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RESEARCH ARTICLE

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Investigating the tipping point of crop productivity induced by changing climatic variables

Fatimah Mahmood[1] · Muhammad Fahim Khokhar[1] · Zafar Mahmood[2]

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Abstract

South Asia is comprised of several countries, including Bangladesh, Pakistan, India, and Sri Lanka, all ranked highly at risk of climatic variability. The region's susceptibility to climate change can be attributed to both its spatial and inherent characteristics. Considering the countries' high dependence on agricultural products, to support their economies and growing populations, it is vital to measure the factors impacting crop productivity. This study quantifies the change in temperature and precipitation, coupled with their respective effects on the productivity of three major crops, wheat, rice and cotton, within two of Pakistan's largest provinces: Punjab and Sindh. Based on the collated data, multivariate regression analysis is conducted. Moreover, highly vulnerable areas to climate change have been identified under RCP scenarios 4.5 and 8.5, until the end of this century. Results reveal that there is a substantial increasing trend in temperature, whereas precipitation has high inter-annual variability. Regression outcomes, based on fixed/random effects models, indicate that temperature above threshold values of 24.3 °C, 33.0 °C and 32.0 °C for wheat, rice and cotton, respectively, negatively impacts productivity (statistically significant). Precipitation is statistically insignificant in explaining its role in crop productivity. Overall, the region is heading towards temperature and threshold exceedances at an alarming rate, which will impact the overall availability of suitable crop-growing areas.

Keywords Climate change · Crop productivity · Food security · Pakistan · Precipitation · Temperature

Regional perspective

The South Asian countries (SACs) is comprised of a group of eight countries, namely, Afghanistan, Bangladesh, Pakistan, India, Bhutan, Maldives, Nepal and Sri Lanka, stretching over an area of approximately 5.2 million km^2 and home to a quarter of the world's population (Thakur and Wiggin 2004). The region is highly diverse in terms of both climate and topography, providing optimal conditions to a wide variety of crops. Cumulatively, SACs contribute a GDP of $3.32 trillion, with the agricultural sector accounting for approximately 30% of the total (Bashir 2000). On the contrary, food insecurity still poses a substantial problem, despite high economic growth in some countries. There are approximately 277.2 million undernourished people in South Asia (FAO 2018). From lack of proper land management, persistent use of conventional methods, to unfavourable climatic conditions, there are a myriad of factors contributing to unsustainable yields.

Climatic conditions are vital pieces of the puzzle, in terms of the growth and total productivity of crops. Deviation from the threshold levels can affect the crop sowing/harvesting dates, duration of growing season, overall health of crops and yield profitability (Iqbal et al. 2009; Miao et al. 2016). Most SACs are ranked amongst the top 20 countries at climate risk (Global Sustainable Development Report 2015). The region is set to lose 1.8%/year of its total GDP by 2050, as a result of climate-related events (Ahmed and Suphachalasai 2014). Thus, it is critical to assess and possibly aid in premeditating action plans to mitigate or adapt to future setups. Currently, within the South Asian region, only a handful of studies have gauged the statistical trends and impact of temperature and precipitation within the crop specific regions and

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✉ Muhammad Fahim Khokhar
fahim.khokhar@iese.nust.edu.pk

[1] Institute of Environmental Sciences and Engineering, National University of Sciences and Technology, Islamabad 44000, Pakistan

[2] School of Social Sciences & Humanities, National University of Sciences and Technology, Islamabad 44000, Pakistan

seasons. This is especially true for projections of future scenarios.

Current study

As is established previously, agriculture plays a critical role with regard to the food and socio-economic security of a country. Pakistan, an agrarian-backed economy, is placed amongst the world's top-ranked producers of sugarcane, wheat, cotton and rice (Rehman et al. 2015). The latter three crops contribute 6.5% of the GDP. Concurrently, 39% of the country's workforce is employed in the agriculture sector (FAO 2020). Despite Pakistan's efforts to increase agricultural productivity, it is continually struggling with the food-hunger gap. More than half of the country's population is food-insecure, with approximately 41.4 million undernourished people (Suleri and Haq 2009). Although crop productivity is enhancing domestically, globally Pakistan has one of the lowest growths in productivity (PBC 2018). Currently, the country's average yield of wheat (70%), cotton (53%) and rice (61%) is lower than the average yields attained internationally (Aslam 2016), unparalleled to its true potential. Factors responsible for the slow growth in productivity include lack of annual per capita availability of water in Pakistan, change in climate, pollution, lack of upgradation of technology and infrastructure, seed variety and land management (Murgai et al. 2001; Aslam 2016; FAO 2018).

