al. 2010; Downing 2013). Extreme weather events and uncertainty in rainfall patterns are affecting agriculture productivity (Lobell and Burke 2008; Ahmed et al. 2018; Rahman et al. 2018). Future projections showed that global surface temperature would be increased by 2.5 °C up to 2050, which would negatively affect the crop production (IPCC 2013). There is dire need to assess the climate change impacts on crops that would be helpful in developing adaptations measures. Pearl millet crop is the main food source grown in arid and semi-arid parts of Africa and Asia.

In Pakistan, it is mostly grown in rainfed areas and cultivated on an area of 0.46 million hectare with a total production of 0.30 million tonnes (Government of Pakistan 2017). Pearl millet is a drought-tolerant crop that could be cultivated in various environments such as arid and semi-arid (Ullah et al. 2017). High temperatures and low and high erratic rainfall are the major constraints for millet production (Schlenker and Lobell 2010; Sultan et al. 2013; Ahmad et al. 2018a). The optimum temperatures for peal millet growth are 33 °C day and 28 °C night (Ong and Monteith 1985). Rise in temperature above 33 °C/28 °C decreases the grain yield by reducing the length of growing period (Fussell et al. 1980; Cooper et al. 2009; Ahmad et al. 2018b). The high temperature at vegetative, stem elongation and reproductive stages decreased the grain yield by reducing the basal tillers, grains per inflorescence, and grain weight (Garcia-Huidobro et al. 1982). The future projections of climate change showed that crops yield would be reduced due to the rise in temperature in arid and semi-arid regions (Fischer et al. 2005; Howden et al. 2007). Knox et al. (2012) reported a 10% reduction in millet yield due to climate change by 2050 in Africa. The rise in 6 °C temperature reduced the millet yield by 41% (Sultan et al. 2013). Increased in CO_2 concentration has a beneficial effect in growth and yield of the crop. High concentration of CO_2 partially minimized the negative impacts of rising temperature (Mitchell et al. 1993). The response of climate indicators such as temperatures, precipitation, and CO_2 on crops can be assessed using crop models. Crop growth models are convenient tools for the assessment of climate change impacts on crops (Hoogenboom et al. 2015). However, among crop models, the most used is the Decision Support System for Agrotechnology Transfer (DSSAT) Table 1. It simulates the crop development, growth, and yield by the interaction of soil, plant genetics, and atmospheric variables such as temperatures and precipitations (Jones et al. 2003). Various approaches have been used for assessing the impact of climate change on pearl millet using crop models (Schlenker and Lobell 2010; Sultan et al. 2013; Singh et al. 2017; Toure et al. 2018), but none of these studies used the low and high emission scenarios, i.e., representative concentration pathways

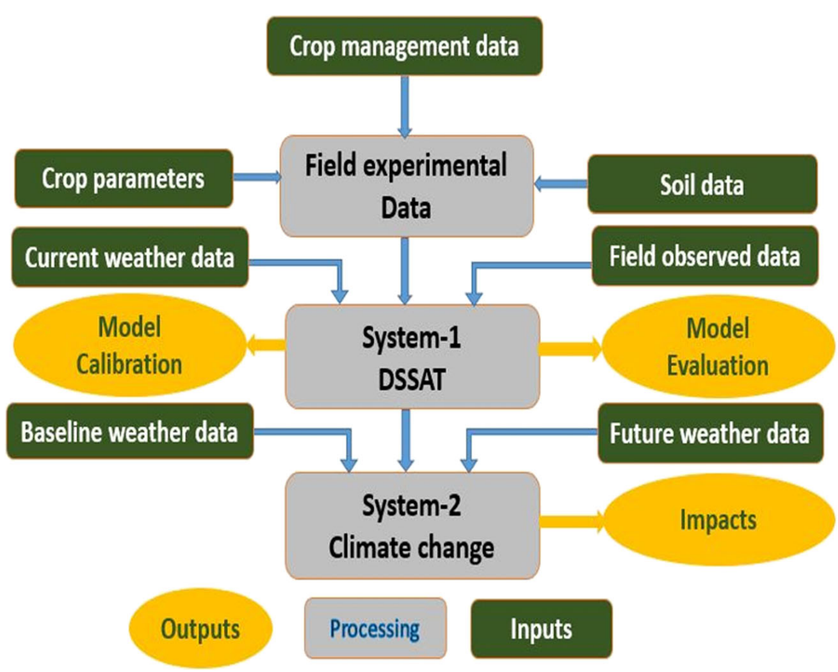


Fig. 1 Methodology showing DSSAT framework and minimum dataset used in system analysis approach

Table 1 List of work on millet using DSSAT

Model application	Country	References
Crop management	Kollo, Niger NE, USA	Fechter et al. 1991; Fechter 1993; Wafula 1995; Soler et al. 2008
Irrigation and water management	Zai, Parakou, Benin, Africa	Fatondji et al. 2012; Akponikpe et al. 2014
Climate change, variability, and risk analysis	Nigeria, Niger	Jones and Thornton 2002; Sultan et al. 2013
Food security	Sudano-Sahelian, Burkina Faso, Africa	Thornton et al. 1997

(RCPs 4.5 and 8.5) for the evaluation of climate change impacts in arid and semi-arid environments. RCPs are plausible emission scenarios which are used to explorer the uncertainties in the future climate (Van Vuuren et al. 2011; Rosenzweig et al. 2013). These new pathways provide the advance scientific understanding of climate system and their impacts on crops. Keeping in views, the present study was planned to assess the impact of climate change on pearl millet for mid-century (2040–2069) in arid and semi-arid environments under RCPs 4.5 and 8.5.

Materials and methods

Study area

This research exploits two field research experiments on the evaluation of millet management options at two different climatic zones. The experiment on optimization of intra-row spacing and nitrogen rate of millet was conducted during the normal millet cropping season at Faisalabad (semi-arid) and Layyah (arid). The details of location with soil properties are shown in Table 2.

Minimum dataset for CSM-CERES-Millet

The experiment comprised of three plant spacings (as the main factor) and four nitrogen levels (0, 150, 200, and 250 kg ha^{-1}) as sub-plot factor. The experiment was executed in a randomized complete block design with split-plot arrangements. The experiment was conducted in the summer season of year 2015 and repeated in 2016 at Faisalabad and Layyah.

