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RESEARCH ARTICLE - ATMOSPHERIC & SPACE SCIENCES

Assessing the impact of climate change on sugarcane and adaptation actions in Pakistan

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Abstract

Climate change is a challenging global issue for the sustainable production of various crops around the world as change in climatic patterns can create a stressful environment for plant growth. This study assesses the impact of climate change on future water demand and sugarcane yield in Pakistan for the baseline (1981–2005) and future timescales (2020s, 2050s and 2080s). For evaluating the crop water requirement and yield under future climate, CROPWAT 8.0 and AquaCrop models were used, respectively. For the estimation of future climate, three different Regional Climatic Models were applied under two projection scenarios i.e. RCP 4.5 and RCP 8.5. Maximum temperature, precipitation and minimum temperature displayed an increasing trend under the projected future climatic conditions. The results revealed a growth in the crop water requirement with a subsequent escalating irrigation demand caused due to rise in projected temperature; this is because the projected increase in precipitation under forecasted weather conditions cannot compensate for the increased evaporative demand. Moreover, the results showed a general increasing trend of sugarcane yield under projected climate. By delaying the crop calendar, an overall decrease in crop water requirement in the range of 10.7–12.6% and increase in the yield in the range of 0.37–6.48 tha^{-1} can be observed under both climate change scenarios. Moreover, 90% of control irrigation level proved beneficial in terms of saving around 10% irrigation water with acceptable yield reduction. The outcomes of the study are supportive for growers to gain more yield using less amount of water and to adapt to changing climate. The results are also helpful for policy makers to develop adaptation strategies to improve sugarcane productivity and to address water stress in Pakistan.

Keywords Water conservation · Impact assessment · Crop modeling · Sugarcane · Adaptation measures · Crop calendar

Introduction

In the twenty-first century, the threat to global food security due to changing climate is considered as a serious challenge (Kang et al. 2009; Najafi et al. 2018). The persistent increase in greenhouse gas emissions causes climatic variations such as temperature and rainfall patterns which can have undesirable impacts on crop yield, water and land resources due to the severity of extreme events i.e. floods and droughts (Ali et al. 2017). Climate change may increase the vulnerability of the universal food supply system. According to an estimate, the surface temperature of the globe may escalate by 4.8 °C by the end of this century and there are chances of variation in the precipitation with varying latitude (IPCC 2014a). Arid to semiarid areas are considered to be the most overblown zones by climate change. These regions suffer from a limited amount of rainfall and the probability of floods and droughts may increase due to spatial and chronological changes in the precipitation patterns (Gheewala et al. 2013; Yano et al. 2007). Moreover, future climate does not only impact the overall food production but also affects the crop growth and water consumption patterns, it also affects the quantity of freshwater required by the crops to grow well

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(Woznicki et al. 2015; Gheewala et al. 2014; Tianwa et al. 2017). Furthermore, a rising evaporation demand can cause water stress due to increased projected temperature and less rainfall. Consequently, this pressure may pose a drop in production or needs supplementary irrigation to preserve yields (Yano et al. 2007). Therefore, it is indispensable to understand the influences of projected climate on crop production to develop adaptation and mitigation plans and to reduce the adverse effects of future climate (Akinnagbe and Irohibe 2014; Shrestha et al. 2018).

Several climatic models have been developed for weather predictions in the past (Stocker 2016). Mostly, two types of models are implemented to assess the dynamics of the atmosphere i.e. General and Regional Climate Models (GCMs & RCMs) (Yu 2000; Wang et al. 2004). RCMs have been derived from parent GCMs to produce climatic information at the regional scale and produce better results than GCMs as the spatial resolution of RCMs is higher. RCMs contain uncertainties which can be removed by using multiple RCMs rather than using a single climatic model (Wang et al. 2004). The Intergovernmental Panel on Climate Change (IPCC) has developed four emission scenarios in its fifth assessment report (AR5) recognized as Representative Concentration Pathways (RCPs) viz. RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 (Tan et al. 2017). The four RCPs represent a variation in the greenhouse gas radiative forcing values from 2.6 to 8.5 W per square meter (Wm^{-2}). RCP 2.6 is the lowest emission scenario, RCP 4.5 and RCP 6 are the stabilization scenarios and RCP 8.5 is the highest emission scenario (Nazarenko et al. 2015). The predicted variations in the temperature and precipitation under future climate could lead fluctuations in the future water accessibility and irrigation water requirement (IWR). So, the use of future climatic data with high resolution models (RCMs) could help in improved understanding of the future climatic impact on food production and crop water requirement (CWR). Lee and Dang (2018a) predicted an increase in sugarcane yield from 1.73 to 8.26% under RCP 4.5 and RCP 8.5 scenarios for future timescales (2020s, 2055s and 2090s) in the Phu Yen province of Vietnam. Similarly, Ruan et al. (2018) found a positive impact on sugarcane yield in southern China under RCP 4.5 and RCP 8.5 for future timescales i.e. 2030s, 2060s and 2090s. Siddiqui et al. (2012) predicted a cumulative loss of 13.56% and 40.09% in sugarcane yield up to 2030 in Pakistan with a respective increase of 1 °C and 2 °C respectively. Magsi et al. (2018) revealed that sugarcane production in Pakistan might be increased by 3493.4 thousand tonnes with 1 °C increase in temperature; 1 mm increase in the precipitation may bring an increase in its production by 17.22 thousand tonnes. Thus, past studies showed that climate change had positively affected the sugarcane production worldwide.

Sugarcane is one of the major crops produced in the tropical to subtropical regions in around 100 countries worldwide. Brazil being the world's biggest sugarcane producer, contributes around 39% of the global sugarcane cultivation (Silalertruksa and Gheewala 2018). Pakistan is the 5th major producer of sugarcane (Khan 2012) and has 6th rank to produce sugar (Iqbal and Iqbal 2014). Sugarcane is the main cash crop of Pakistan (Azam and Khan 2010) occupying around 5% of the total harvested land and responsible for 17% of the total economic productivity added by all crops (Nazir et al. 2013). In Pakistan, cane is planted in the province of Sindh; Khyber Pakhtunkhwa and Punjab with the leading cane production in Punjab having a regular yield around 75 tonnes per hectare (Nazir et al. 2013). The total share of Punjab is around 64% of the total cane produced in the country. According to the statistics of 2016, the average annual rainfall in Faisalabad and Rahim Yar Khan is about 430 mm and 111 mm respectively. The total area under sugarcane is about 705,000 hectares in Punjab with around 56% cane cultivation in the divisions of Faisalabad and Rahim Yar Khan. The total cane production in Punjab is around 42,000 tonnes with 30% and 29% share of the total production in Rahim Yar Khan and Faisalabad division respectively (Punjab Development Statistics 2016). Sugarcane is considered to be an intensive water consuming crop and according to an estimate, it requires around 402 m^3 of irrigation water in the country to produce one tonne of sugarcane (Linstead et al. 2015). Sugarcane is grown in the plains of the Indus, the largest river in Pakistan which is also an area of severe water stress (Gerbens-Leenes and Hoekstra 2009).

