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Chapter 6

Development of Climate Change Adaptation Strategies for Cotton–Wheat Cropping System of Punjab Pakistan

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Introduction

Climate change has adverse effects on food security all over the world, especially in developing countries where increasing population is confronting food insecurity and malnutrition (Brown and Funk, 2008; Lobell *et al.*, 2008). The challenge is compounded by the need to adapt to the changing climate to minimize the potential impacts on agriculture production. The Agricultural Model Intercomparison and Improvement Project (AgMIP) aims to improve the world's food security issues under changing climate conditions and enhance the adaptive capacity in both developing and developed countries (Rosenzweig *et al.*, 2013).

Over-irrigation has resulted in waterlogging and salinity in the areas of Southern Punjab. Cotton is the main cash crop of Pakistan and is cultivated in Southern Punjab and in some parts of Sindh. It requires high temperature during its growing season and cooler conditions at the time of harvesting. Extreme weather events like heat waves badly affect its yield and have resulted in severe economic crises.

Regional agriculture and climate change challenges

Pakistan is the second largest country by area in South Asia and 36th in the world. The total geographical area of Pakistan is 79.6 million hectares (mha) with 22 mha used for production of crops. The farmers generally have small land holdings: 86% of the farms have less than 5 ha and only 5% of the farms have land holdings greater than 10 ha (Government of Pakistan, 2017). Pakistan has two major cropping seasons: *rabi* (winter season) and *kharif* (summer season). These two seasons make Pakistan an agricultural economy. The *rabi* crops are grown in the months of November to April and *kharif* are grown from May to October. Wheat is the major *rabi* season crop, while cotton is grown in the *kharif* season in southern parts of Punjab (Ahmad *et al*., 2015).

The most important crops grown in Pakistan are wheat, rice, maize, cotton, and sugarcane, which contribute 29% in value addition in agriculture and 6% to GDP (Hussain *et al*., 2016). Pakistan has three main cropping systems: rice–wheat, cotton–wheat, and mixed wheat. These systems are present in the semi-arid area in the central part of country and arid areas in the southern part of country. Cotton and wheat are the major crops, which fulfil the food and fibre requirements of the population (Usman, 2012; Rahman *et al*., 2018). These crops are grown on an area of 11.60 mha in Pakistan and 8.83 mha in Punjab (Government of Pakistan, 2017).

Pakistan has diverse climatic conditions due to its arid and semi-arid ecosystems. The northern part of the country reaches the Himalayas, while the southwest and coastal regions are lowland plains of the Indus River (Sarfaraz *et al*., 2014). The coolest average annual temperature goes below 0°C in the north and reaches as high as 35°C in the southeast. Most of the country receives little rainfall (240–360 mm per year), while the highest rainfall (2400 mm per year) is received in northern areas (McSweeney *et al*., 2012).

Pakistan is at high risk to present and future extreme climate events due to its geographical location, rapidly increasing population, prevailing poverty, and dependence on agriculture and natural resources (Farooqi *et al*., 2005). According to the Global Climate Index (CRI), Pakistan ranks seventh among countries affected by climate change. The CRI was based on the average weighted ranking score of the last two decades (Eckstein *et al*., 2017). Pakistan is at risk to several natural disasters that are associated with changing climate. It is vulnerable to a rise in sea level, more frequent and heavier floods, glacier melting, higher temperatures, and increasing frequency of drought, each of which affect the current and future decision-making and can have devastating impacts on agriculture and threaten water, energy, and food security (Farooqi *et al.*, 2005).

In July 2010, floods resulting from heavy monsoon rains affected 20 million people and caused ∼3000 deaths. The flood in 2012 also affected the Pakistan economy and damaged critical infrastructure and thousands of hectares of agriculture crops (Blunden and Arndt, 2012). Droughts in 1998 and 2002 were the worst in the country's history, which inevitably affected economic growth (Sheikh, 2001). Severe heat waves in June 2015 (with temperature reaching 49°C in Southern Punjab) caused the deaths of more than 2000 people from dehydration and heat shock, and also the mortality of numerous livestock (Masood *et al.*, 2015).