Climatologically, Pakistan classifies as an arid to semi-arid region (FAO 2018). A shift in weather patterns can impact the supply of both ample rain and irrigation supplies, together with unwarranted temperature intensity. Presently, the country is enlisted as the fifth 'most vulnerable country to climate change' (GW 2019). Salient features of this position include frequent extreme weather events, sea level rise, glacial melting, unpredictable precipitation patterns and temperature extremities, ensued by economic instability, climate-induced health hazards, increased pressure on resources and most prominently crop damage (IPCC 2012).

Within the above perspective, the current study attempts to quantify changes in climate variables (temperature and precipitation) and their impacts on crop productivity, specifically focusing on wheat, rice and cotton growing seasons in Pakistan, which are divided into two seasons of cultivation: *Kharif* (summer crops) and *Rabi* (winter crops). The regions under study are selected crop-growing districts of Punjab and Sindh, primarily divided into three climatic zones (Fig. 1), namely, mild cold, dry and hot and arid to hyper-arid (Qasim et al. 2014; Haider et al. 2017; Safdar et al. 2019; Safdar et al. 2020). This diversity allows cultivation of various crops owing to varied conditions and response to stressors. On average,16.7 million hectares of the province of Punjab is under cultivation; contributing to 83% cotton, 76% rice and 80% wheat in the agriculture economy of Pakistan (GoP 2016). The total cropped area of Sindh is about 3.1 million hectares; further adding 35% rice, 12% wheat and 20% cotton to the total crop output (Raza 2015).

Material and methodology

The study area is determined using the 'Agriculture Cropping Pattern–Pakistan' mapped by FAO (2012b), to identify districts specific to wheat, rice and cotton crop growing. The identified districts are further filtered according to the availability of weather station data, as displayed in Fig. 1. After the final selection of the districts under study, the raw data are arranged into average crop growing seasons, from cultivation to harvest, with reference to the crop calendar presented in Table 1.

Datasets included in the study for climate variables (temperature, precipitation) are obtained from the Pakistan Meteorological Department, comprising of:

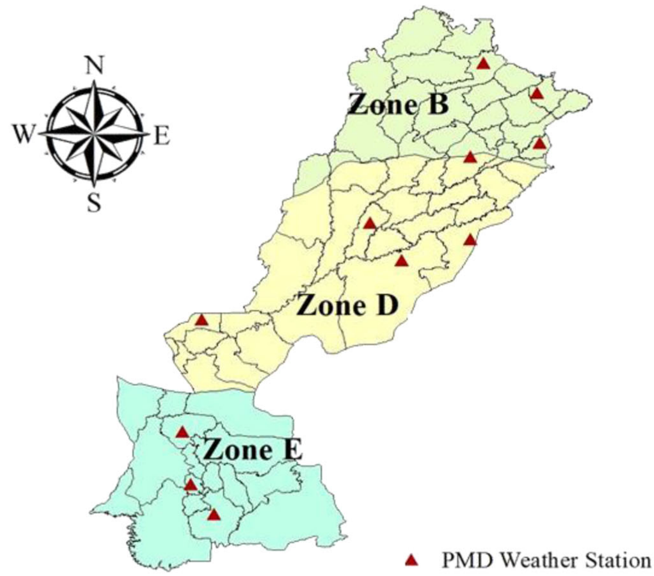
i. Weather station–observed values (1978–2016).
ii. Statistically downscaled data (grid size: 25 km) of baseline (1975–2005) and projections (2010–2100) data under IPCC's Fifth Assessment Report representative concentration pathways (RCP) 4.5 and 8.5[1], using the Community Climate System Model (CCSM4)[2]. The CCSM4 model simulates the Earth's climate system and is composed of five geophysical models simultaneously simulating the Earth's atmosphere, ocean, land, land-ice and seas-ice and one central coupler component (Vertenstein et al. 2010).

Absolute change in temperature and precipitation is calculated using observed weather station temperature and precipitation data. The change is computed for the decade 2006–2016, in comparison with the selected baseline period of 1978–2005. Mann Kendall trend test is applied to assess existing temporal trends.

Forecasted climate variables are analysed for change, from the year 2010 until the end of the century (2100), with respect to the selected baseline period of 1978–2005. Prior to this, the CCSM4 model is tested, to evaluate its forecasting ability, through an error analysis (root mean square, mean average error and mean bias).

[1] The two selected scenarios RCPs 4.5 and 8.5; the former is a stabilization scenario, whereas the latter illustrates rising emissions thorough out the century.

[2] Baseline and projected data were developed by the Numerical Modelling group of Research and Development Division, PMD, Islamabad, Pakistan) using the "Community Climate System Model, version 4" by the National Center for Atmospheric Research (NCAR).