The CSM-CERES Millet model of the DSSAT Version 4.6 (Hoogenboom et al. 2015) was selected for a system analysis approach. The minimum dataset required for the model was framed according to the desired format. Weather data were considered as crop seasonal weather, while daily historical data/baseline data (1981–2010) for Faisalabad location were collected from Physiology Section, Department of Agronomy, University of Agriculture, Faisalabad. The baseline data for climate (1980–2010) regarding second location (Layyah) was statistically downscaled as described by (Ullah et al. 2017; Rahman et al. 2018). **Collection of data from field experiments as input for the model:** Crop phenology data were recorded from field experiments during the year 2015 and 2016. Ten plants were tagged in each plot to record the data of days to 50% flowering and days to maturity and it was used to create average (A) file of the model. Time series growth data of leaf area index (LAI) and total dry matter accumulation (TDM) were also recorded fortnightly that was used to create time series (T) file of the model. At maturity, half of the plot was harvested to record the grain and final biological yield. The protocol for data collection was used as described by Ahmed et al. (2018). **Collection of Soil and Weather data for model:** The soil data of experimental sites (Faisalabad and Layyah) were collected from the Soil Survey of Pakistan. Lyallpur and Rangpur soil series were selected for the study region of Faisalabad and Layyah, respectively. Details of soil characteristics are described by Ahmed et al. (2018). According to USDA classification of soils, the soil of Faisalabad was sandy loam to fine clay, silk, and hyper-thermic, while the soil of Layyah was sandy to sandy loam, mixed, hyper-thermic, and typic torripsamments. Both soils were layered into nine profiles due to variations in fertility components. The soils were found alkaline in nature. It was observed that the organic matter, EC and pH, decreased as the depth of soil increased. The data of soil profile, soil horizon, sand (%), silt (%), clay (%), SOC (%), pH, CEC (cmol/kg), and total nitrogen in percentage were used as input data set for soil file in crop model. The drainage upper limit, lower limit, saturation percentage, bulk density (g cm−3), saturated hydraulic conductance (cm h−1), and root growth factors were assessed by following the procedure used by Rawls et al. (1982) and Ahmed et al. (2018).

Daily-basis weather data (T_{max}, T_{min}, rainfall) were collected from the Department of Agronomy, Crop Physiology Section,

Table 2 Study area showing geography, soil, and climatic characteristics

Study area	Latitude, N °	Longitude, E °	Altitude (m)	Soil series, USDA classification	Climatic zone
Faisalabad	31° 26′ 24.34″	73° 04′ 34.43″	184	Lyallpur (fine, loamy, silk, thermic)	Semi-arid
Karor (Layyah)	31° 13′ 10.97″	70° 58′ 31.88″	158	Rangpur (sandy, mixed, hyper-thermic, typic torripsamments)	Arid

University of Agriculture Faisalabad and Pakistan Meteorological Department, Karor-Layyah, as shown in Fig. 1. Results showed that the year 2016 was warmer than 2015 for both locations. Higher values of temperature were recorded in Layyah as compare to Faisalabad due to rainfed conditions. The data were used to create weather input file in DSSA (Fig. 1).

Model calibration

The CSM-CERES Millet model under the shell of Decision Support System for Agro-Technology Transfer (DSSAT) V4.6.1 was used for this study (Hoogenboom et al. 2015). The model was calibrated with optimum treatment (15 cm of plant spacing and 200 kg N ha^{-1}) for the pearl millet hybrid 86M86 at Faisalabad location during the year 2016. During model calibration, genetic coefficient was estimated with the field observations on phenology, growth, grain, and biological yield. Generalized likelihood uncertainty estimation (GLUE) and sensitivity analysis tools built in DSSAT were used for the estimation of the genetic coefficient. A similar approach was used by Rahman et al. (2018) and Ahmed et al. (2018).

Model evaluation

After calibration, the CSM-CERES Millet model was evaluated with the other plant spacings and nitrogen levels during the years 2015 and 2016 at Faisalabad and Layyah. The accuracy and reliability of model was assessed by calculating the statistical indices between observed and simulated values as described by Ahmad et al. (2018a). Statistical indices are shown in Eq. (1)–(3).

$$\mathrm{RMSE} = \left[\sum_{i=1}(P_i - \mathrm{O}_i)^2/n\right]^{0.5} \quad (1)$$

$$d = 1 - \left[\sum_{i=1}(P_i - O_i)^2 / \sum_{i=1}(|P_i| + |O_i|)^2\right] \quad (2)$$

$$\mathrm{Error}\ (\%) = \left[\frac{(Pi - Oi)}{Oi}\right] \times 100 \quad (3)$$

$$\mathrm{MPD} = \left[\sum_{i=1}\{|O_i - P_i|/O_i\} \times 100\right]/n \quad (4)$$

where P_i and O_i show the simulated and recorded values for variables, respectively, and n means the number of observations. Linear regression analysis between predicted and observed millet grain yield and biomass at harvest was scrutinized to evaluate the performance of the model. Millet model action to perform improves as near unit value of R^2 and d while RMSE and error proceed to zero. **Climate Change Projections and Statistical Downscaling:** Historical climate data (1980–2010) on solar radiation, maximum and minimum temperatures, rainfall, and wind speed were obtained from the Pakistan Meteorological Department (PMD). Based on historical data, delta scenario approach described by Wilby et al. (2004) was used to generate the climate scenarios under representative concentration pathways (RCPs 4.5 and 8.5) of mid-century (2040–2069) for Layyah and Faisalabad. The five GCMs were selected for both locations from the Coupled Model Inter-comparison Project (CMIP5) family according to the protocol described by Taylor et al. (2011). Selection of GCMs was done to represent the uncertainty in temperatures and precipitation. During GCM selection, scatter plot of growing season precipitation and temperatures was made from 29 GCMs. The highlighted GCMs from represented set of cool/wet, cool/dry, hot/wet, hot/dry, and middle were selected as shown in Table 3 (Ruane et al. 2015; Ullah et al. 2017). After selection of GCMs, mean variability scenarios were generated. For this, monthly changes in mean temperatures and precipitation were calculated and were compared from future 30 years to baseline period (1980–2010). These monthly changes were imposed on the baseline climate to both locations and analyzed using a stretch distribution approach. Solar radiation and wind speed were assumed unchanged. The mean variability scenarios were generated from CMIP5 GCMs using the methodology described by Ruane and McDermid (2017).

CSM-CERES-Millet model application

The calibrated treatment was run after editing change in temperature with future most effective general circulation model in environmental modifications including desired CO_2 level for the related representative concentration pathway (RCP) (8.5) that is 571 ppm. The impact of the change in climate variables in environmental modification was overviewed in millet model for mid-century (2040–2069) scenarios in the future.

Climate change impact assessment

A well-calibrated and evaluated CSM-CERES-Millet model was used for climate change impact assessment for mid-century (2040–2069). Seasonal analysis files were created from the crop management practices of optimum treatment (15 cm of plant spacing and 200 kg N ha^{-1}) for both locations. The data of baseline climate (1980–2010) and climate scenarios under RCPs 4.5 and 8.5 were used to create weather files in the model. The CO_2 concentration of 499 ppm for RCPs 4.5 ppm and 571 ppm for RCPs 8.5 was used in the environmental modification of the seasonal file. The future concentrations of CO_2 were purposed by Rosenzweig et al. (2013). The impact of climate change was calculated by comparing the mean yield of each GCM with baseline using Eq. (4). % Reduction = (Sim. − Obs.)   (Obs.) × 100.

Table 3 Selected GCMs for mid-century (2040–2069) climate scenarios

Model code (RCPs 4.5 and 8.5)	Climate	Study area	Model
PKFSGFXF	Cool wet	Faisalabad	CESMI-BGL
PKFSGLXF	Cool dry	Faisalabad	Inmcm4
PKFSGNXF	Hot wet	Faisalabad	IPSL-CM5A-MR
PKFSGWXF	Hot dry	Faisalabad	CMCL-CSM
PKFSGTXF	Middle	Faisalabad	NorESMI-M
PKLOGBXF	Cool wet	Layyah	CESMI-BGL
PKLOGLXF	Cool dry	Layyah	Inmcm4
PKLOGDXF	Hot wet	Layyah	IPSL-CM5A-MR
PKLOGWXF	Hot dry	Layyah	CMCL-CSM
PKLOGAXF	Middle	Layyah	NorESMI-M

Results

Model calibration

Genetic coefficients of pearl millet hybrid 86M86 were estimated using generalized likelihood uncertainty estimation (GLUE) and sensitivity analysis tool in DSSAT in Faisalabad. The coefficients P1, P2O and P2R, and P5 are related to crop phenology, while G1 and G4 are for growth. The coefficients were determined by several iterations in cultivar file of the model in such a way that observed and simulated values of phenology, growth, and yield were closed to each other. The final estimated coefficients are given in Table 4.