Increase in maximum and minimum temperature in the winter season will shorten the winter and lengthen the summer season in Pakistan. Late onset and early ending of winter will reduce the length of crop growing seasons so that crops complete their biological cycle quickly, causing reduction in economic yield (Ghani Akbar *et al.*, 2007; Ahmed *et al.*, 2019). Early ending of winter means that temperatures will start to rise in February when wheat is at the grain formation stage. A sudden rise in mid-March temperature reduces the size of grain due to shorter grain-filling duration and less accumulation of starch content that leads to reduced yield (Rasul *et al.*, 2012; Ahmad *et al.*, 2018). Maize yield would be reduced by 43% due to a rise in temperature of 4.4°C in Pakistan (Ahmed *et al.*, 2018), while pearl millet yield will decline by 10% due to an increase in temperature of 3.7°C (Ullah *et al.*, 2019).

Climate change effects are already visible in Pakistan and there is a dire need to quantify potential impacts and develop adaptation strategies that reduce negative consequences. The current study (AgMIP, 2013) examines the impact of climate change in the cotton–wheat cropping system of Punjab, Pakistan: the study at the farm level uses a regional integrated assessment (RIA) methodology developed by AgMIP linking climate, crop, and economic modeling techniques (Antle *et al.*, 2015). The principal goal of AgMIP RIA is to provide scientific information to stakeholders that could be helpful in decision-making. Working with stakeholders, the AgMIP RIA defines four core questions for assessing climate impacts and development of adaptation strategies.

Core Question 1 defines the sensitivity of the current agricultural production system to climate change, assuming that the system will not change from its current state. Core Question 2 assesses the effect of adaptation on the current state of the world. Core Question 3 addresses the impact of climate change on the future agricultural production system; it will be different from the current system due to the development of the agriculture sector related to others factors besides the changing climate. Core Question 4 addresses the benefits of climate change adaptation for the future production system (Rosenzweig and Hillel, 2015).

The goals are to quantify the potential impacts of climate change under different scenarios of socio-economic and agricultural system development, and then identify adaptation measures to improve the livelihood of farmers. Dissemination of results to stakeholders, such as farmers, policy makers, academia, and researchers, is also important to ensure that the project results contribute to evidence-based decision-making in Pakistan and beyond.

Description of Farming System Investigated

Cotton–wheat is a long-established crop production system in the northwestern plains of the Indian subcontinent, and this rotation occupies a prominent place in the agricultural growth of India and Pakistan. Cotton and wheat contribute largely to the economic well-being of many people engaged in farming, value chain processing, and the textile industry. The cotton–wheat cropping system is a grain-plus-cash enterprise, which contribute to the livelihoods of farmers through cultivation of cotton as an industrial product and wheat as a constituent of food security. Being a cash and grain cropping system, it is extremely remunerative with secure returns. The total agricultural area under the cotton–wheat cropping system in Pakistan is 8.83 mha, which is 37% of the total cropped area of Pakistan.

Wheat is the major *rabi* (winter season) crop and in *kharif* (summer season) cotton is predominant in this system due to favorable climatic conditions in the southern parts of Punjab. Cotton is planted during April–June and harvested in October–November, while wheat is grown during the winter season (November–April) on stored soil moisture with supplemental irrigation. The cotton–wheat belt has its rainy season from July to October, when nearly 400–600 mm of rainfall is received. In some areas, rain (5% to 10% of the total annual) is also received during the winter (November–March). Most cotton in this system is planted during mid-April to mid-May using canal irrigation. Cotton is very specific in climatic condition requirements for its proper growth and development. Wheat sown in November matures by the end of April or the first fortnight of May and the fields are mechanically prepared quickly for cotton sowings.

In the cotton–wheat areas, a major concern is delay of the last harvest of cotton to get more economic return; this takes place normally from the beginning of December to the first week in January, which results in delays in the planting of the wheat crop leading to reduced wheat yields. The delay in planting after mid-November causes losses in wheat grain yield by 1% per day (Khokhar *et al.*, 2010), because the recommended planting time for wheat in the studied areas is from the first week of November to first week of December. The recommended planting time reduces the risk of exposure to hot weather in the critical period of flowering and grain formation. Late planting of cotton also leads to serious threats to productivity due to severe insect pest attacks and incidence of cotton leaf curl virus disease. Modification in management practices, such as adjustment of planting time, optimization of fertilizers, and efficient methods of fertilizer use on cotton and wheat, could increase the yield under changing climate.