Zone	Climate	Selected Districts
B	Mild Cold	Jhelum, Lahore, Sialkot,
D	Dry And Hot	Bahawalnagar, Bahawalpur, Faisalabad, Jacobabad, Multan
E	Arid to Hyper Arid	Badin, Hyderabad, Shaheed Benazir Abad,

Fig. 1 Map displaying spatial distribution of Pakistan Meteorological Department (PMD) weather stations and discrimination climatic zones of Pakistan (Salma et al. (2012). The table denotes the selected districts under study, within the climatic zones B, D and E

$$RMSE = \sqrt{\frac{1}{n}\sum_{i}^{n}\left(T_{(model)i} - T_{(observation)t}\right)2} \quad (1)$$

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}\left|T_{(model)i} - T_{(observation)t}\right| \quad (2)$$

$$\mathrm{MB} = \frac{1}{n}\sum_{i}^{n}\left(T_{(model)i} - T_{(observation)t}\right) \quad (3)$$

n represents the number of observations.

Crop production and area under cultivation for wheat, rice and cotton crops are obtained from Pakistan Bureau of Statistics and Directorate of Agriculture Punjab. The data spans over 1981–2016 (for Sindh, the latest crop data are until 2013). Data are fine-tuned by estimating missing data, using nearest neighbour method.

In order to carry out the impact analysis of temperature and precipitation on crop productivity, a panel multi-regression is run. A panel is created using temperature, precipitation and crop productivity data from the 11 districts under study (Fig. 1), over the time period 1981–2013. To select the appropriate regression model, the data are passed through a rigorous pre-regression analysis, including the Harris-Tzavalis unit root test, Pearson chi-square test, Ramsey RESET and calculation of variance inflation factor, to check for the presence of multicollinearity and unit root. The final statistical model selection (i.e. fixed or random effects) is made using the Haussmann test.[3]

Regression model overview

To carry out the impact exploration of climate variables on crop productivity, a multivariate econometric model is used:

$$CP_{it} = \alpha_i + \beta_1(T) + \beta_2(P) + \epsilon_{it} \quad \text{(ModelI)}$$

$$CP_{it} = \alpha_i + \beta_1(T) + \beta_2(P) + \beta_3\left(T^2\right) + \epsilon_{it} \quad \text{(ModelII)}$$

$$CP_{it} = \alpha_i + \beta_1(T) + \beta_2(P) + \beta_3\left(P^2\right)\ \epsilon_{it} \quad \text{(ModelIII)}$$

where:

α_i: constant term
CP_{it}: crop productivity in the i^{th} district for time period t (kg/hectare)
β: measures the dependence of productivity on the climate variables
T: averaged temperature for crop growing season

[3] The H_0 assumes that the favoured model is random effects (Greene 2008). Prob > chi-square values less than 0.05 indicate that fixed effects model is the correct choice, rejecting the null hypothesis (Torres-Reyna 2007).

Table 1 Crop calendar for wheat, rice and cotton crops (Punjab, Lower (L.) Sindh and Upper (U.) Sindh. The green highlighted cells indicate the average crop growing months (Source: FAO 2012a)

Cultivation | Mid-Season | Harvest

Crop	Province	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
Wheat	Punjab	Mid-Season	Mid-Season	Mid-Season	Harvest							/ Cultivation	Cultivation
	L.Sindh	Mid-Season	Mid-Season	Harvest								/ Cultivation	Cultivation
	U.Sindh	Mid-Season	Mid-Season	Mid-Season / Harvest	Harvest							Cultivation	Cultivation / Mid-Season
Rice	Punjab						Cultivation	Mid-Season	Mid-Season	Mid-Season	Harvest	Harvest	
	Sindh	Mid-Season	Mid-Season	Harvest		/ Cultivation	Cultivation	Mid-Season	Mid-Season	Mid-Season	Mid-Season	Mid-Season	Mid-Season
Cotton	Punjab					Cultivation	Cultivation / Mid-Season	Mid-Season	Harvest	Harvest	Harvest	Harvest	
	L. Sindh					Cultivation	Cultivation / Mid-Season	Mid-Season	Harvest	Harvest	Harvest	Harvest	
	U. Sindh				Cultivation	Cultivation / Mid-Season	Mid-Season	Mid-Season	Harvest	Harvest	Harvest	Harvest	

P: average precipitation for crop growing season

ϵ_{it}: error terms

Calculation of tipping point

The tipping point in the present study is defined as the point (optimal value or threshold value) beyond which any increase in temperature or/and precipitation will lead to a decrease in crop productivity. This tipping point can be determined by assessing the non-linearity of the relationship between the dependent (crop productivity) and independent variables (temperature or precipitation), by addition of squared variables of temperature (T^2) and precipitation (P^2), as shown in the 'Regression model overview' section: models II and III.

To find the estimated value of the tipping point for temperature, for instance, the estimated regression for model II was used as under:

$$\widehat{Y} = \alpha_i + \beta_1\left(\widehat{T}\right) + \beta_2\left(\widehat{P}\right) - \beta_3\left(\widehat{T^2}\right)$$

Next, the derivative was taken by the following equation:

$$\frac{d\widehat{Y}}{d\widehat{T}} = \beta_1\left(\widehat{T}\right) - \beta_3 \times 2\widehat{T}$$

To solve for the optimal value, $\frac{d\widehat{Y}}{d\widehat{T}}$ was set equal to zero.

$$\widehat{T} = \frac{\beta_1}{\beta_3}$$

Similar procedure is undertaken to work out tipping point values for precipitation as well.