The model's calibration results showed good model performance in simulating phenology, growth, and millet yield. The model simulated days to emergence, anthesis, and maturity without any error percentage (Table 5). Model simulated millet crop emergence with 5 days, anthesis in 64 days, and maturity in 89 days. These values are quite likewise to recorded data of phenology. In the case of biomass, the model below (Table 5) simulated it with an error of 7.4%. Similarly, the model predicts a 6.9% less leaf area index and a 1.1% more millet grain yield. Overall, the predicted values for phenology, growth, and yield are in close agreement with recorded data.

Table 4 Genetic coefficients for model calibration

Cultivar	P1	P2O	P2R	P5	G1	G4	PHINT
86M86	310.0	14.00	505.0	285.0	10.9	19.00	71.00

P1 Thermal time from seedling emergence

P2O Critical photoperiod or the longest day length (in hours)

P2R Extent to which phasic development leading to panicle initiation

P5 Thermal time (degree days above a base temperature of 10 °C)

G1 Scaler for relative leaf size

G4 Scaler for partitioning of assimilates to the panicle (head)

PHINT Interval in thermal time (degree days) between successive leaf tip appearances

Model evaluation results

The model was evaluated with remaining treatments of experiment conducted at Faisalabad during crop season 2016 and validated with the same experiment in the year 2015 at Faisalabad, while experiments for the year 2015 at Layyah were evaluated and validated with that of the year 2016. The results of the model evaluation are given through 1:1 graph as follows:

Days to anthesis

The results showed that there was good agreement between observed and simulated days to anthesis with RMSE 2.12 and 1.35 days during 2015 and 2016 at Faisalabad, respectively. The *d*-index was 0.94 during both years (2015 and 2016) at Faisalabad. At Layyah, the RMSE was 2.21 and 1.58 days while the values of *d*-stat were 0.94 and 0.98 during 2015 and 2016, respectively (Fig. 2).

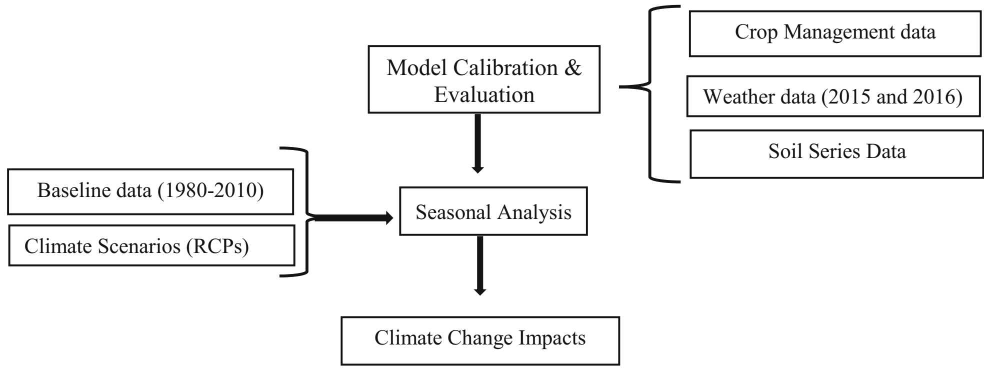
Days to maturity

The RMSE values for days to maturity were 2.35 and 1.59 days during 2015 and 2016 at Faisalabad, respectively. The *d*-index values were 0.99 in 2015 and 0.93 in 2016 at Faisalabad. The RMSE values were 2.43 and 2.81 days in 2015 and 2016 at Layyah, respectively. The *d*-index for days to maturity was 0.99 in 2015 and 2016 at Layyah (Fig. 3).

Table 5 Model calibration results

S#	Variable	Unit	Observed	Simulated	Error (%)
1	Emergence	Days	5	5	0
2	Anthesis	Days	64	64	0
3	Maturity	Days	89	89	0
4	Biomass	kg ha^{-1}	19,341	17,898	− 7.4
5	LAI	m^2 m^{-2}	4.6	4.28	− 6.94
6	Grain yield	kg ha^{-1}	3693	3735	1.14

Fig. 2 Simulated and observed days to anthesis for Faisalabad (**a**, **b**) and Layyah (**c**, **d**) for the years 2015–2016



Leaf area index

The results showed that there was good agreement between observed and simulated leaf area index with RMSE 0.35 and 0.20 during 2015 and 2016 at Faisalabad, respectively. The *d*-index values were 0.95 in 2015 and 0.98 in 2016 at Faisalabad. At Layyah, the RMSE was 0.5 and 0.21 days while the values of *d*-stat were 0.90 and 0.96 during 2015 and 2016, respectively (Fig. 4).

Total dry matter (kg ha^{-1})

The RMSE values for TDM were 1642 and 1386 kg ha^{-1} during 2015 and 2016 at Faisalabad. This shows that the total dry matter simulated by crop model is close to observed data. The *d*-index values were 0.96 for 2015 and 0.97 for 2016 at Faisalabad. The RMSE values were 1217 and 1689 kg ha^{-1} in 2015 and 2016 at Layyah, respectively. The *d*-index values for the total dry matter were 0.97 in 2015 and 0.96 in 2016 at Layyah (Fig. 5).

Grain yield (kg ha^{-1})

The simulated grain yield was very close to observed yield during both years (2015 and 2016) and locations (Faisalabad and Layyah). The RMSE values were 172 and 184 kg ha^{-1} for Faisalabad and 182 and 193 kg ha^{-1} for Layyah in 2015 and 2016, respectively. The *d*-index was 0.98 at both locations in both years (Fig. 6).