Key Decisions and Stakeholder Interactions

Stakeholder engagement

A main objective of the AgMIP RIA was to make "science easier to uptake" by stakeholders. The engagement used by the Pakistani team was based on a "demand-driven" approach that helped focus scientific analysis on stakeholder needs. Stakeholders were initially prioritized according to the following factors:

- Importance
- Power
- Proximity
- Urgency
- Relevance

The identified stakeholders were policy makers, farmers, researchers, and peer groups (influential to society in the decision-making process). Among these, the two stakeholders found to be most relevant to the project outcomes were farmers and policy makers. Researchers were very helpful in the formulation of the adaptation packages and to determine future development projections called representative agricultural pathways (RAPs), and refinement of the project findings. Farmers were more interested in knowing about the adaptations and policy makers wanted to know about future scenarios. The stakeholders helped in interpreting findings and making plans for future refinements. Stakeholder engagement followed the demand-driven process shown in Fig. 1.

Stakeholder engagement was an iterative process. Multiple sessions were held to build strong relationships and trust. Stakeholder engagement activities were helpful in many ways during the research and result refinement process. Policy makers and farmers were most interested in the climatic adaptations and scenarios of future farming systems under which they would benefit. Researchers were keenly interested in AgMIP's multidimensional and multidisciplinary methodological framework (climate, crop, and economic modeling).

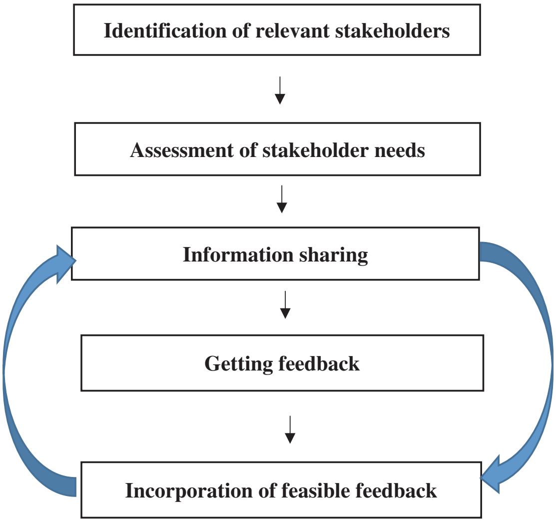


Fig. 1. Demand-driven stakeholder engagement process.

Representative Agricultural Pathways (RAPs)

RAPs were developed to portray potential future agricultural production systems. This included world demand for food and fibre coupled with technological advancement. The world is undergoing a transformative process in terms of biophysical resources, institutions, policies, technological advancements, and socio-economic conditions. It has been observed that production has been increasing as a function of inputs and technological advancements. Persistent mechanized farming, increasing crop intensity, and ecosystem disturbances are also destroying the natural resources in agricultural production systems (Valdivia *et al*., 2015).

Future agricultural production systems are characterized using RAPs. The RAPs were developed through a continuous engagement process with scientists and stakeholders, with information inputs available from literature. Changes in key national- and regional-level drivers were evaluated and inputs from global models, such as population growth and economic growth rate, were also used. Two crop models, Decision Support System for Agrotechnology Transfer (DSSAT) and Agricultural Production Systems Simulator (APSIM), were used to predict yield changes with and without climate change with future management defined in the RAPs. The Trade-off Analysis Model for Multi-dimensional Impact Assessment (TOA-MD) was used to assess the impacts of socio-economic indicators.

Two RAPs were designed after conducting several consultative sessions. A Sustainable Development Pathway (RAP 4) and a Unsustainable Development Pathway (RAP 5) were developed (Table 1). Experts of various disciplines such as agricultural

Table 1. Trends of variables for sustainable (RAP 4) and unsustainable (RAP 5).

Variable	Sustainable Development Pathway (RAP 4)	Unsustainable Development Pathway (RAP 5)
Farm size	Moderate decrease ↘	Large decrease ↘
Household size	Moderate increase ↗	Large increase ↗
Non-agricultural income	Small increase ↗	Small increase ↗
Herd size	Small increase ↗	Large decrease ↘
Input prices	Moderate increase ↗	Large increase ↗
Output prices	Moderate increase ↗	Large increase ↗

Source: Developed by authors on the basis of expert opinion and existing information in literature.

economics, soil science, pathology, irrigation and water management, plant and animal breeding, veterinary science and demography were engaged in the consultation process to project biophysical, socioeconomic and policy factors and construct the corresponding narratives that describe the pathways to future conditions. The consultants included researchers, academics, leading farmers, members of local NGOs, and government officials involved in policy formulation and implementation. Invitations to experts included background information about the project, the RAP development event, and the scenarios about which consultation was requested. Four RAPs meetings and consultative sessions were held with experts at different time periods.