Mapping vulnerable areas

After the tipping points are calculated, it can be inferred that future estimates of temperature and precipitation above this threshold can provide an 'indication' of potential vulnerable areas in terms of less than optimal productivity. Thus, the projected temperature and precipitation under RCPs 4.5 and 8.5 are mapped, with addition of a threshold band, using Arc

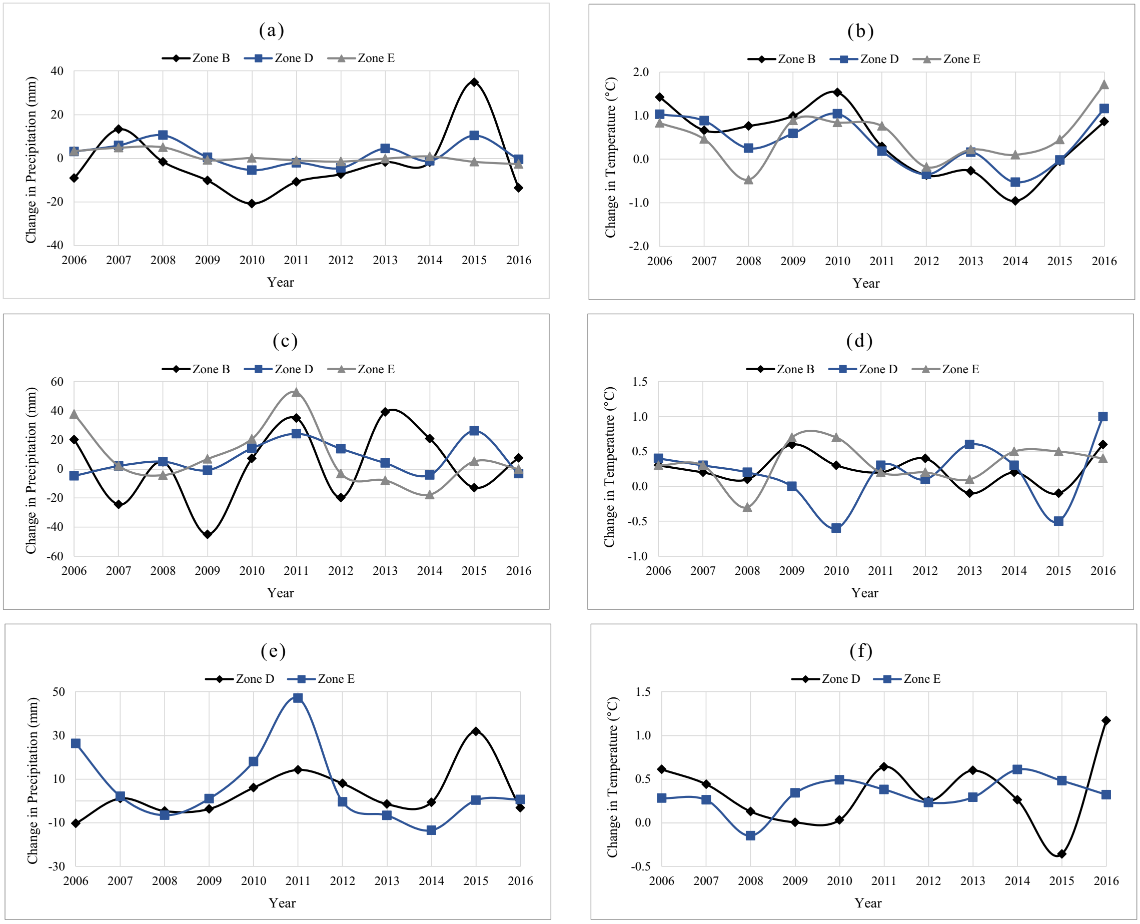


Fig. 2 Change in precipitation and temperature in crop growing season: (reference period 1978–2005) **a** change in temperature in wheat growing season; **b** change in precipitation in wheat growing season; **c** change in temperature in rice growing season; **d** change in precipitation in rice growing season; **e** change in temperature in cotton growing season; **f** change in precipitation in cotton growing season

Map 10.3.1. Areas with temperature and precipitation above the tipping point are illustrated in red and dark blue, respectively.

Results

Temporal trends of climate variables

The collective assessment of temperature and precipitation within the decade 2006–2016 bracket indicates that there is a steady increasing trend in temperature (p value is < 0.05)[4]; on the contrary, precipitation shows a relative decrease in most crop seasons. Compared with the base period (1978–2005), approximately 8 out of 10 cropping seasons observed a negative precipitation record; however, overall high inter-annual variability is evident (p value > 0.05)[2]. Figure 2a–f depicts this change in precipitation and temperature. The years 2010 and 2011 stand out, as they demonstrate the steepest dip in precipitation in wheat crop growing season (winter), parallel to peak precipitation in rice and cotton growing season (summer).