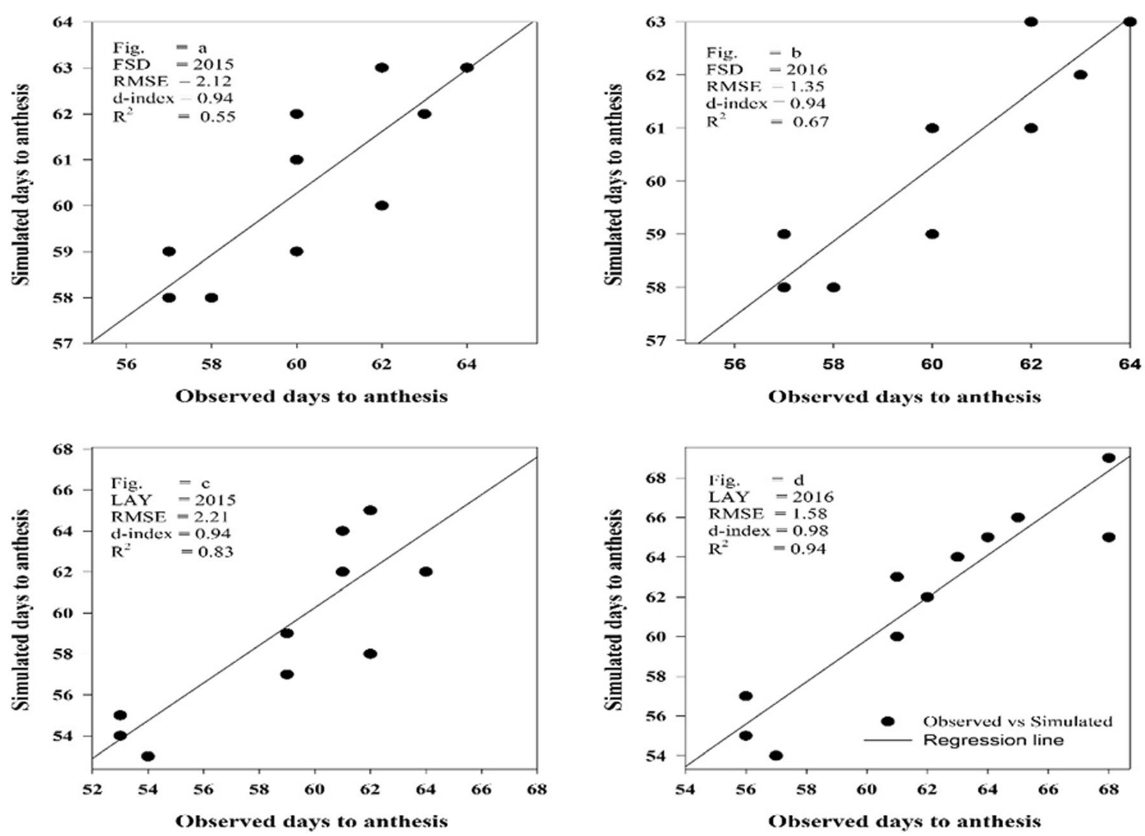


Fig. 3 Simulated and observed days to maturity at harvest for Faisalabad (**a**, **b**) and Layyah (**c**, **d**) for the years 2015–2016

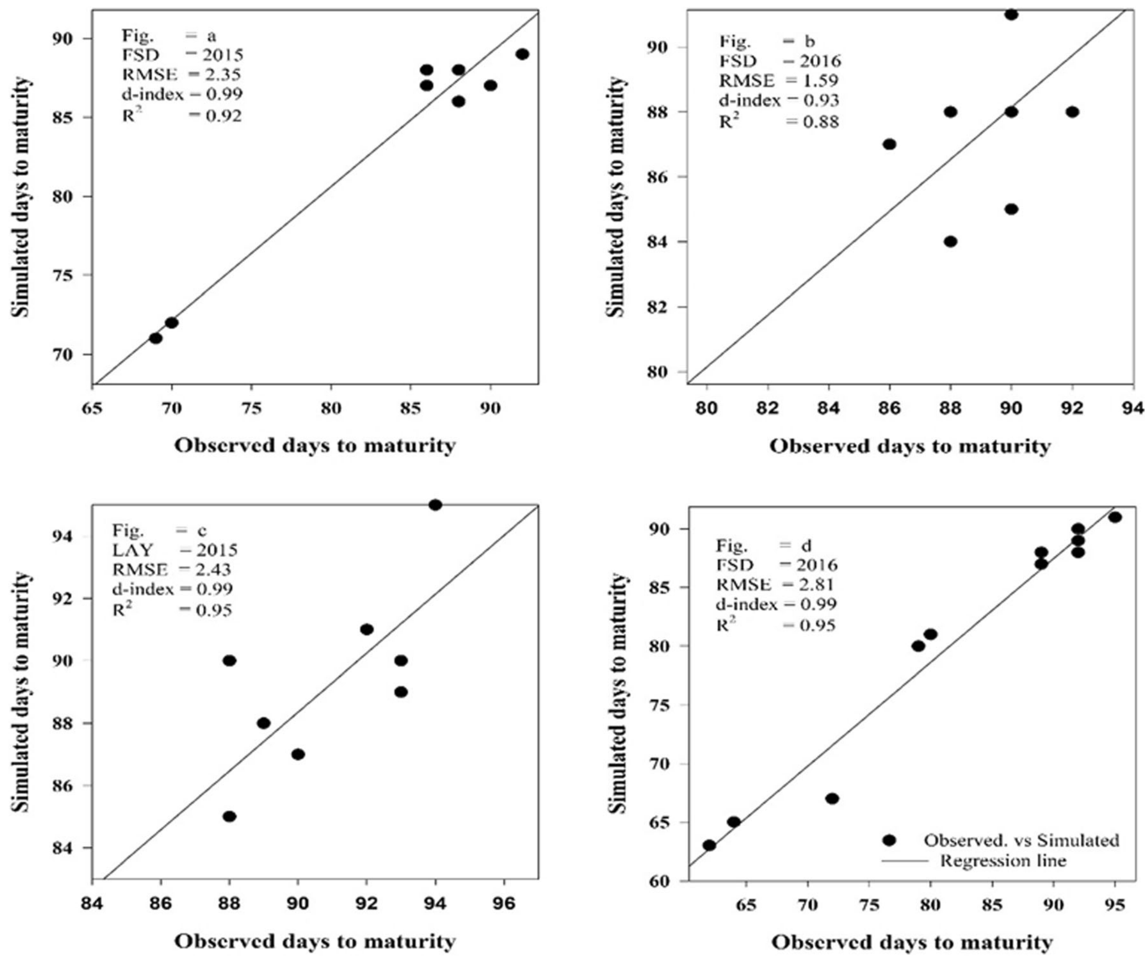


Fig. 4 Simulated and observed maximum LAI for Faisalabad (**a**, **b**) and Layyah (**c**, **d**) for the years 2015–2016

Optimizing planting time, intra-row spacing, and nitrogen using CSM-CERES-Millet

The well-calibrated model was used to find out the optimum level of management options for pearl millet. Different treatment combinations were used to check the optimum level of different management options for pearl millet crop for Faisalabad and Layyah. The model predicts the increase of millet yield up to 4125 kg ha^{-1} at a 15-cm spacing when sown during of the first week of July for both locations. Further research can be conducted to explore nitrogen losses in a millet production system for different nitrogen application rates and economic level of N can be estimated using field setting and crop modeling.

Quantification of climate change impacts on millet production in mid-century (2040–2069) using CERES-Millet

Projected changes in temperature in Faisalabad (semi-arid) and Layyah (arid)

It is projected that there will be an increase in T_{max} (2.5 °C) and T_{min} (2.8 °C) under RCP 4.5 for Faisalabad. The increase in T_{max} 3.7 °C and T_{min} 4.0 °C for mid-century (2040–2069) for Faisalabad under RCP 8.5 is also quite significant. The maximum variations were observed in hot dry climatic conditions. The increase in T_{max} 2.7 °C and T_{min} 2.9 °C will be observed in Layyah under RCP 4.5, which consisted of mild climatic conditions. It is projected that there will be an increase in T_{max} at 3.9 °C and 4.0 °C for mid-century (2040–2069) for Layyah.