Challenges in RAPs development included agreement of experts, especially on policy variables. Anticipated future percentage changes with respect to current conditions are important but, in some cases, difficult to quantify (for example, disease outbreaks, impact of farm mechanization, irrigation availability, quality of irrigation water). The extent of losses due to diseases and water resource depletion is difficult to assess in the era of technological advancements. Pakistan agriculture is still quite traditional and great potential exists in terms of mechanization. Conversely, it is facing the challenges of climate change and natural resource depletion.

Adaptation packages

Agricultural production systems are complex, interlinked, and highly dependent on natural ecosystems. Crop production is a climate-dependent sector of the economy. Adaptation to the impacts of climate change is very important for developing

Table 2. Adaptation packages for climate change in Punjab, Pakistan.

Biophysical Adaptations	Socio-economic Adaptations	Institutional and Policy Adaptations
Virtual cultivars (heat- and drought-tolerant varieties)	Construction of water storage	Agricultural insurance/finance
Plant population	Participatory management approach	Farm mechanization (mechanical picker for cotton)
Improved agricultural practices	Increasing off-farm income opportunities	Subsidies/taxation
Efficient irrigation practices	Population control measures	Input/output price policies
Changes in cropping patterns		Trade, off-farm employment
Soil reclamation projects		Efficient input/output markets

economies. There are planned and unplanned adaptations regarding climate vulnerability in agricultural systems that maintain ecosystem balance and minimize economic losses. The policies regarding development must have a synergistic effect with climate change to enhance the adaptive capacity of the nation. To minimize climate losses, farm-level adaptation strategies can be designed with support of on the farm level, as well as on the sectoral and national and policies. To evaluate the benefits of adaptations, we formulated adaptation packages through a continuous engagement process with researchers, farmers, and policy makers with the goal of combatting current and future climatic vulnerabilities (see Table 2).

For current and future climatic vulnerabilities, different short-term and long-term adaptations were combined in which biophysical, socio-economic, and policy parameters were assessed. Current adaptations regarding climatic hazards are increasing in cropping intensity, fertigation, efficient irrigation, and imported genetic varieties. Important adaptation parameters for the future are genetic improvements, drought-resistant and heat-tolerant varieties, deep tillage, soil and water conservation practices, construction of water storage, efficient irrigation systems, crop diversification, agricultural insurance, and farm mechanization (i.e., mechanical harvesters for cotton).

The farmers in Punjab are very concerned about climatic impacts and vulnerability and showed interest in adopting the proposed adaptations. However financial, technological, and socio-economic factors often hinder the farmers from better adapting to climatic variations. The formulated adaptation packages were incorporated into the simulations by the crop modelers. The practicality of the proposed adaptations was also an issue that was tackled with the farmers' and field researchers' feedback.

Data and Methods of Study

Climate

The baseline period consisted of a 1980–2009 historical daily weather record, which had a mid-year atmospheric CO_2 concentration of 360 ppm. Historical climate of the study region was analyzed using observed weather data provided by the Pakistan Meteorological Department (PMD). We categorized each farm in the economic analysis into a smaller number of groups that experience nearly the same climate and then created climate series for these groups rather than each individual farm. We identified weather stations that best represented selected crop modeling regions (Bahawalpur, Bahawalnagar, Multan, and Rahim Yar Khan) and obtained as much of the 1980–2010 period as possible (daily precipitation, maximum and minimum temperatures, solar radiation or sunshine duration, wind speed, dew point temperature, vapour pressure, and relative humidity).

The quality of the observed weather data was checked and datasets were converted to the AgMIP format as described in the AgMIP protocols (Rosenzweig *et al*., 2013; Ahmad *et al*., 2015). Additional climate series were also obtained for Lodhran district from the AgMIP climate forcing dataset based on the NASA Modern-Era Retrospective Analysis for Research and Applications (AgMERRA) (Ruane *et al*., 2015). AgMERRA corrects to gridded temperature and precipitation, incorporates satellite precipitation, and replaces solar radiation with NASA/GEWEX SRB in order to fully cover the 1980–2010 period.