The information regarding agricultural production is necessary to support decision making at all levels due to population growth and stress on land and water resources (FAO 2011). Various crop models used in the past to evaluate the influence of future climate on crop development and productivity, for example CropSyst, CERES, CROPWAT, SWAP/WOFOST, DSSAT, AquaCrop, and EPIC (Hunink and Droogers 2011). The AquaCrop 4.0 model successfully used to assess sugarcane yield fort future change (Lee and Dang 2018a; Bahmani and Eghbalian 2018) and to estimate the past and future yield trends for the sugarcane crop in the Lower Mekong Basin (Hunink et al. 2014). Hence, AquaCrop is an appropriate decision support tool to evaluate the future climatic impact on water demand and yield predictions.

In this study, the base period has been selected as 1981–2005 and future periods are designated as 2019–2039 (2020s), 2049–2069 (2050s) and 2079–2099 (2080s). In Pakistan, no research was performed to evaluate the effect of climate change on yield and CWR for sugarcane under climate change scenarios. Thus, the central goals of this study are: (1) to predict the effect of climate change on the CWR and yield of sugarcane (2) to suggest adaptations for sustainable sugarcane production under future climate in the province of Punjab in Pakistan.

Materials and method

Study area

Two divisions of Punjab in Pakistan i.e. Faisalabad located at 31.45° N latitude and 73.13° E longitude and Rahim Yar Khan at 25.02° N latitude and 69.33° E longitude, are selected for the study as they are the main domains of cane cultivation in Punjab and responsible for about 50% sugarcane production in the whole province (Cheema et al. 2006; Ahmad et al. 2012).

It can be seen in Fig. 1 that Faisalabad lies in the center of Punjab and Rahim Yar Khan lies in the south of Punjab with the mean annual maximum temperature ranges between 28–31 °C and 31–33 °C, respectively. Moreover, the central stations receive more rainfall than southern stations in Punjab (Khattak and Ali 2015).

Data input

To successfully conduct this study, the daily meteorological data (solar radiation, wind speed, maximum temperature, precipitation, minimum temperature, sunshine duration and relative humidity), soil and crop characteristics were used to run CROPWAT 8.0 and AquaCrop 4.0 models to assess the CWR and sugarcane yield. The climatic data were taken from Pakistan Meteorological Department (PMD) for two rainfall stations (Faisalabad and Rahim Yar Khan) for the past 36 years (1981–2017). The daily weather data (maximum temperature, rainfall, and minimum temperature) for the base period (1981–2005) were applied to bias correct the climatic data from three RCMs for future climatic projections for three time slices i.e. 2019–2039 (2020s), 2049–2069 (2050s) and 2079–2099 (2080s). Due to the unavailability of RCM data, the following climatic parameters were presumed to be the same such as; wind speed, humidity and sunshine hours as that for the historical period. The baseline data (1981–2005) are provided as Online Resource 1. Three RCMs used to forecast the future

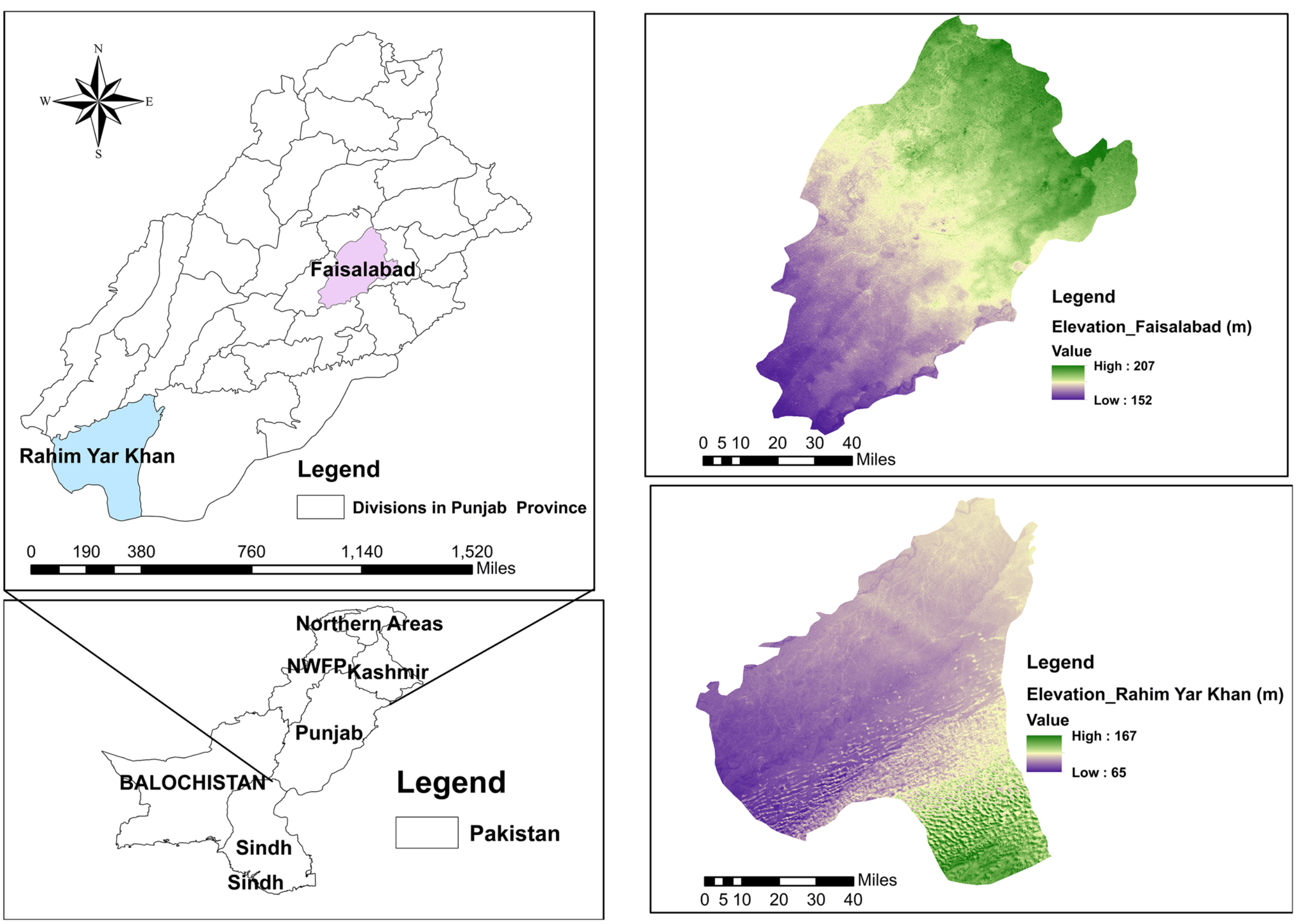

Fig. 1 Study area location in the Punjab province of Pakistan

climate under RCP 4.5 and RCP 8.5. The selected RCMs were developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) and their description along with the driving GCMs is presented in Table 1. The downloaded RCMs were already dynamically downscaled by Coordinated Regional Climate Downscaling Experiment (CORDEX). CORDEX is a well-organized program to generate the climate change scenarios globally, at a regional scale. The spatial resolution of CORDEX which are products of Coupled Model Inter-comparison Project phase five (CMIP5) coarse GCMs is about 50 km with a daily-based temporal resolution (Ghimire et al. 2015).