Impact of climate change on millet yield in mid-century

Millet grain yield is an important economic return and desirable outcome of the farming community. Climate change significantly impacts the yield due to change in climate for semi-arid (Faisalabad) and arid (Layyah) environments of Punjab, Pakistan. Therefore, these impacts were quantified for the future to sensitize the researchers, farming community, and academia to combat possible climatic changes. Hence, it quantified and projected that there will be 11% and 14% reduction rates in irrigated millet yield under RCP 4.5 for Faisalabad and Layyah, respectively, under RCP 4.5, while 14% and 19% reduction rates in millet grain yield are projected during mid-century (2040–2069) for Faisalabad and Layyah,

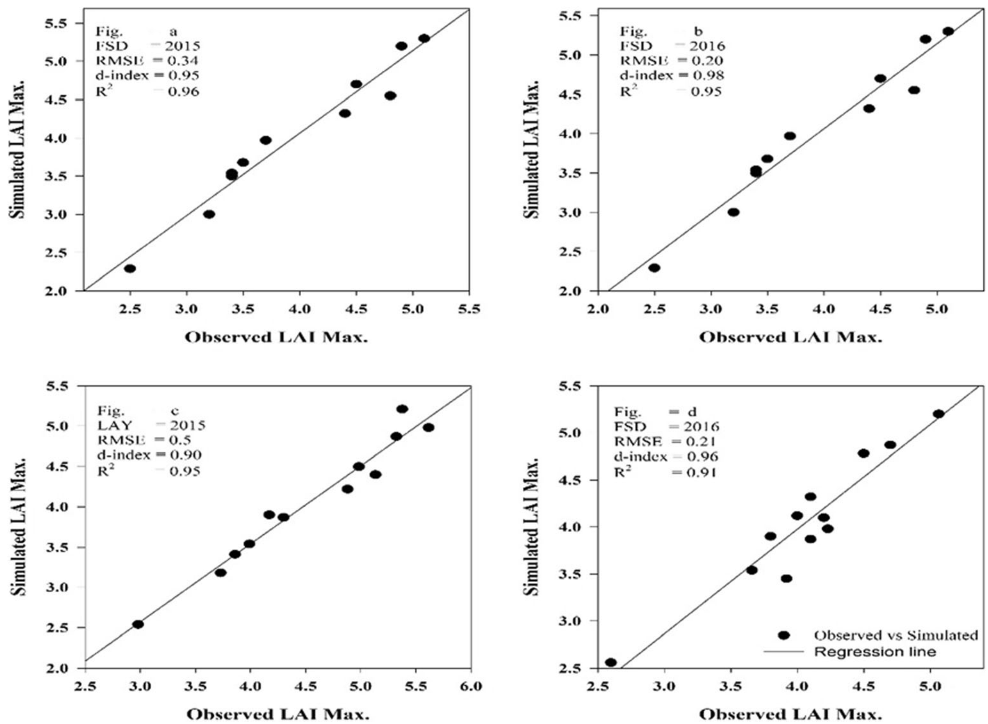


Fig. 5 Simulated and observed total dry matter (kg ha^{-1}) at harvest for Faisalabad (**a**, **b**) and Layyah (**c**, **d**) for the years 2015–2016

respectively, due to the increase in temperature under RCP 8.5 (Figs. 7 and 8).

Discussion

The two different climatic conditions of studies were identified by the difference in climatic variables and to some extent to soil properties. The experiments were conducted during crop seasons 2015 and 2016 under climatic conditions of Faisalabad and Layyah. The millet hybrid 86M86 was sown at different planting times; hence, there were differences in crop development; growth stages and yield were recorded for both locations. The early panting delayed the maturity that took more days (90) due to the effect of photoperiod and temperature (Soler et al. 2008). The results showed a significant increase in flowering when the day length decreases. The finding of this study is agreed with Reddy et al. (2013), who concluded the exposure of millet crop above 12 h causes a delay in maturity. Similarly, the late planting delayed the maturity in this study due to late panicle initiation and seed setting in millet crop.

There was good agreement between simulated and observed data of phenology for both days to anthesis and maturity under both studied climatic conditions. CERES-Millet model had good statistical indices for phenology, lower RMSE and quite high *d*-index for both study sites. CERES model under DSSAT has potential to simulate phenology reasonably well under arid to semi-arid climatic conditions as similarly reported by Ahmed et al. (2018) for CERES-Maize under semi-arid climatic conditions. Generally, all crop modules under DSSAT has the potential to simulate the phenology reasonably well under all types of environmental conditions (Ahmed et al. 2018; Rahman et al. 2018). CERES-Millet model also simulates the growth especially leaf area index with statistical indices in a good range while TDM and grain yield also showed good agreement between simulated and observed values having *d*-index values > 0.96 and lower RMSE values. Generally, the model performed good for each factor (plants spacing and nitrogen) and treatments at both studied locations under contrasting environments while the overall model performance was also good with reasonably good values for all studied statistical indices under both arid and semi-arid climatic conditions in Pakistan.

So, the model results in phenology showed the applicability of CERES-Millet model to simulate phenology, millet growth, and yield. This tool is very effective to optimize the nitrogen requirement of millet under arid and semi-arid environments. After a successful evaluation of the model against the calibrated treatment (non-stressed conditions), the model was analyzed for different planting dates to figure out optimum planting time for each location. Sowing date analysis showed that the third week of June to early July is the suitable sowing time under semi-arid climatic conditions of Punjab while the whole month of July is the favorable sowing time under arid climatic conditions of Punjab in Pakistan. Differences in sowing time at both sites are due to differences in environmental conditions. Weather variables are the most