The outputs are a high-quality version of *in situ* climate observations in AgMIP format for each location where crop models are used (Table 3), a file documenting the changes made to the original raw observations, and summary maps and statistics characterizing the region being analyzed.

Mean and trends in baseline climate

The mean baseline climate is shown for the cotton and wheat seasons to identify climate patterns of the districts across the region (Table 4). In terms of maximum

Table 3. Study districts with latitude and longitude.

No.	District	Latitude (°N)	Longitude (°E)
1	Bahawalnagar	29.56	73.10
2	Bahawalpur	29.60	72.25
3	Lodhran	29.61	71.65
4	Multan	30.19	71.45
5	Rahim Yar Khan	28.65	70.68

Table 4. Observed maximum temperature, minimum temperature, and precipitation for the baseline period (1981–2010).

	Obs. Station	Latitude	Longitude	Cotton	Wheat	Annual
Rain (mm)	Multan	30.19	71.46	116.40	54.00	210.70
	Bahawalpur	29.34	71.68	102.80	38.20	168.60
	Bahawalnagar	29.99	73.25	157.40	58.40	242.10
	Lodhran	29.53	71.63	100.22	40.06	167.30
	Rahim Yar Khan	28.42	70.29	77.50	26.20	120.70
Tmax (°C)	Multan	30.19	71.46	39.98	26.44	32.61
	Bahawalpur	29.34	71.68	40.22	26.94	32.98
	Bahawalnagar	29.99	73.25	40.21	26.93	32.96
	Lodhran	29.53	71.63	40.5	28.06	33.74
	Rahim Yar Khan	28.42	70.29	40.3	27.41	33.32
Tmin (°C)	Multan	30.19	71.46	27.72	10.82	18.4
	Bahawalpur	29.34	71.68	27.17	11.11	18.3
	Bahawalnagar	29.99	73.25	27.18	11	18.25
	Lodhran	29.53	71.63	27.48	11.63	18.72
	Rahim Yar Khan	28.42	70.29	26.33	10.02	17.3

temperature, Lodhran and Rahim Yar Khan display the warmest climate with nearly a 40°C upper temperature limit in the cotton season, 29°C for the wheat season, and 33°C on an annual basis. In terms of minimum temperature, Multan and Lodhran are warmest with a 27°C lower temperature limit in the cotton season, 12°C in the wheat season, and 19°C on an annual basis. In terms of precipitation, the highest is observed in Bahawalnagar with up to 157 mm in the cotton season, up to 58 mm in the wheat season, and an annual precipitation of 242 mm over the district. Lowest precipitation is observed in Rahim Yar Khan with 78 mm in the cotton season, 26 mm in the wheat season, and 121 mm on an annual basis over the district.

The districts averaged maximum temperature of the baseline is 33.1°C on an annual basis, 40.2°C for the cotton season, and 27.2°C for the wheat season. The districts averaged minimum temperature of the baseline is 18.2°C on an annual basis, 27.2°C for the cotton season, and 10.9°C for the wheat season. Annual rainfall averaged over the five districts is 182 mm, whereas it is 111 mm for the cotton season and 43 mm for the wheat season.

Long-term linear trends were calculated in the 1980–2009 baseline period for solar radiation, maximum temperature, minimum temperature, and precipitation over the five focus districts in Southern Punjab region of Pakistan (Fig. 2). Trends generally indicate warmer and wetter conditions, although the trend for precipitation was not significant.

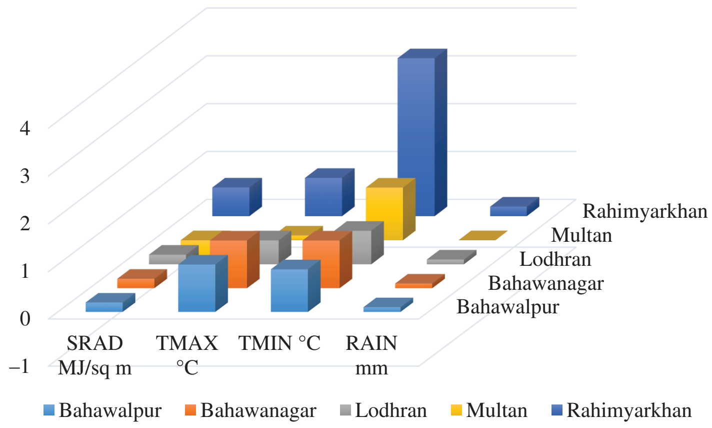


Fig. 2. Historical trends of climatic parameters for the period 1980–2010 over the target sites.