Error analysis (Table 2) indicates that the accuracy of the climate model CCSM4 varies; however, its ability to simulate temperature is greater, as opposed to precipitation. The mean bias values specify that the model tends to slightly overestimate temperature and underestimate precipitation. The future climate scenarios' results (Tables 3, 4 and 5) specify that the projected temperature remains in line with the previously 'observed' data analysis, i.e. an increasing trend. Towards the last quarter of the twenty-first century, under RCPs 4.5 and 8.5, the model predicts 4–5 and 8–10 °C rise, respectively, within all three crop seasons. Precipitation shows variability throughout 2010–2100, with a predominantly *wetter* outlook for the latter half of the century, under both RCPs.

Regression results

Pre-regression testing results are as follows: the Harris-Tzavalis unit root test confirms stationarity of data (p value

[4] Mann Kendall trend test

Table 2 Error analysis CCSM4 climate model with respect to Pakistan Meteorological Department Weather Station Observations (period 1978–2005). 'O' denotes observed data mean and standard deviation (S.D.); 'M' denotes model data

Zone	Precipitation (mm)							Temperature (°C)						
	RMSE	MAE	Bias	Mean (O)	S.D. (O)	Mean (M)	S.D. (M)	RMSE	MAE	Bias	Mean (O)	S.D. (O)	Mean (M)	S.D. (O)
B	26.52	22.65	− 0.19	60.07	17.12	41.94	8.98	0.63	0.58	0.00	24.13	0.60	24.19	0.50
D	8.80	7.82	− 0.13	19.96	9.66	15.42	4.81	0.48	0.35	0.00	25.57	0.66	25.75	0.49
E	8.28	5.58	− 0.05	15.31	13.02	10.98	8.00	0.57	0.46	0.01	26.99	0.56	27.27	0.40

< 0.05), that is, variability in data over time is constant. Pearson's chi-square test results exhibit values of ≥ 0.234, and the variance inflation factor (VIF) values are below 5, indicating that there is no multicollinearity between the independent variables. Ramsey RESET > 0.05 specifies no statistical influence of omitted variable bias. The Haussmann test results direct the use of fixed effects model for wheat and rice crops and random effects for cotton crop. Diagnostic tests, including F-test, indicate that models utilized produce statistically robust results (Table 6). However, the adjusted R^2 values are not very large, which can be attributed to non-availability of data at district level on technological advancement, fertilizer uptake, seeds use, etc. as well as the fact that we use a panel dataset that, unlike time series, normally gives lower adjusted R^2 values (i.e. less than 0.5).

Table 7 illustrates regression results in detail. Coefficients estimated from model I show that crop (wheat, rice and cotton) productivity is positively influenced from increase in temperature and precipitation. Response to temperature is 231.73 kg/ha increase in wheat productivity with 1 °C increase, whereas a 1 mm increase in precipitation leads to an increase of 2.79 kg/ha. Model II gives a coefficient for T^2 at − 24.58 kg/ha. The P^2 coefficient derived from model III is − 0.11 kg/ha. For rice crop, model I calculates the temperature coefficient with productivity increase of 193.0 kg/ha per rise in 1 °C. The precipitation leads to a rising productivity of 0.083 kg/ha per mm increase. Model II gives an output for T^2 as − 25.83 kg/ha; model III generates P^2 coefficient as − 0.012 kg/ha. For cotton crop, the regression model estimated temperature coefficient is + 115.3 kg/ha with 1° increase, and

Table 3 Projections of precipitation and temperature anomaly calculated for cotton crop growing season during different periods of the twenty-first century

	2010–2040	2041–2070	2071–2099
Precipitation (mm)			
RCP 4.5			
Zone B	27.2	− 3.1	24.0
Zone D	10.9	− 1.3	9.0
Zone E	6.4	4.3	12.4
RCP 8.5			
Zone B	− 4.0	− 3.2	1.2
Zone D	− 0.5	0.3	5.7
Zone E	6.9	6.3	8.8
Temperature (°C)			
RCP 4.5			
Zone B	1.3	2.6	3.9
Zone D	2.3	3.5	4.6
Zone E	2.4	3.9	5.0
RCP 8.5			
Zone B	1.9	3.2	7.0
Zone D	2.8	4.4	8.1
Zone E	2.5	4.6	8.7

Table 4 Projections of precipitation and temperature anomaly calculated for rice crop growing season during different periods of the twenty-first century