The details of the field experiments were taken from the Ayub Agricultural Research Institute of Faisalabad and the Agriculture Department of Punjab in Rahim Yar Khan. In the corresponding regions, four trials were performed with different planting dates for assessing the level of sugar contents for each planting design. Table 2 illustrates the description of each trial with the planting time, harvesting time and number of irrigations applied. Furrow irrigation was used for irrigating the fields. Every 10 m × 25 m plot comprised of 5 rows and the insect control measure was performed in each trial and a conventional land preparation technique was used in the corresponding regions. The fertilizer application rate was the same in Faisalabad and Rahim Yar Khan for each trial i.e. 280 kg Nitrogen/ha, 250 kg Phosphorus/ha and 120 kg Potassium/ha. These fertilizers were applied in 2 equal splits i.e. application of fertilizers prior to planting and 90 days after planting. For retaining the water in the planted regions, soil bunds were made. The plantation time of 15th February and the harvesting time of 16th December were taken as the base cropping calendar of sugarcane in the Punjab province of Pakistan. The most commonly used cultivar in the corresponding regions for sugarcane was HSF-240 in Faisalabad and Rahim Yar Khan (validated from the Agriculture Departments in Punjab). The values of crop coefficients were provided as 0.45 (Initial stage), 1.3 (mid-season) and 0.52 (late-season) for Faisalabad and 0.41 (Initial stage), 1.25 (mid-season) and 0.46 (late-season) for Rahim Yar Khan. The soil data were collected from the National Engineering Institute of Pakistan (NESPAK) including the information about soil horizons, their depths and chemical and physical properties of each horizon.

The methodology adopted for this study is displayed in Fig. 2. Linear bias correction technique (Luo et al. 2018) was used to remove biases from the predicted atmospheric variables to build the quantitative relationships between predicted and observed atmospheric variables. The Linear bias correction technique is simple to use which has been applied to have a better match between the observed and historical climatic data on mean monthly basis (Babur et al. 2016). Linear bias correction technique can be used to remove biases based on the mean and standard deviation and to have a better fit between monthly observed and simulated values. This method corrects the climatic data based on the differences of monthly raw and observed values. For correcting

Table 1 Selected RCMs for the projection of future climate under climate change scenarios

RCM	Driving GCM	Organization	Contributing institute	Resolution (latitude × longitude)
ACCESS-CSIROCCAM	ACCESS1.0	Commonwealth Scientific and Industrial Research Organization (CSIRO), Conformal Cubi Atmospheric Model (CCAM; McGregor and Dix, 2001)	CSIRO Marine and Atmospheric Research, Melbourne, Australia	0.44° × 0.44°
CNRM-CM5-CSIROCCAM	CNRM-CM5			0.44° × 0.44°
MPI-ESM-LR CSIRO-CCAM	MPI-ESM-LR			0.44° × 0.44°

Table 2 The planting date, harvest dates, number of irrigations and yield of sugarcane used for calibration and validation

Region	Trials	Planting date	Harvest date	No. of irrigations	Yield	Calibration/validation
Faisalabad	1	01/03/2016	25/11/2016	15 (1740 mm)	54.08	Validation
	2	15/02/2016	16/12/2016	20 (2040 mm)	68.90	Calibration
	3	12/03/2016	05/12/2016	16 (1893 mm)	58.61	Validation
	4	15/02/2016	02/02/2017	18 (2145 mm)	68.67	Validation
Rahim Yar Khan	1	15/02/2016	16/12/2016	20 (2434 mm)	76.05	Calibration
	2	03/03/2016	27/12/2016	18 (2131 mm)	73.88	Validation
	3	05/03/2016	15/01/2017	20 (2570 mm)	78.22	Validation
	4	05/02/2016	16/11/2016	17 (1820 mm)	65.19	Validation

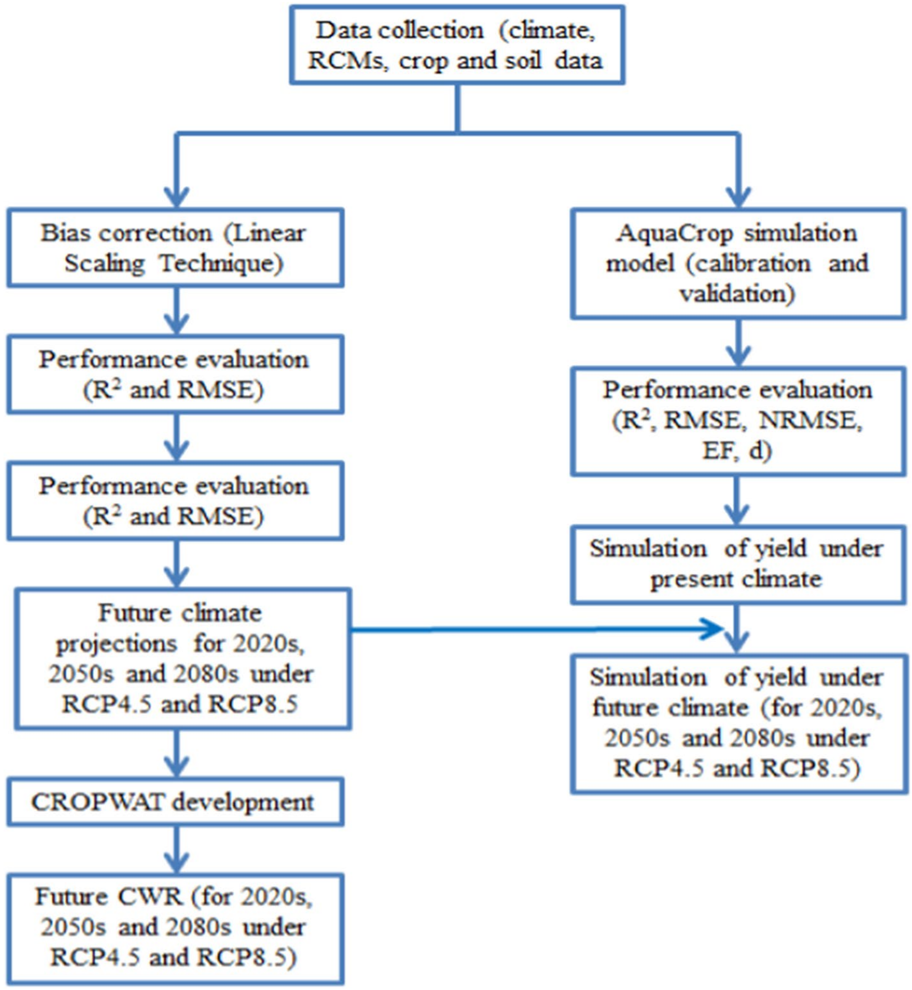

Fig. 2 Methodological outline for evaluating the effect of future climate on the CWR and sugarcane yield under climate change scenarios

precipitation, a multiplier is used, while for the temperature, an additive factor is developed by using the monthly values as follows;

$$P_{\text{cor},m,d} = P_{\text{raw},m,d} \times \frac{\mu\left(P_{\text{obs},m}\right)}{\mu\left(P_{\text{raw},m}\right)} \quad (1)$$

$$T_{\text{cor},m,d} = T_{\text{raw},m,d} + \mu\left(T_{\text{obs},m}\right) - \mu\left(T_{\text{raw},m}\right) \quad (2)$$

where, *P*cor,*m,d* represents the corrected value of precipitation, and *T*cor,*m,d* is the monthly corrected temperature for the *m*th month and *d*th day. Similarly, *P*raw,*m,d* denotes the monthly raw precipitation and *T*raw,*m,d* denotes the monthly raw temperature for the *d*th day. The observed mean precipitation and temperature is represented by μ(*P*obs, *m*) and μ(*T*obs, *m*) respectively (Fang et. al. 2015).