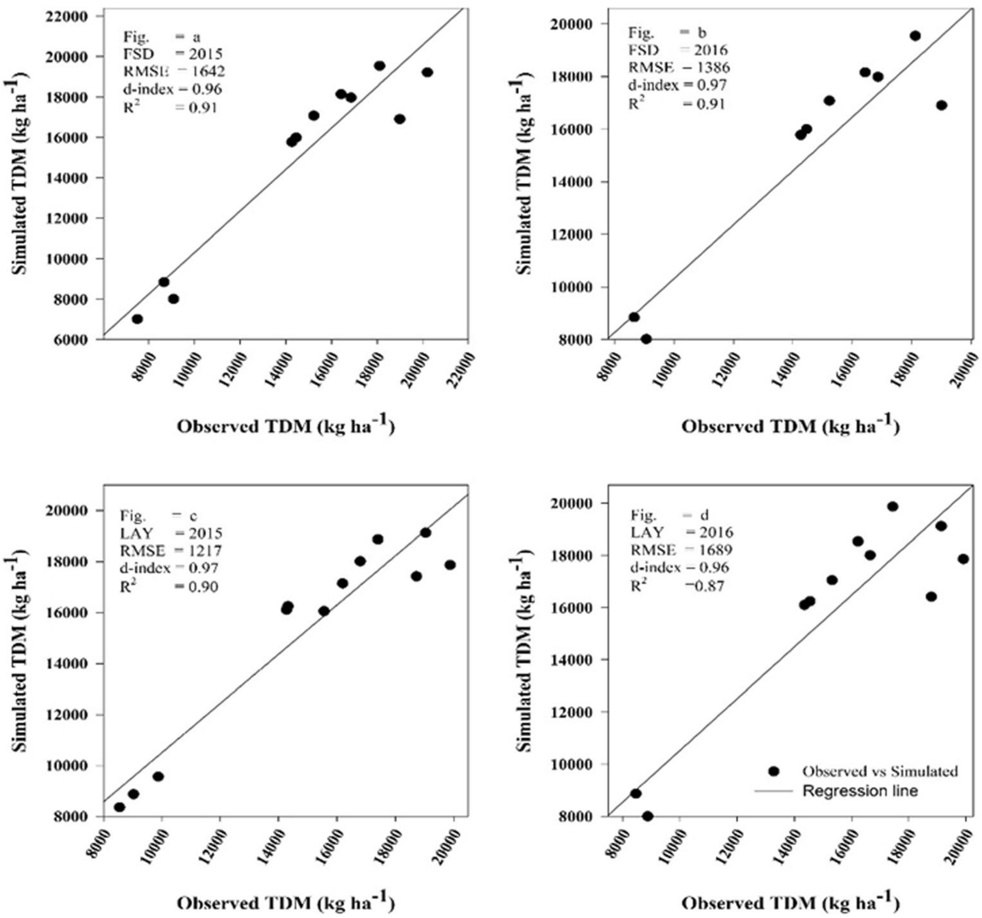


Fig. 6 Simulated and observed millet grain yield (kg ha^{-1}) at harvest for Faisalabad (**a**, **b**) and Layyah (**c**, **d**) for the years 2015–2016

driving force to determine the sowing date and base temperature (Rahman et al. 2017). Pearl millet crop can be sown at the farmer field from the third week of June to early July and July in semi-arid and arid climates, respectively, in Punjab, Pakistan. Same genotype is being cultivated for fodder and grain purposes at farmer field in this region under arid and semi-arid climatic conditions. Crop models are useful tools to analyze different management options like nitrogen applications and intra-row spacing as reported by Mavromatis et al. (2001) and Saseendran et al. (2005). According to Soler et al. (2008), the choice of suitable planting date plays a key role in maximizing the production and it is temperature-dependent. This further explains that the cost of labor due to the re-sowing of millet is increased in most of the cases. In case of our study, the sowing of irrigated millet has not any risk related to crop establishment. The observed crop establishment values for millet in both locations was at par with simulated values of days to emergence. The work on millet regarding modeling is limited all over the world while not reported to date in Pakistan. There are few studies conducted on millet crop in the USA, as different planting time was evaluated by MacCarthy et al. (2012) in Kansas. They did not find too much effects of regions on the yield of millet like in the case of our study but explored a different yield response with various planting times. Similarly, Pale et al. (2003) studied the effect of several planting time of yield of millet for many years in Nebraska. They did not communicate a clear relation between millet grain yield and different planting time and even the climatic conditions of Nebraska, USA, were variable during the study period. They summarized the best planting time mid-May for one site in a year and the first week of July on the other site in 2 years. In our study, the planting window for Faisalabad was found from the third week of June to early July, while the whole month of July for Layyah (second location). The planting date window is almost 1 month for the both locations, but in different time points.

The simulated results of both locations were observed in quite significant agreement with the observed values of planting times. So, the CERES-Millet model is in close agreement with the most of studies conducted as compared to our study in various sites for planting time. In short, CERES-Millet has the ability to simulate growth, phenology, and yield accurately for pearl millet crop sown with different management options (planting time, intra-row spacing, and nitrogen rates). These results also confirmed the past trends in similar studies and highlight the important role of CERES-Millet model in system

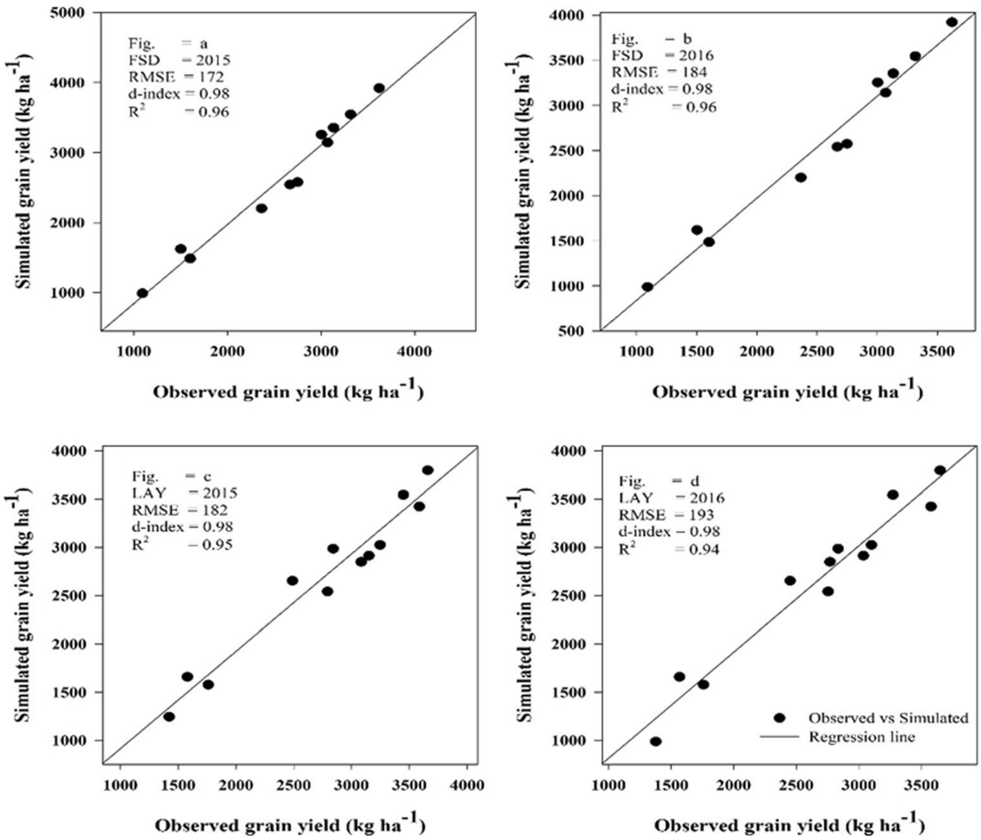


Fig. 7 Climate change impact assessment on millet grain yield for mid-century (2040–2069) under RCP 4.5

analysis approach. The planting of millet in the first week of August significantly decreased millet yield at both locations. Further studies can be conducted to focus the application of the model for other climatic zones in Pakistan.