	2010–2040	2041–2070	2071–2099
Precipitation (mm)			
RCP 4.5			
Zone B	− 16.3	− 8.5	− 9.7
Zone D	3.7	8.6	5.8
Zone E	17.2	8.5	5.3
RCP 8.5			
Zone B	− 33.0	14.7	− 8.7
Zone D	3.2	15.8	9.6
Zone E	4.7	0.0	3.6
Temperature (°C)			
RCP 4.5			
Zone B	1.2	3.9	5.7
Zone D	1.2	4.1	5.7
Zone E	0.9	1.5	2.5
RCP 8.5			
Zone B	1.6	4.9	8.4
Zone D	1.8	4.7	8.8
Zone E	1.0	2.7	5.1

Table 5 Projections of precipitation and temperature anomaly calculated for cotton crop growing season during different periods of the twenty-first century

	2010–2040	2041–2070	2071–2099
Precipitation (mm)			
RCP 4.5			
Zone D	5.9	10.0	5.8
Zone E	16.3	14.5	15.6
RCP 8.5			
Zone D	7.8	10.0	16.3
Zone E	18.2	13.3	23.5
Temperature (°C)			
RCP 4.5			
Zone D	1.4	3.8	4.6
Zone E	1.2	2.4	2.8
RCP 8.5			
Zone D	1.5	4.6	7.7
Zone E	2.0	3.6	5.3

precipitation is + 1.90 kg/ha per mm increase, for Model I. Model II gives an output for T^2 as − 44.28 kg/ha; model III resultant P^2 coefficient is − 0.019 kg/ha.

The estimated tipping points of temperature for wheat, rice and cotton are 24.3 °C, 33.0 °C and 32.0 °C, and for precipitation, they are 47.8 mm, 98.3 mm and 21.2 mm, respectively. Figure 3a–f maps out the vulnerable areas to temperature and precipitation in the wheat, rice and cotton production areas, with respect to the tipping points calculated above. It is evident that in all cases temperature exceeds the threshold, especially post mid-century. RCP 8.5, as is, paints a wary picture with complete depletion of suitable areas for crop growth towards the end of the century. Figure 3e and f indicate that cotton crop is greatly affected by change in both temperature and precipitation, with complete depletion of suitable areas from 2040 onwards.

Table 6 Diagnostic test for regression model

Variables: crop productivity, temperature and precipitation			
Test	Wheat	Rice	Cotton
R squared	0.47	0.41	0.13
Adjusted R squared	0.46	0.39	0.10
F statistic	23.34	5.79	10.24
Probability (F–stat)	0.000	0.003	0.001

Discussion

Temperature and precipitation patterns

The temperature in wheat, rice and cotton growing seasons continues to rise within the study area. This pattern is in agreement with the previous studies undertaken by Chaudhary (2017), Haider et al. (2017) and Bokhari et al. (2017). Precipitation displays inter-annual variability; this is especially visible in anomalous years such as 2010 and 2011 (Fig. 2). While the impact of *El Niño Southern Oscillation* pattern can be recognized in its effect on the region's precipitation, uncertainty remains in the presence of isolated nonconforming years or districts (Park et al. 2010; Bhutto and Ming 2013). This is indicative of other factors at play. Largely, variability in weather within the study area is controlled by movement of wind systems from the Bay of Bengal, Arabian and Mediterranean Sea (Western disturbance), alongside indigenous topography and climate (aridity) (Snead 1968). Therefore, extreme climate trends and anomalies occur as a result of harsh local conditions, exasperated by the global teleconnections. Similarly, the projected climate data results display increasing temperature trends (Tables 3, 4 and 5), whereas in terms of precipitation, the non-homogenous change continues, leading to an overall augmentation, under both scenarios (Rajbhandari et al. 2015). Partially, this increase can be attributed to the increased moisture holding capacity of the atmosphere and greater rate of evaporation as a result of rising temperatures (IPCC 2001). However, this increase cannot be generalized; rather, accounting of frequency of intense rainfall events and dry days (period) is required. Previous studies demonstrate that enhanced forcing of greenhouse gases induce an increase in dry spells and frequency of extreme precipitation events (Ashfaq et al. 2009; Nicholls et al. 2012). Ikram et al. (2016) in their study on Pakistan's monsoon season support this notion, observing longer breaks (dry periods) and frequent intense precipitation events in the future. This pattern can prove to be damaging, with alternating risk of drought and flooding.