The root mean square error (RMSE) and coefficient of determination (R^2) calculated before and after bias correction. The lower values of RMSE and values of R^2 close to 1 are considered to have good agreement between the historical and simulated variables. The performance valuation of linear bias correction method for separate RCMs is provided as Online Resource 2. Moreover, a non-parametric Menn–Kendall analysis was performed due to its robustness to identify the trends in the climatic time series data (Khattak et al. 2011; Yadav et al. 2014). The bias corrected data (based on historical climate data) were used to set up CROPWAT and crop model, AquaCrop. Then the CROPWAT model used to assess the CWR for the future and baseline climatic data. The data was available for different field experiments; so, AquaCrop was calibrated and validated for the available data (Table 2) for the corresponding regions. Ruan et al. (2018) also successfully used field experimental data for the year 2015–2016 to calibrate the model for the sugarcane crop. After that, the calibrated model was undertaken to calculate the effect of projected climate on sugarcane yield under climate RCP 4.5 and RCP 8.5 by providing the climatic input to AquaCrop for the baseline period, 2020s, 2050s and 2080s. Moreover, the effect of agro-adaptation actions was also evaluated in this study to better adapt to climate change.

CROPWAT model

CROPWAT is a decision support tool established by the Food and Agricultural Organization of the United Nations (FAO) to help the agronomists and irrigation engineers for the management of irrigation schemes (Allen et al. 1998). This model calculates the effective rainfall (P_e), actual evapotranspiration (ET_c) and reference evapotranspiration (ET_0) (evapotranspiration from a reference surface i.e. imaginary grass with explicit properties having no stress) with the basic inputs including precipitation, sunshine hours, maximum temperature, relative humidity, minimum temperature and wind speed (Surendran et al. 2015). From several methods as proposed by researchers, the Penman–Monteith method is suggested as an appropriate approach to assess ET_0 (Eq. 3) (Allen et al. 1998; Cai et al. 2007).

$$ET_0 = \frac{0.408\Delta\left(\left(R_n - G\right) + \gamma \frac{900}{T+273} u_2\left(e_s - e_a\right)\right)}{\Delta + \gamma\left(1 + 03.4u_2\right)} \tag{3}$$

where heat flux density (MJm^{-2} day^{-1}), slope of the vapor pressure curve (kPa°C^{-1}), air temperature (°C), psychrometric constant (kPa°C^{-1}), saturated vapor pressure (kPa), actual vapor pressure (kPa), wind speed (ms^{-1}) at 2 m height and net radiation (MJ m^{-2} day^{-1}) are denoted by G, Δ, T, γ, e_s, e_a, u_2,R_n espectively (Lee and Dang 2018b; Cai et al. 2007).

The CWR is estimated through effective rainfall which is stated as the portion of rain efficiently consumed by the crop after rainfall lost in runoff and percolation (Ali and Mubarak 2017). The lost volume of water from soil surface through evaporation and by the crop through transpiration (for proper crop growth) is known as CWR calculated by using Eq. 4 (Lee and Dang 2018b; Allen et al. 1998).

$$ET_c = ET_0 \times K_c \tag{4}$$

The value of K_c is affected by soil evaporation, crop growth stages, crop type, and climatic conditions (Surendran et al. 2015). The difference between ETc and the effective rainfall (P_e) give the irrigation requirement calculated by Eq. 5 (Zare and Koch 2017).

$$IWR = ETc - Pe \tag{5}$$

where P_e is the rain efficiently consumed by crops, calculated by using Eqs. 6 or 7 (Babu et al. 2015).

$$P_e = ((P \times (125 - (0.2 \times 3 \times P))/125 \, for P \le \frac{250}{3} \tag{6}$$

$$P_e = \frac{125}{3} + (0.1 \times P) \, for P > 250/3 \tag{7}$$

where P is the total amount of rainfall in mm.

Crop simulation model

To assess the effect of future climate on cane yield, AquaCrop 4.0 model was used. The model is useful for various water management systems, whether it is deficit irrigation, supplemental irrigation, rainfed agriculture or full irrigation.

AquaCrop simulates the ultimate crop yield (Y) by multiplying the harvest index (HI) with the above-ground biomass (B). HI represents the amount of harvested product as a percentage of the total above-ground biomass (B).

$$Y = HI \times B \tag{8}$$

The value of HI may change from its reference value (HI_o) depending on the water and temperature stresses. HI_o begins to develop right after flowering stage of the crops and goes to its maximum value at maturity phase if no stresses occur (FAO 2017).

The model provides the yield response to the application of water according to the Eq. 9.

$$\left(\frac{Y_x - Y_a}{Y_x}\right) = K_y \times \left(\frac{ET_x - ET_a}{ET_x}\right) \tag{9}$$

where Y_a, ET_a, Y_x and ET_x represent the actual yield, actual evapotranspiration, maximum yield and maximum evapotranspiration, respectively and a loss in yield is directly linked with the reduction in the evapotranspiration denoted by K_y (Bahmani and Eghbalian 2018).

Results and discussion

Future projected temperature

As related to the base period, maximum temperature is expected to increase under future climate for both climate change scenarios in the main cultivation regions of the Punjab province. The maximum temperature in Faisalabad is predicted to escalate by 1.87 °C (RCP 4.5) and 4.1 °C (RCP 8.5) in the 2080s comparative to the baseline (Table 3). The amount of predicted increase in the minimum temperature is more in Faisalabad such as 2.44 °C and 5.15 °C in the 2080s for the corresponding scenario. In Rahim Yar Khan, a similar rising trend of minimum and maximum temperature is expected. The expected rise in temperature in Pakistan will be between 4 and 6 °C by the end of this century according to the Asian Development Bank (2017), supporting the results of this study.

The projections of average monthly minimum and maximum temperature for the baseline (1981–2005) and future timescales (2020s, 2050s and 2080s) are displayed in Fig. 3.