CERES-millet model is an important tool to assess climate change impacts on millet crop yield for mid-century (2040–2069) scenarios under different RCPs. In this study, 14.8% reduction in millet yield is projected during mid-century under RCP8.5 for hot/dry climate scenarios in Faisalabad and 19% reduction in yield is expected in Layyah for a future scenario of mid-century. The more reduction in millet yield in Layyah is due to its harsh climatic conditions (low humidity, high

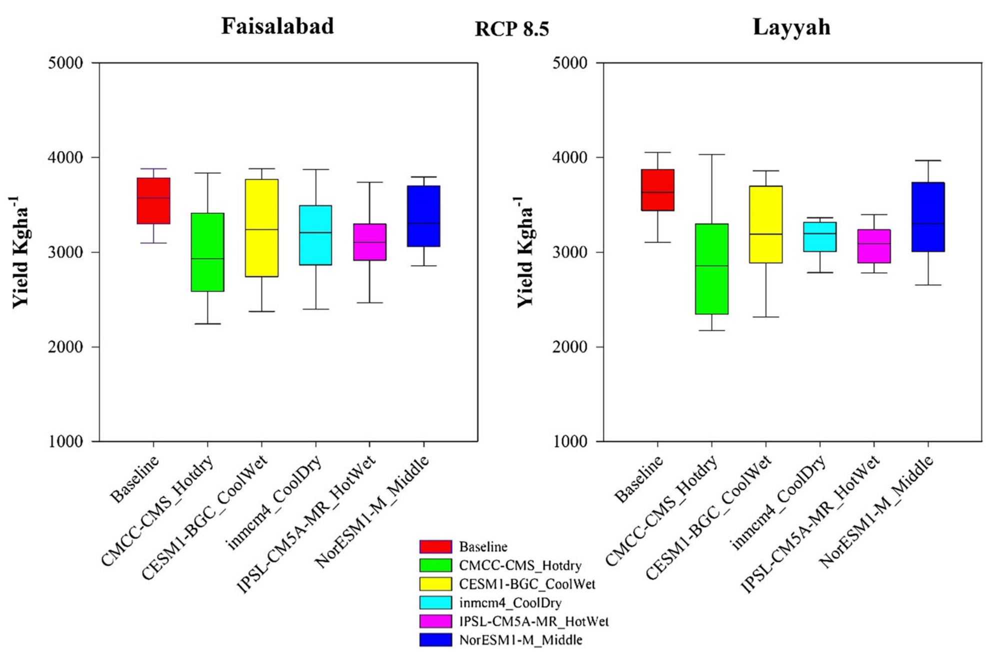


Fig. 8 Climate change impact assessment on millet grain yield for mid-century (2040–2069) under RCP 8.5

T_{max}). Generally, more yield reduction was observed at both locations under RCP 8.5 scenario due to its harsh climatic conditions than RCP 4.5. Higher temperature and rainfall variability especially dry spell in future climate shorten the plant growing period and overall, the short pearl millet crop cycle is the main cause of the reduction in yield especially under arid climatic conditions of Punjab, Pakistan. The impact of climate change and variability on millet grain yield was investigated and a relationship between climate and nutrient availability by Haussmann et al. (2007) was found. They assessed the good numerical model's performance in predicting sensitivity of millet yield to climate variability. They recommended to improve the model in quantifying nutrient leaching and endorsed that good fertilizer management strategy significantly increase the yield of millet under future climate change scenarios. It was the same with our results, where we calculate the optimum nitrogen rate for millet and recommended economical optimum nitrogen level for different locations.

Similarly, SAARA-H model was used to assess the climate change impact on millet yield in West Africa by using 35 different climate change scenarios by Sultan et al. (2013). They concluded that most of the climate scenarios (31/35) showed negative impacts by decreasing yield of pearl millet up to 41% for + 6 °C and 20% due to uneven rainfall in the twenty-first century. In our study, these possible climate change impacts on millet yield were reversed through developing adaptations using CERES Millet model. Climatic adaptations include effective investments, changes in technologies, and policies in response to future climate change. Non-climatic adaptations emphasize management options. Crop models frame comprehensive, cost-effective, and reliable adaptation packages by changing the planting time, fertilizer dose, planting geometry, and cultivar/hybrid and residue management. An increasing number of grains and crop growth rate, refitting crop season length by changing growing degree days (GDD) to anthesis and maturity, adjusting grain filling period, and decreasing root length of the crop are important elements of adaptations in crop model configuration. These elements of adaptations give sound genetic concepts as an important intervention in designing cultivar which is called "virtual cultivar." These adaptations are referred to as genetic modification through modeling. Further studies need to identify genetically modified cultivar in the face of future climate.

Conclusion

CSM-CERES-Millet model was calibrated very well using field experimental data. The model showed a good agreement between observed and simulated values of grain yield during calibration with a 1.14% error. The performance of the model during evaluation was good. The RMSE values of grain yield were 172 and 184 kg ha−1 for Faisalabad during 2015 and 2016, while 182 and 193 kg ha−1 for Layyah. Climate change projections showed that there would be an increase in T_{max} of 2.5 °C and T_{min} of 2.8 °C under RCP 4.5 for Faisalabad (semi-arid climate). However, under RCP 8.5, there would be an increase in T_{max} of 3.7 °C and T_{min} of 4.0 °C for mid-century (2040–2069). While in Layyah (arid climate), there would be an increase in T_{max} of 2.7 °C and T_{min} of 2.9 °C was observed in Layyah under RCP 4.5 but RCP 8.5 showed that there would be an increase in T_{max} of 3.9 °C and 4.0 °C in hot/dry GCM in the arid climate of Layyah. The results showed the pearl millet yield would be reduced by 7% and 10% under RCPs 4.5 and 8.5, respectively, in Faisalabad (semi-arid climate); however, huge losses in yield of pearl millet was observed in Layyah (arid climate) which ranges from 10 to 13% under RCPs 4.5 and 8.5, respectively, for mid-century. Future study may focus on the detail investigation about millet crop adaptations in terms of management practices under future climate for sustainable millet crop production in semi-arid to arid environmental conditions.

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References

Ahmad I, Saeed U, Fahad M et al (2018a) Yield forecasting of spring maize using remote sensing and crop modeling in Faisalabad-Punjab Pakistan. J Indian Soc Remote Sens:1–11

Ahmad I, Wajid SA, Ahmad A, et al (2018b) Optimizing irrigation and nitrogen requirements for maize through empirical modeling in semi-arid environment. Environ Sci Pollut Res 1–11

Ahmed I, ur Rahman MH, Ahmed S et al (2018) Assessing the impact of climate variability on maize using simulation modeling under semi-arid environment of Punjab, Pakistan. Environ Sci Pollut Res:1–18

Akponikpe PBI, Gerard B, Bielders CL (2014) Soil water crop modeling for decision support in millet-based systems in the Sahel: a challenge. African J Agri Res 9(22):1700–1713

Christianson CB, Bationo A, Henao J, Vlek PLG (1990) Fate and efficiency of N fertilizers applied to pearl millet in Niger. Plant Soil 125:221–231

Cooper P, Rao KPC, Singh P, et al (2009) Farming with current and future climate risk: Advancing a'Hypothesis of Hope'for rainfed agriculture in the semi-arid tropics. J SAT Agric Res 7:1–19

Downing TE (2013) Climate change and world food security. Springer Science & Business Media, University of Oxford, Oxford, U.K

Fatondji D, Bationo A, Tabo R, et al (2012) Water use and yield of millet under the Zai system: understanding the processes using simulation. In: Improving soil fertility recommendations in Africa using the Decision Support System for Agrotechnology Transfer (DSSAT). Springer, p 77–100

Fechter J (1993) The simulation of pearl millet (Pennisetum glaucum L.) growth under the environmental conditions of southwestern Niger, West Africa. Ph.D. thesis, Universitaat Hohenheim, Institute fur Bodenkunde und Standorslehre, p 121

Fechter J, Allison BE, Sivakumar MVK, et al (1991) An evaluation of the SWATRER and, CERES-Millet models for southwest Niger

Fischer G, Shah M, Tubiello FN, Van Velhuizen H (2005) Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080. Philos Trans R Soc London B Biol Sci 360: 2067–2083