Impact of temperature and precipitation on crop productivity

The regression model results show that under model I configurations, increase in the temperature and precipitation increases crop productivity positively for all three crops. However, with the addition of the variable T^2 and P^2 in models II and III, respectively, the non-linearity of the relationship between temperature, precipitation and crop productivity is exposed (Burney and Ramanathan, 2014; Kumar et al. 2011). This is depicted through the negative sign of coefficients of T^2 and P^2. The non-linearity of the relationship between the climate variables and crop productivity suggests

Table 7 Regression results: assessing change in crop productivity (kg/hectare) with change in one—unit of temperature (°C), precipitation (mm). Values in the brackets denote t-statistic

Variable	Model (I)	*p* value	Model (II)	*p* value	Model (III)	*p* value
Wheat						
Temperature (T)	231.73 (6.76)	0.00	1191 (2.55)	0.01	231.67 (6.77)	0.00
Precipitation (P)	2.79 (0.94)	0.35	4.51 (1.47)	0.14	10.52 (1.62)	0.11
T^2			− 24.58 (− 2.06)	0.04		
P^2					− 0.11 (− 1.34)	0.18
Rice						
Temperature (T)	193.0 (3.30)	0.00	1704.93 (2.26)	0.03	195.36 (3.33)	0.00
Precipitation (P)	0.083 (0.07)	0.95	0.205 (0.17)	0.87	2.360 (0.92)	0.36
T^2			− 25.83 (− 2.01)	0.04		
P^2					− 0.012 (− 1.01)	0.31
Cotton						
Temperature (T)	121.73 (4.48)	0.00	3005.83 (2.09)	0.04	120.06 (4.37)	0.00
Precipitation (P)	1.58 (1.42)	0.16	1.68 (1.52)	0.12	0.550 (0.20)	0.84
T^2			− 46.97 (-2.01)	0.04		
P^2					− 0.013 (0.42)	0.67

that beyond a threshold value (*see* "Regression results" section), crop productivity will be impacted negatively. The calculated tipping points (threshold values), depicting optimal temperature, for all the crops are in line with the previous studies (Riaz 2001; Siddiqui et al. 2012; Hussain and Bangash 2017; Abbas and Mayo 2020). In the case of precipitation, the estimated threshold levels are below the water requirements of each crop, implying that the remaining water 'requirement' is met through the irrigation systems for attaining maximum output per hectare (Hussain and Bangash 2017).

Overall, the regression model results for all crops indicate that the temperature variable is statistically significant. These findings are consistent with earlier studies including Ali et al. (2017) and Siddiqui et al. (2012). Conversely, precipitation is observed as statistically insignificant in all cases. Interestingly, these findings are also consistent with earlier studies such as Burney and Ramanathan (2014), Exenberger et al. (2014), Javed et al. (2014) and Hussain and Bangash (2017). Weak statistical relationship between precipitation and crop productivity in a multiple regression may occur due to the reduced sensitivity of the former variable in the presence of multiple soil types in different climatic zones, availability of alternative irrigation sources and potential magnitude of measurement error in rainfall due to spatial heterogeneity (Lobell and Burke 2008; Lobell and Burke 2010; Zampieri et al. 2018). Moreover, changes in precipitation are rarely the governing factor for predicting impact on productivity, in the presence of more dominating factors, like temperature (Lobell and Asseng 2017).

Figure 3 illustrates the spread of vulnerable areas, projecting reduced crop productivity within the study area, under RCPs 4.5 and 8.5. This can be attributed to the proximity of the minimum/average temperature to the threshold value, leaving behind a small window of exceedance. Cotton crop shows the greatest intensity of vulnerability to rise in temperature (Fig. 3c). Even though cotton can grow in hot climates, heat stress is a major constraint in production of cotton in various countries including Pakistan; thus, any slight rise in temperature and water imbalance can deplete production (Raza and Ahmad 2015).

The above findings lead to the following conclusions: (i) temperature in all climatic zones is increasing within the 2006–2016 decade under study; forecasts observe that under RCPs 4.5 and 8.5 temperature may increase 3 to 9 °C in all