Table 3 The forecasted variations in the maximum temperature (T_{max}) and minimum temperature (T_{min}) related to the base period, °C (all values are calculated as annual average for each study period)

Time period	Faisalabad					Rahim Yar Khan				
	Baseline (1981–2005)	RCP 4.5		RCP 8.5		Baseline (1981–2005)	RCP 4.5		RCP 8.5	
		T_{max}	Change	T_{max}	Change		T_{max}	Change	T_{max}	Change
2020s	35.16	36.24	1.08	36.16	1.00	37.06	37.48	0.42	38.21	1.15 °C
2050s		36.26	1.10	37.33	2.17		38.36	1.30	39.33	2.27 °C
2080s		37.03	1.87	39.26	4.10		39.04	1.98	41.34	4.28 °C
		T_{min}	Change	T_{min}	Change		T_{min}	Change	T_{min}	Change
2020s	18.24	19.30	1.06	19.52	1.28	19.18	20.30	1.12	20.49	1.31
2050s		19.95	1.71	21.18	2.94		21.03	1.85	22.16	2.98
2080s		20.68	2.44	23.39	5.15		21.70	2.52	24.43	5.25

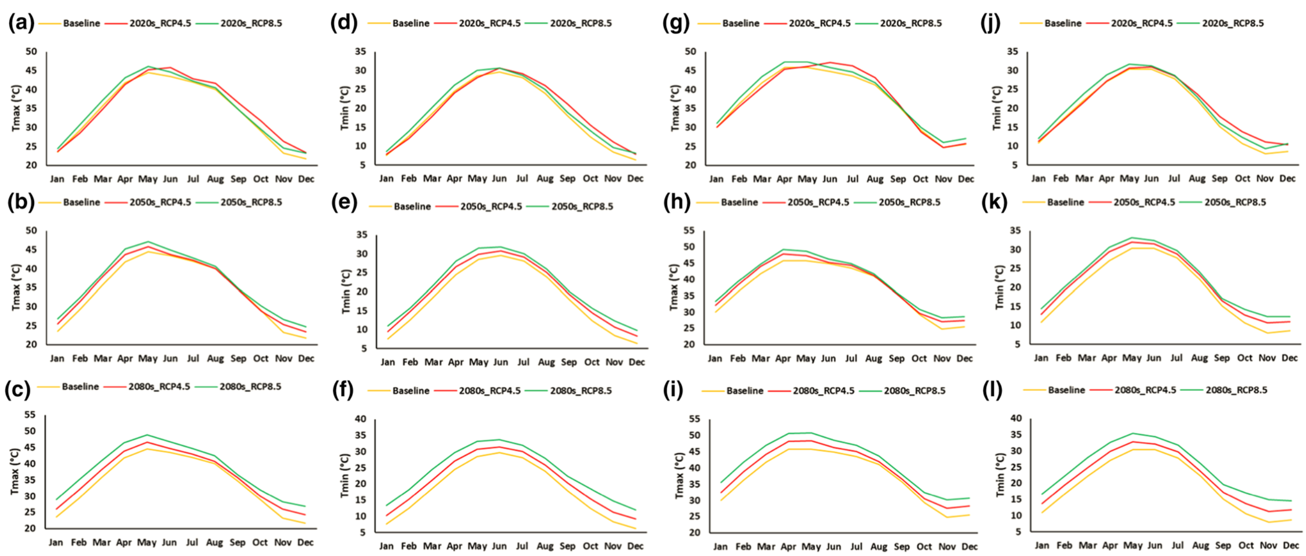

Fig. 3 Projections of average monthly maximum and minimum temperature for the RCP 4.5 and RCP 8.5 scenarios, **a–f** for Faisalabad and **g–l** for Rahim Yar Khan

The results show insignificant trends of minimum and maximum temperature under RCP 4.5. However, a decline in the maximum and minimum temperature is predicted in Faisalabad in February, March and April with the maximum decrease of 0.73 °C (minimum temperature) and 0.98 °C (maximum temperature) in March for the 2020s. Same kinds of trends are expected in Rahim Yar Khan for the minimum and maximum temperature. As compared to the RCP 4.5 scenario, a growing trend of the minimum and maximum temperature is predicted under RCP 8.5 for all future periods for the corresponding regions (Fig. 3).

Future projected rainfall

The predictions of mean annual rainfall show an increasing trend for the RCP 4.5 and RCP 8.5 scenarios relative to the base period. For the RCP 4.5 scenario, a maximum rise in precipitation of 31% for the 2080s in Faisalabad and 37.14% for the 2050s in Rahim Yar Khan is expected compared to the baseline. The results of RCP 8.5 scenario show that the maximum increase in precipitation of 25.14% and 32.44% for the corresponding regions is expected in the 2080s (Table 4).

Figure 4 shows the analysis of projected monthly precipitation in two regions of Punjab indicating insignificant changes throughout future periods for both climate change scenarios. A negative change is expected in February for all time periods under RCP 8.5 and especially from May to September in the 2020s under RCP 4.5. The decrease in rainfall from May to September in the 2020s can influence the crop water availability in future under the scenario RCP 4.5. The precipitation trends in Pakistan are projected to be ambiguous in future as reported by the Asian Development Bank (2017) supporting the results of this study.

Table 4 The forecasted variations in the average annual rainfall related to the base period

Precipitation (Precp) (mm)										
Time period	Faisalabad					Rahim Yar Khan				
	Baseline (1981–2005)	RCP 4.5		RCP 8.5		Baseline (1981–2005)	RCP 4.5		RCP 8.5	
		Precp	Change (%)	Precp	Change (%)		Precp	Change (%)	Precp	Change (%)
2020s	366.96	396.89	8.16	409.77	11.67	59.74	61.86	3.55	65.10	9.00
2050s		444.78	21.20	441.97	20.44		81.93	37.14	77.81	30.25
2080s		480.59	31.00	459.23	25.14		76.54	28.12	79.12	32.44

Babur et al. (2016) found a growing trend for the future minimum and maximum temperature and projected an increase in precipitation in Pakistan by using five GCMs. Moreover, the annual average temperature of Pakistan was expected to increase by 4.3 °C to 4.9 °C by the year 2085 (Akram and Hamid 2015). An increase in the temperature by 1.4 °C to 3.7 °C with the increasing rainfall patterns was projected for the coastal areas and in the south of Pakistan by 2060s (Zahra et al. 2016). The past studies on the projected climate change thus support the results of this study.

Menn–Kendall test statistics

The test statistics of Menn–Kendall analysis were performed on the base period and the future timescales (2020s, 2050s and 2080s) to assess the trends of the maximum temperature, precipitation and the minimum temperature in the province of Punjab. The obtained results of Z_c (direction of trend) and Q (Sen's Slope) statistics of Menn-Kendall test are provided as Online Resource 3. The significance level (*S*) of trends has been divided into five main categories as; *S* value of 0.0–0.01, 0.01–0.05, 0.05–0.1, 0.1–0.5 and 0.5–1.0 which correspond to very low, low, weak, strong and very strong level of significance of trends respectively (Khattak et al. 2011; Yadav et al. 2014). The results revealed that the direction of precipitation and minimum and maximum temperature could be increasing or decreasing under future timescales with a varying level of significance i.e. very low to strong (Online Resource 3).