Temperature–precipitation sensitivity in projected changes for global climate models selection

Global climate model (GCM) projections may be briefly summarized in temperature–precipitation change charts for a particular growing season (Ruane and McDermid, 2017). The spread in GCM projections is divided into five different characteristics (relatively cool/wet, hot/wet, relatively cool/dry, hot/dry, and middle) to understand the relative probability of the different classes of outcomes. The temperature–precipitation sensitivity charts in the projected changing climate are constructed to observe the behaviour of the 29 GCMs. The growing season is taken as a complete annual cycle JJASONDJFMA (June–April) to encompass the whole growing and harvesting of cotton–wheat cropping system.

Initially, in the GCM selection process, for each site and for each representative concentration pathway (RCP) we selected a different GCM that rendered difficulties in comparisons among sites and among RCPs. A close inspection of the scatter plots showed some uncertainties related to precipitation in the region. Four GCMs *viz.*, bcc-csm1-1, CSIRO-Mk3-6-0, MRI-CGCM3, and IPSL-CM5B-LR, projected more than 200% increase in precipitation over the target districts (see Fig. 3 for Multan district). We did not include the four GCMs and selected the remaining 25 for the analysis. In the end, we selected five representative GCMs for application to all sites and seasons.

In addition to statistically analysing the GCMs (i.e., establishing the selection criterion as 0.5 times the standard deviation), we also evaluated the simulation of the spatial climatology of the region. For this, we constructed maps of the targeted locations and selected GCM projections. The distance between the farms in the districts is quite small compared to the scale of the GCM grid boxes; there are

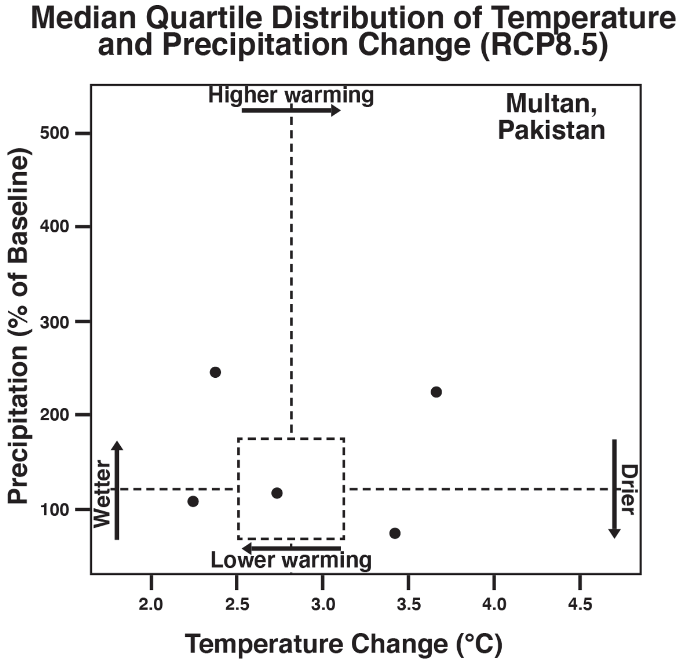


Fig. 3. Uncertainty arising from projected change in precipitation (%).

greater differences due to local climate features in the observations than due to projected climate changes (Fig. 4).

From the analysis, we learned that the GCMs have biases in areas in proximity to mountains. The precipitation change maps include patterns of both the GCM projections (large squares) and the AgMERRA historical precipitation changes (small squares). The precipitation changes are applied on a monthly basis as factorial adjustments, meaning that the total annual difference reflects both the size of the projected monthly changes and the historical rainfall in each month. We focused on the large-scale patterns in GCM selection for the study.

In general, we looked at sites in Punjab and identified the GCMs that were consistently relatively warm/dry, warm/wet, cool/dry, cool/wet, and in the middle of the distribution. The GCM grid boxes typically are on the order of 100s of km, and neighbouring grid boxes do not often differ greatly unless there is a major elevation change. The farthest linear distance between two sites in the study area is 261 km (2.46°) and there is a high mountain less than 100 km away from the western sites.