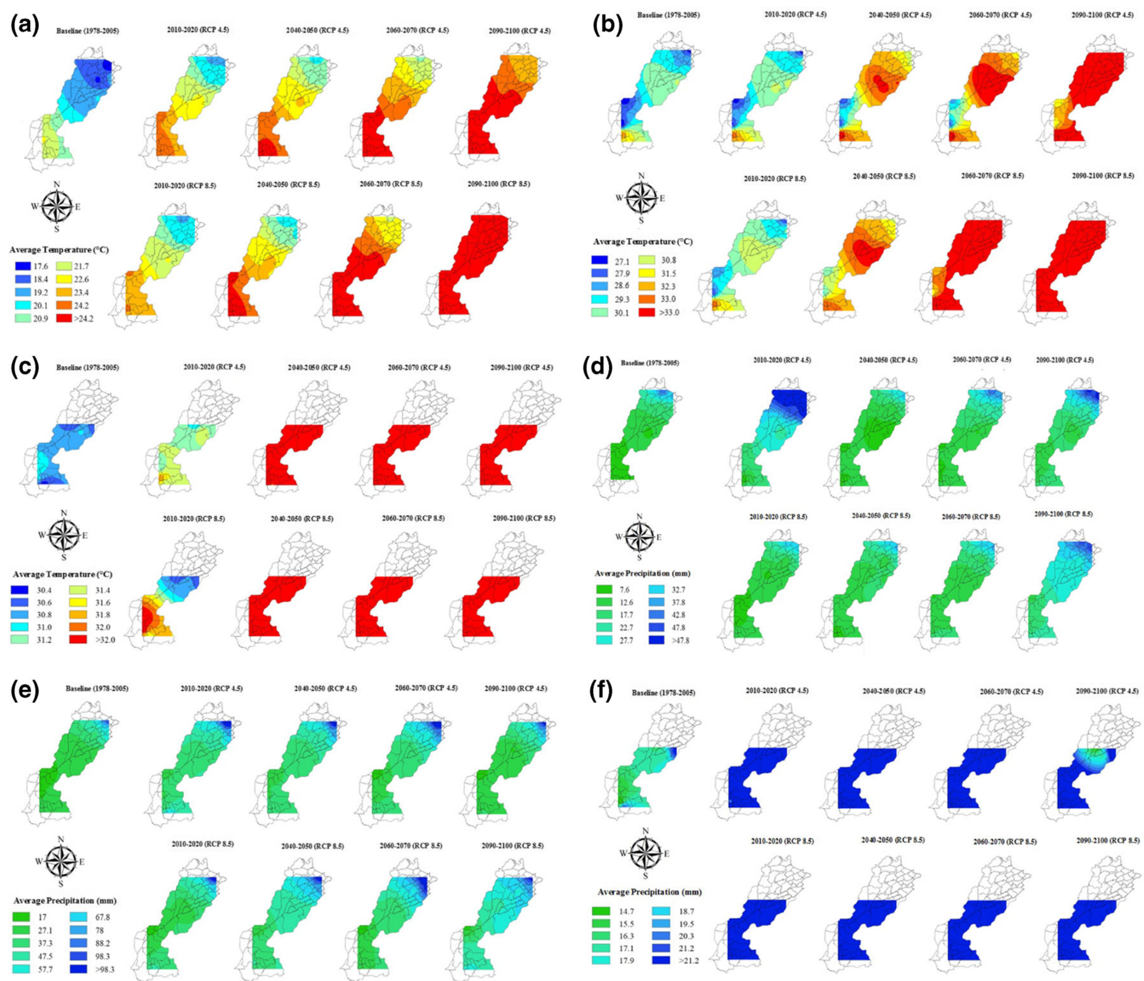


Fig. 3 Maps depicting average temperature and precipitation change under IPCC scenarios RCPs 4.5 and 8.5. Baseline (1975–2005), 2010–2020 (current), and projections for the periods of 2040–2050, 2060–2070 and 2090–2100. **a** Average temperature wheat growing season, **b** average temperature rice growing season, **c** average temperature cotton growing season, **d** average precipitation wheat growing season, **e** average precipitation rice growing season, **f** average precipitation cotton growing season

crop growing seasons until the end of this century; (ii) precipitation has high inter-annual variability with no distinct pattern; (iii) regression results indicate that wheat, rice and cotton productivity is significantly and positively impacted by temperature until it reaches the tipping point (threshold level); precipitation has a similar impact but is statistically insignificant; and (iv) there will be a dearth/depletion of suitable crop growing area towards the end of the twenty-first century, if present warming rates continue.

Recommendations and policy implications

Having identified and quantified the potential impact of the variables under study, it is evident that policies need to be carved to retard, if not diminish the causative factors. It necessitates management of cropland and rigorous study of indigenous agricultural applications. Practices like improvement and diversification of crop varieties (increasing tolerance), updating crop calendars and rotations, climate-smart agricultural practices (aiding decision-making) and recognition of the importance of incorporation of holistic farming and technology.

Above all, greater research is required, aided by creation of data inventories, which are currently scarce. This study would provide a more comprehensive impact assessment if long-term data, at district level, are available on agricultural technology used, infrastructure, fertiliser intake, pesticide usage, etc. Likewise, the current study only uses a single climate model simulation (i.e. CCSM4), embodying one trajectory of the climate system, due to it being readily available. In order to further enhance the analysis, future studies should incorporate different global climate models which represent varying climate sensitivities and trajectories of change. Nevertheless, this research is a first step that provides an apt indication and direction for studying, planning and strategizing future crop productivity.

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Availability of data and materials The datasets generated and/or analysed during the current study are available in the Pakistan Meteorological Department, Islamabad, Pakistan (temperature and precipitation data), and Pakistan Bureau of Statistics/Agriculture Department of Punjab (crop yield and production data) repository.

Author's contribution a) FM envisaged the initial idea for the research study and was responsible for undertaking data acquisition, processing and analysis, along with final composition and writing of the main manuscript, including the figures and tables.

b) MFK supervised the research work and oversaw the analysis of temperature, precipitation and crop productivity, along with input into statistical analysis and reviewed the final manuscript.

c) ZM provided technical assistance for selection and analysis of the statistical models used and reviewed the manuscript.

Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

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