Effect of climate change on future water demand

Simulations of CROPWAT show a significant rise in the CWR for all future time periods for RCP 4.5 and RCP 8.5 in the two regions of Punjab. The maximum increase in CWR of 4.2% (RCP 4.5) and 6% (RCP 8.5) in Faisalabad is anticipated for the 2080s related to the base period. Similar trends of CWR are expected in Rahim Yar Khan. The IWR is also projected to raise in future time scales for the corresponding regions under both climate change scenarios. Only a decrease of 1.8% in the IWR is expected in the 2050s under RCP 4.5 in Faisalabad due to 18.3% increase in the effective rainfall from the baseline (Table 5). For the rest of the future periods, the increase in rainfall may not be sufficient to compensate the effect of increasing temperature (Table 3) and to fulfill the CWR. Hunink et al. (2014) reported that the IWR of sugarcane varies between 1500 and 2500 mm. In this study, the IWR ranges between 1950 and 2497 mm in Faisalabad and Rahim Yar Khan. Past studies have reported that the CWR for different crops may increase in the future.

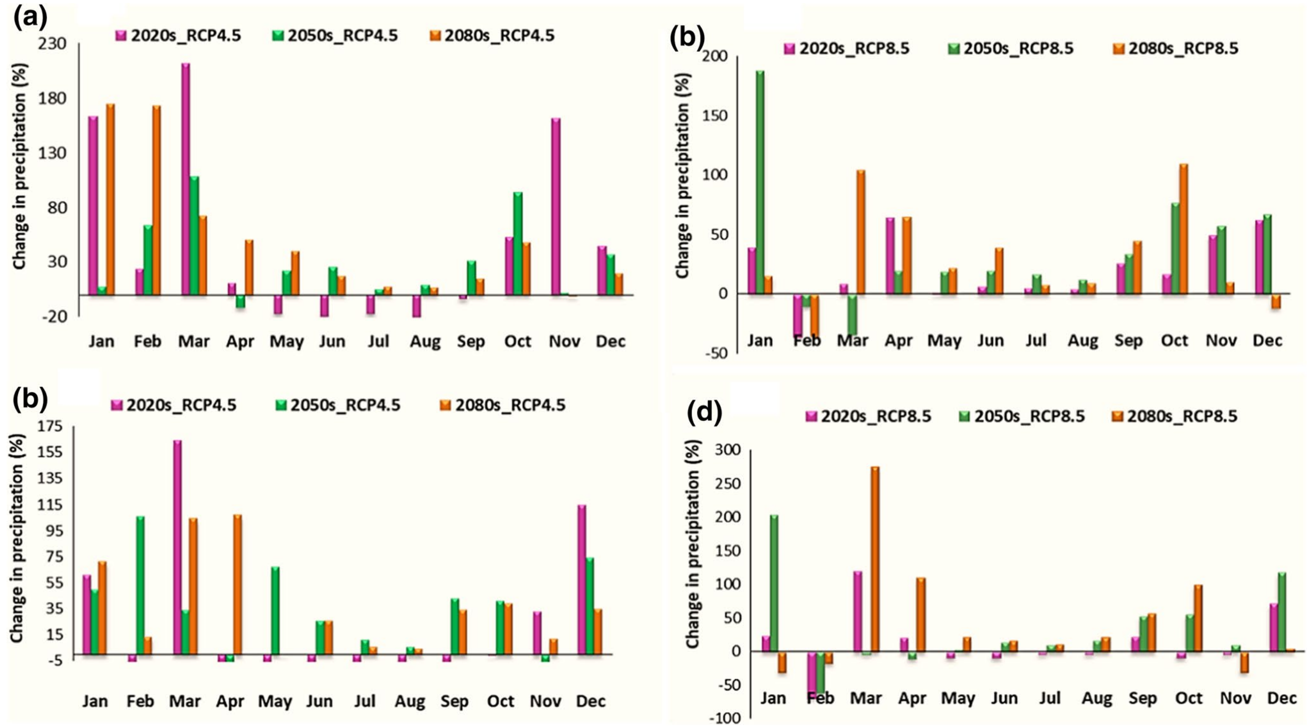

Fig. 4 Projected changes (%) in monthly precipitation under the RCP 4.5 and RCP 8.5 scenarios relative to the baseline, **a, b** for Faisalabad and **c, d** for Rahim Yar Khan

Table 5 Projected CWR, IWR and effective rainfall for future climate

Parameter	Baseline	RCP4.5			RCP8.5		
		2020s	2050s	2080s	2020s	2050s	2080s
Faisalabad							
CWR (mm)	2296	2334	2316	2392	2329	2357	2437
Change in CWR (%)		1.7	0.9	4.2	1.5	2.7	6
IWR (mm)	1985	2018	1950	2016	1986	2006	2047
Change in IWR (%)		1.7	−1.8	1.6	0.05	1.1	3.1
Effective rainfall (mm)	312	319	369	378	344	352	390
Change in effective rainfall (%)		2.2	18.3	21.15	10.3	12.8	25
Rahim Yar Khan							
CWR (mm)	2408	2455	2442	2480	2452	2482	2568
Change in CWR (%)		2.0	1.4	3.0	1.8	3.0	6.6
IWR (mm)	2307	2408	2377	2417	2399	2425	2497
Change in IWR (%)		4.4	3.0	4.8	4.0	5.1	8.2
Effective rainfall (mm)	51	48	67	63	54	57	71
Change in effective rainfall (%)		−5.9	31.4	23.5	5.9	11.8	39.2

Ouda et al. (2018) reported that the water requirement for the sugarcane crop may increase under future climate. The previous studies thus sustain the results of this study.

Impact of climate change on sugarcane yield

Sensitivity analysis of the crop model AquaCrop

Before calibration, a sensitivity analysis was performed on 8 parameters to choose the most sensitive parameters for calibrating the model. In relevance to the default

Table 6 Calibrated values of parameters for sugarcane (AquaCrop)

Parameters	Unit	Faisalabad	Rahim Yar Khan
Initial canopy cover (CC_0)	%	0.26	0.39
Days to max. canopy cover (CC_{max})	Days	95	100
Normalized water productivity (WP*)	g/m^2	40	38
Harvest index (HI)	%	69	75
Crop coefficient for transpiration (K_{cTr})	Unit less	1.5	1.5

and simulated values, the input values of the parameters were adjusted by ± 25%. The response of the yield to the changed parameters was noted and the parameters then categorized as less sensitive, moderately sensitive and highly sensitive, if the model response (sensitivity factor) to changes in input was smaller than 2%, between 15 and 2% and more than 15%, respectively based on the criteria defined by Bahmani and Eghbalian (2018). It was observed that harvest index (HI), normalized water productivity (WP*) and the crop coefficient for transpiration (K_{cTr}) had a significant influence on crop yield. These parameters were observed to be more sensitive to the crop yield and used for model calibration. The model was also found sensitive (low to moderate) to the maximum canopy cover (CC_{max}) and initial canopy cover (low sensitivity). The sensitivity analysis has been provided as Online Resource 4.