In the process of selecting the GCMs, we considered each RCP on its own and selected GCMs for each, allowing greater consistency within each future RAP/RCP combination. By analysing the GCM precipitation maps, we revised our selection of the GCMs based on their representation of the monsoon over the Pakistani region

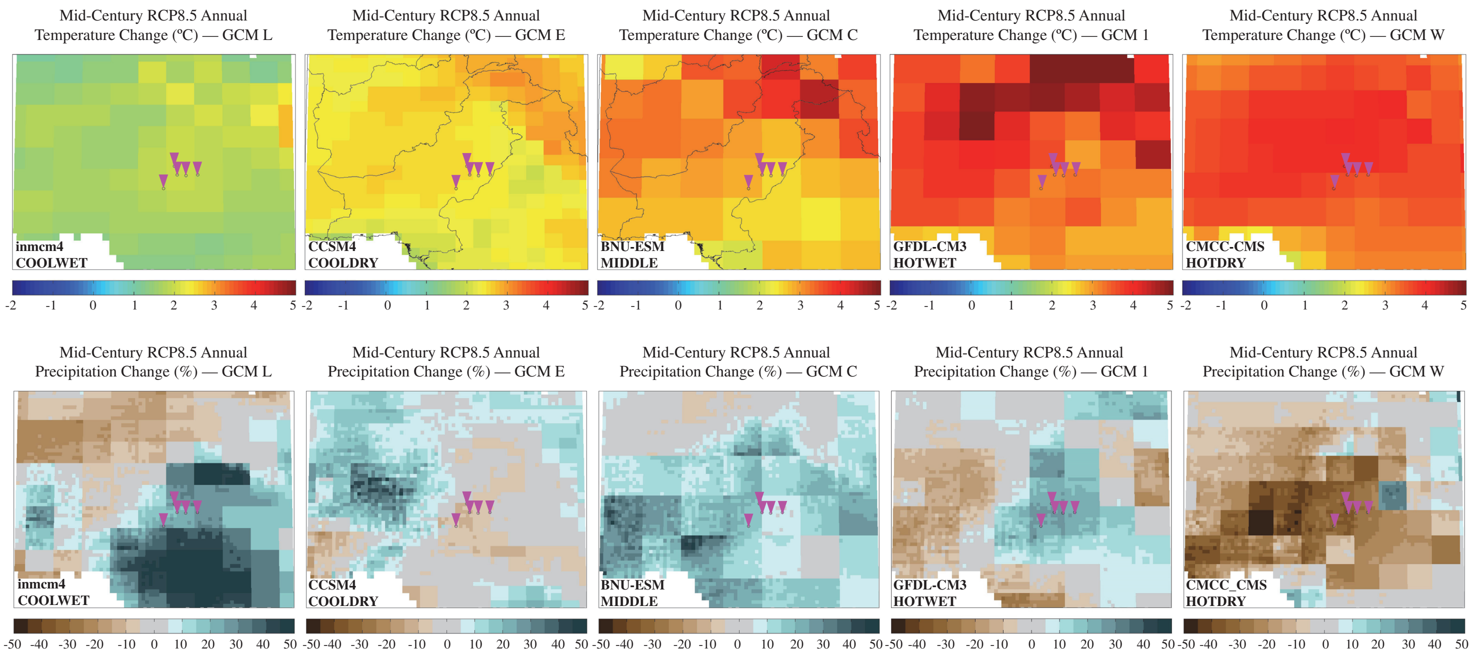


Fig. 4. Projected climate changes for the selected GCMs overlaid on study districts. Top row is delta mean temperature and bottom row is percentage precipitation change.