Fussell LK, Pearson CJ, Norman MJT (1980) Effect of temperature during various growth stages on grain development and yield of Pennisetum americanum. J Exp Bot 31:621–633

Garcia-Huidobro J, Monteith JL, Squire GR (1982) Time, temperature and germination of pearl millet (Pennisetum typhoides S. & H.) I. Constant temperature. J Exp Bot 33:288–296

Godfray HCJ, Beddington JR, Crute IR, et al (2010) Food security: the challenge of feeding 9 billion people. Science (80-) 327:812–818

Government of Pakistan (2017) Economic survey of Pakistan. Econ Advis Wing, Financ Div Govt Pakistan 29–30

Hafner H, Bley J, Bationo A et al (1993) Long-term nitrogen balance for pearl millet (Pennisetum glaucum L.) in an acid sandy soil of Niger. Z Pflanzenernähr Bodenkd 156:169–176

Haussmann BIG, Boureima SS, Kassari IA et al (2007) Mechanisms of adaptation to climate variability in West African pearl millet landraces–a preliminary. J SAT Agric Res 3:1–3

Hoogenboom G (2000) Contribution of agrometeorology to the simulation of crop production and its applications. Agric For Meteorol 103:137–157

Hoogenboom G, Jones JW, Wilkens PW, et al (2015) Decision Support system for agrotechnology transfer (DSSAT). Version 4.6. DSSAT Foundation, Prosser, WA

Howden SM, Soussana J-F, Tubiello FN, et al (2007) Adapting agriculture to climate change. Proc Natl Acad Sci 104:19691–19696

IPCC (2013) Climate Change 2013: The physical science basis. working group I contribution to the IPCC 5th assessment report—changes to the underlying scientific/technical assessment

Jagtap SS, Abamu FJ, Kling JG (1999) Long-term assessment of nitrogen and variety technologies on attainable maize yields in Nigeria using CERES-maize. Agric Syst 60:77–86

Jones PG, Thornton PK (2002) Spatial modeling of risk in natural resource management. Conserv Ecol, p 5

Jones JW, Hoogenboom G, Porter CH et al (2003) The DSSAT cropping system model. Eur J Agron 18:235–265

Kang Y, Khan S, Ma X (2009) Climate change impacts on crop yield, crop water productivity and food security–A review. Prog Nat Sci 19:1665–1674

Knox J, Hess T, Daccache A, Wheeler T (2012) Climate change impacts on crop productivity in Africa and South Asia. Environ Res Lett 7: 34032

Lobell DB, Burke MB (2008) Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation. Environ Res Lett 3:34007

MacCarthy DS, Vlek PLG, Fosu-Mensah BY (2012) The response of maize to N fertilization in a sub-humid region of Ghana: understanding the processes using a crop simulation model. In: Improving soil fertility recommendations in Africa using the Decision Support System for Agrotechnology Transfer (DSSAT). Springer, p 61–75

Mavromatis T, Boote KJ, Jones JW et al (2001) Developing genetic coefficients for crop simulation models with data from crop performance trials. Crop Sci 41:40–51

Mitchell RAC, Mitchell VJ, Driscoll SP, et al (1993) Effects of increased CO2 concentration and temperature on growth and yield of winter wheat at two levels of nitrogen application. Plant Cell Environ 16: 521–529

O'Leary GJ, Joshi NL, Van Oosterom EJ (2008) A simulation study of the response of plant-type and nitrogen fertilization on the grain yield of pearl millet. Ann Arid Zone 47:121–137

Ong CK, Monteith JL (1985) Response of pearl millet to light and temperature. F Crop Res 11:141–160

Pale S, Mason SC, Galusha TD (2003) Planting time for early-season pearl millet and grain sorghum in Nebraska. Agron J 95:1047–1053

Rahman MH, Ahmad A, Wajid A, et al (2017) Application of CSM-CROPGRO-Cotton model for cultivars and optimum planting dates: Evaluation in changing semi-arid climate

Rahman MH, Ahmad A, Wang X et al (2018) Multi-model projections of future climate and climate change impacts uncertainty assessment for cotton production in Pakistan. Agric For Meteorol 253:94–113

Reddy AA, Rao PP, Yadav OP, et al (2013) Prospects for kharif (rainy season) and summer pearl millet in Western India. Working Paper Series no. 36

Ritchie JT, Alagarswamy G (1989) Simulation of sorghum and pearl millet phenology

Ritchie JT, Singh U, Godwin DC, Bowen WT (1998) Cereal growth, development and yield. In: Understanding options for agricultural production. Springer, p 79–98

Ruane AC, Goldberg R, Chryssanthacopoulos J (2015) Climate forcing datasets for agricultural modeling: Merged products for gap-filling and historical climate series estimation. Agric For Meteorol 200: 233–248

Ruane AC, McDermid SP (2017) Selection of a representative subset of global climate models that captures the profile of regional changes for integrated climate impacts assessment Earth Perspect 4:1

Rosenzweig C, Jones JW, Hatfield JL et al (2013) The agricultural model intercomparison and improvement project (AgMIP): protocols and pilot studies. Agric For Meteorol 170:166–182

Sanders JH, Shapiro BI, Ramaswamy S (1996) The economics of agricultural technology in semiarid sub-Saharan Africa. Johns Hopkins University Press, Baltimore

Saseendran SA, Ma L, Nielsen DC et al (2005) Simulating planting date effects on corn production using RZWQM and CERES-Maize models. Agron J 97:58–71

Schlenker W, Lobell DB (2010) Robust negative impacts of climate change on African agriculture. Environ Res Lett 5:14010

Singh P, Boote KJ, Kadiyala MDM et al (2017) An assessment of yield gains under climate change due to genetic modification of pearl millet. Sci Total Environ 601:1226–1237

Soler CMT, Maman N, Zhang X et al (2008) Determining optimum planting dates for pearl millet for two contrasting environments using a modelling approach. J Agric Sci 146:445–459

Sultan B, Roudier P, Quirion P et al (2013) Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian savannas of West Africa. Environ Res Lett 8: 14040

Taylor KE, Balaji V, Hankin S, et al (2011) CMIP5 data reference syntax (DRS) and controlled vocabularies. In: PCMDI

Thornton PK, Bowen WT, Ravelo AC et al (1997) Estimating millet production for famine early warning: an application of crop simulation modelling using satellite and ground-based data in Burkina Faso. Agric For Meteorol 83:95–112

Toure HA, Serme I, Traore K, Kyei-Baffour N (2018) Assessment of the changes in the yields of millet crop under different scenarios of climate change using DSSAT model. Int J Biol Chem Sci 12:363–380

Tsuji GY, Uehara G, Balas S (1994) DSSAT Version 3, vol. 2

Ullah A, Ahmad A, Khaliq T, Akhtar J (2017) Recognizing production options for pearl millet in Pakistan under changing climate scenarios. J Integr Agric 16:762–773

Van Vuuren DP, Edmonds J, Kainuma M, et al (2011) The representative concentration pathways: an overview. Clim Change 109:5

Wafula BM (1995) Applications of crop simulation in agricultural extension and research in Kenya. Agric Syst 49:399–412

Wilby RL, Charles SP, Zorita E, et al (2004) Guidelines for use of climate scenarios developed from statistical downscaling methods