Calibration and validation of the AquaCrop model

Following sensitivity analysis, the most sensitive parameters were chosen for the calibration and validation of the model for the respective trials as provided in Table 2. Then simulations were performed which gave a noteworthy difference between estimated and observed yield which was minimized by fine adjustment of the calibrated parameters to have the closest match between the estimated and observed yield. For the validation of the model, the calibrated model was applied to authenticate the estimated results with observed yield for validation trials. The values of the calibrated parameters are shown in Table 6. The observed and simulated yield was compared to evaluate the performance of the model. The model evaluation criteria were based on root-mean-square error (RMSE), Nash–Sutcliffe model efficiency coefficient (EF), Willmott's index of agreement (d), coefficient of determination (R^2) and normalized root-mean square error (NRMSE) (details available in AquaCrop manual) (FAO 2018). The performance statistics for the calibration and validity of the model are provided in Table 7. The overall performance of the model was found to be acceptable for this study.

Table 7 Performance statistics of the AquaCrop model

Statistical criteria	Crop	R^2	RMSE (t ha^{-1})	NRMSE (%)	EF	d
Calibration results						
Faisalabad	Sugarcane	0.82	0.34	0.58	0.98	0.99
Rahim Yar Khan		0.91	0.28	0.53	0.93	0.98
Validation results						
Faisalabad	Sugarcane	0.78	0.68	0.82	0.95	0.99
Rahim Yar Khan		0.81	0.44	0.66	0.97	0.99

Table 8 Simulated sugarcane yield for future climate in Faisalabad and Rahim Yar Khan

Time period	Yield (t ha^{-1})									
	Faisalabad					Rahim Yar Khan				
	Baseline (1981–2005)	RCP 4.5		RCP 8.5		Baseline (1981–2005)	RCP 4.5		RCP 8.5	
		Yield	Change (%)	Yield	Change (%)		Yield	Change (%)	Yield	Change (%)
2020s	64.99	64.00	− 1.5	65.21	0.3	53.44	54.35	1.7	54.71	2.4
2050s		66.10	1.7	66.02	1.6		55.88	4.6	55.63	4.1
2080s		65.15	0.3	64.60	− 0.6		55.72	4.3	54.71	2.4

Effect of climate change on sugarcane yield

The average yield of sugarcane crop for the time scales of 2020s, 2050s and 2080s has been projected in the main cane cultivation regions of Punjab under RCP 4.5 and RCP 8.5. The results reveal an increase in the expected yield under both climatic scenarios. Only a decrease of 1.5% in the 2020s under RCP 4.5 and 0.6% in the 2080s for the highest emission scenario (RCP 8.5) is expected in Faisalabad compared to the base period (Table 8).

The CO_2 concentration level in the air has risen from 280 parts per million (ppm) to 400 ppm from the year 1850 to 2005 (IPCC 2014b) and this concentration is expected to increase to 550 ppm by the middle of this century having a beneficial impact on sugarcane crop (Madan et al. 2014). Therefore, the increase in the sugarcane yield can be linked with the increasing temperature due to increasing CO_2 level in the atmosphere.

The effect of future climate on the crop yield may be positive or negative. The results of this study can be validated by the outcomes of recent studies. Ruan et al. (2018) carried out a study in southern China to see the influence of climate change on sugarcane yield and the results revealed a progressive influence of future climate on sugarcane yield. Worldwide, an increasing trend has been observed for the sugarcane yield due to changing climate. Marin et al. (2012) predicted an increase from 15 to 59% in the sugarcane yield by the 2050s than the current state average yield in Brazil. Under changing climate, sugarcane yield is expected to be positively influenced in Vietnam and the sugarcane yield could increase from 1.73 to 8.26% under future climate for the RCP 4.5 and RCP 8.5 scenarios, respectively (Lee and Dang 2018a). Generally, sugarcane is expected to be positively influenced under changing climatic conditions.

Evaluating the impact of agro-adaptation measures

Climate change projects to have adverse and positive effects on agronomic production. Therefore, the adaptation strategies have a significant role in coping with the ultimate vulnerable effects of climate change (Sutton et al. 2009). In this study, the evaluation of adaptation strategies (in terms of shifting planting dates and deficit irrigation) has been performed to evaluate the impact on sugarcane yield, CWR and water productivity (WP) level to better adapt to changing climate.

Shifting the planting calendar

By shifting the planting dates, sugarcane crop shows a noteworthy impact on the CWR and yield under changing climate in two main regions of cane cultivation in Punjab. It can be perceived from the results that a delay in planting by 40 days proves to be valuable in terms of reduction in the CWR and increase in yield under future climate (Fig. 5). The outcomes indicate that a maximum increase in the yield of 9.46% (RCP 4.5) and 10.59% (RCP 8.5) can be obtained in Rahim Yar Khan for the 2080s by planting sugarcane on 27 March instead of current planting date (15 February). In Faisalabad, the results are expected to be similar as that of Rahim Yar Khan. The increase in the yield could be due to the reason that a delay in planting by 40 days can help the crop to meet its evaporative demand through increased precipitation throughout the generative stage of crop development.

A relative decrease in the CWR can be seen in Fig. 6 for planting sugarcane on 27 March (40 days delay) for all future periods under both climate change scenarios. A general

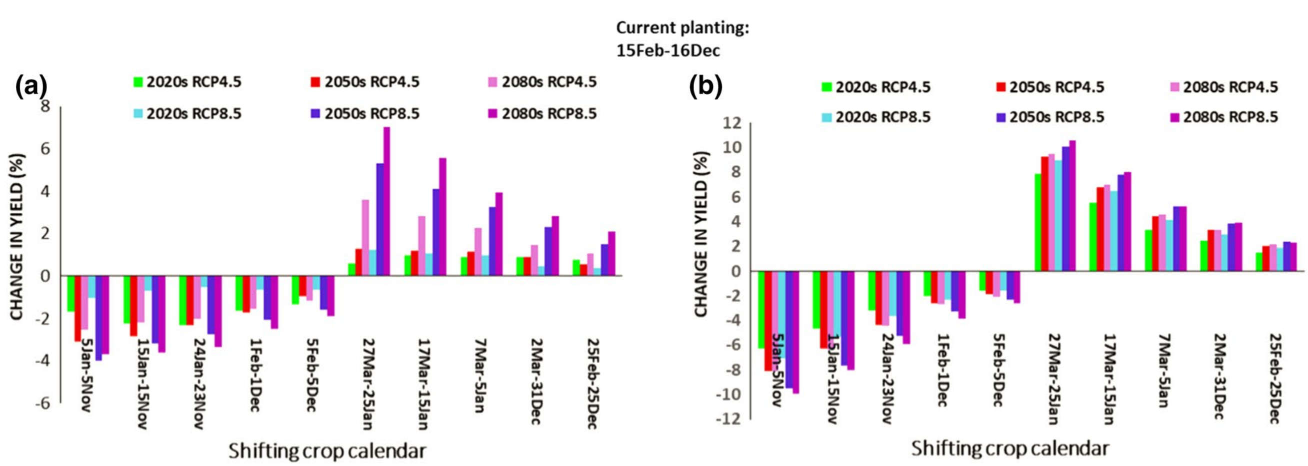

Fig. 5 Change in sugarcane yield for different planting dates under the RCP 4.5 and RCP 8.5 scenarios, **a** Faisalabad and **b** Rahim Yar Khan

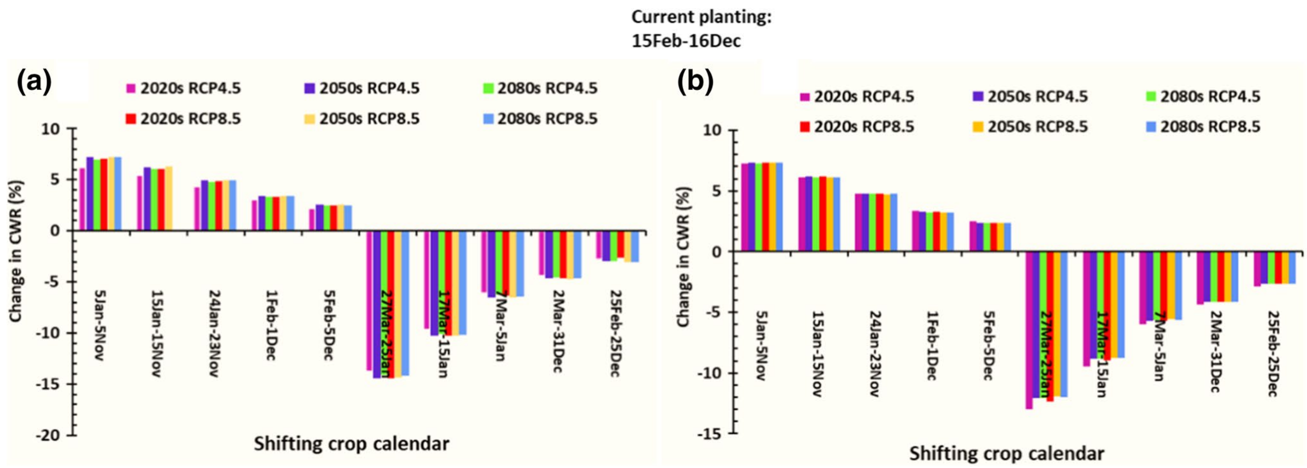

Fig. 6 Change in CWR for sugarcane crop for different planting dates under the RCP 4.5 and RCP 8.5 scenarios, **a** Faisalabad and **b** Rahim Yar Khan

decrease from 10.8 to 12.6% in the CWR can be obtained in Faisalabad and Rahim Yar Khan if sugarcane will be planted with a delay of 40 day (27 March). Lee and Dang (2018b) found that the CWR can decrease by 9% from the baseline by 20 days delay planting for summer-autumn planted crops. Therefore, shifting the planting calendar can prove to be a non-cost adaptation strategy to climate change for sugarcane cultivation in Pakistan.

Effect of deficit irrigation on crop yield and water productivity

AquaCrop has been used for different irrigation treatments i.e. S_1, S_2, S_3, and S_4 (S_1 = control irrigation (100%); S_2 = 90% of control irrigation; S_3 = 85% of control irrigation and S_4 = 80% of control irrigation) under climate change impact to assess the difference in the obtained yield and WP level from the control irrigation scenario (Table 9). As Compared to S_1 scenario, the yield can significantly decrease for S_3 and S_4 scenarios in Faisalabad and Rahim Yar Khan under the RCP 4.5 and RCP 8.5 scenarios. Corresponding to the decrease in yield under the S_3 and S_4 scenarios, there will be

Table 9 Change in yield and water productivity under different irrigation scenarios compared to the S_1 scenario (%)

Period	Irrigation scenarios											
	S_2				S_3				S_4			
	Faisalabad		Rahim Yar Khan		Faisalabad		Rahim Yar Khan		Faisalabad		Rahim Yar Khan	
	Yield	WP	Yield	WP	Yield	WP	Yield	WP	Yield	WP	Yield	WP
RCP4.5												
2020s	−2.91	10.66	−2.97	9.93	−10.56	−2.65	−10.58	−1.59	−14.35	−3.97	−15.13	−2.55
2050s	−1.45	11.32	−2.13	10.35	−8.67	−1.61	−10.55	−1.89	−12.04	−2.58	−15.13	−3.15
2080s	−1.71	11.21	−2.56	10.09	−8.98	−1.99	−8.89	−1.89	−12.51	−2.98	−15.18	−3.15
RCP8.5												
2020s	−1.95	11.13	−3.55	9.78	−9.30	−1.95	−10.63	−1.91	−13.01	−2.60	−15.24	−3.18
2050s	−1.38	11.56	−2.26	10.42	−8.52	−1.62	−10.68	−1.90	−11.92	−2.27	−15.37	−3.17
2080s	−1.74	11.25	−2.35	10.21	−9.05	−2.04	−10.72	−2.30	−12.76	−3.40	−15.51	−3.61

Irrigation scenarios for Faisalabad: S_1 = 101 mm, S_2 = 91 mm, S_3 = 86 and S_4 = 81 mm, total irrigations = 20

Irrigation scenarios for Rahim Yar Khan: S_1 = 109 mm, S_2 = 98 mm, S_3 = 93 and S_4 = 87 mm, total irrigations = 20 a relative decrease in WP level as well in the corresponding regions under future climate.

While, under the S_2 irrigation scenario, there will be a considerable rise in WP level with an acceptable yield reduction. In Faisalabad, compared to the control irrigation scenario, a maximum increase of 11.32% (RCP 4.5) and 11.56% (RCP 8.5) in WP level will occur in the 2050s with an acceptable yield reduction for the S_2 scenario. Similar results are obtained for Rahim Yar Khan. Therefore, 10% percent deficit irrigation (S_2) is expected to be an appropriate irrigation treatment under changing climate to be applied at field level to conserve water by 10%. Similar results were found by Bahmani and Eghbalian (2018); providing 85% of full irrigation scenarios as the appropriate scenario for sugarcane crop to increase the WP level between 14–17% in the Khuzestan province of Iran.

Conclusion

The future crop water requirement and cane yield along with the adaptation measures to better adapt to changing climate are assessed under climate change scenarios for the two main sugarcane producing regions in Pakistan. The following conclusions can be drawn from this study:

- As compared to the base period (1981–2005), the climatic parameters i.e. maximum and minimum temperature and rainfall, are projected to rise in the future.
- The results showed an increase in the CWR during 2080s under RCP 8.5 with a maximum increase of 6–6.6% in Punjab.
- The results also revealed that the IWR in the future would increase due to less contribution of rain to fulfill the CWR. The highest increase in IWR of around 3% and 8% in the 2080s from the base period was observed in Faisalabad and Rahim Yar Khan respectively.
- Shifting the crop calendar may prove to be an appropriate technique for adaptation to climate change. Delay in planting by 40 days and 90% of control irrigation can prove beneficial in terms of improved water productivity for sugarcane under future climate conditions.
- The results of the study are valuable for the policy makers and shareholders to propose plans and strategies for sugarcane production under future climate conditions. Moreover, the results of this study can be used as a guideline for adaptation against climate change in other parts of the world.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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