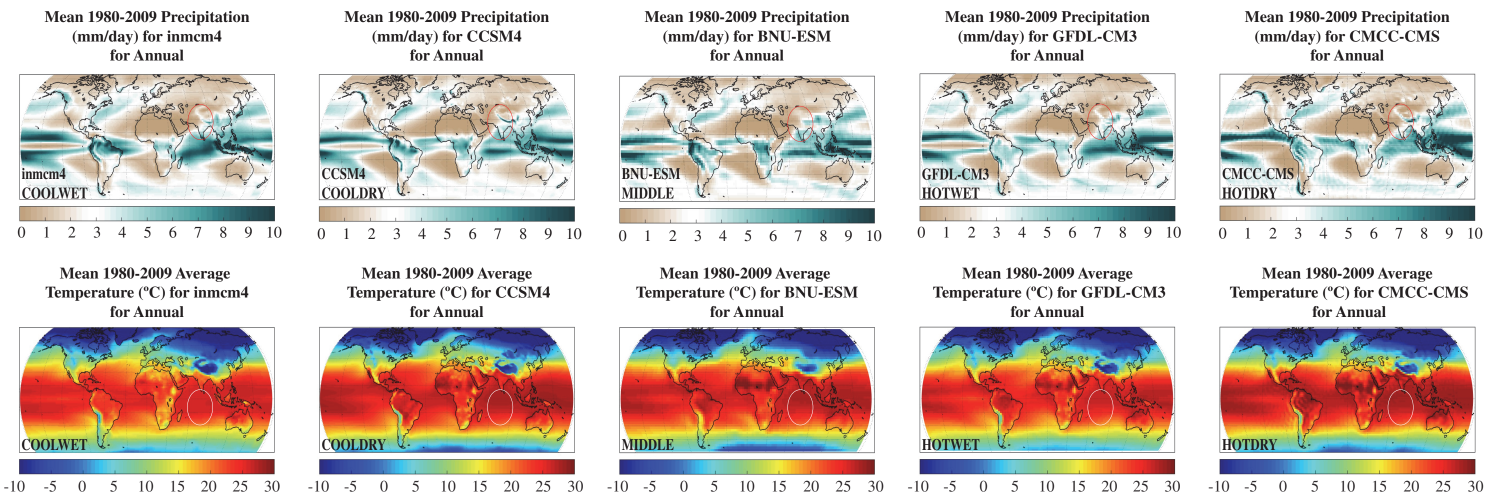


Fig. 5. Representation of annual climatology of the selected GCMs focusing on emulation of the South Asian Monsoon. Top panel presents precipitation (mm/day), while bottom panel presents temperature (°C).

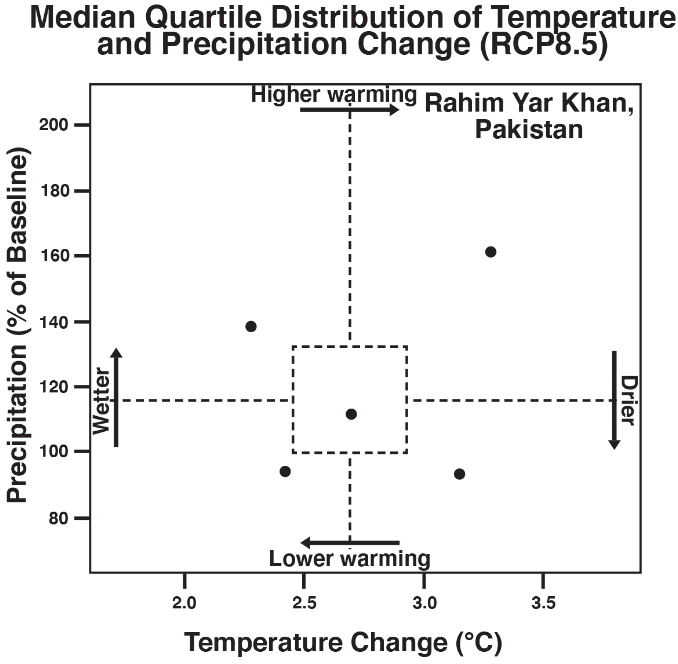


Fig. 6. Delta T — delta P scatter plot for RCP 8.5 of the Rahim Yar Khan district for the purpose of GCM selection.

(Fig. 5). The GISS-E2-R GCM that we selected initially for the cool/wet scenario did not emulate the monsoon well in the region. So, it was decided to take the next most representative cool/wet model (inmcm4) as it was important that the monsoon be plausibly simulated. Based on the recurrence of a characteristic GCM in a specific quadrant for all five districts each under both RCPs, we selected the GCMs for the RIA (Fig. 6 and Table A.1 in the Appendix).

Climate projections with mean and variability changes

Climate change projections for the region were generated using output of the five selected GCMs from CMIP5 for the mid-century (Taylor *et al.*, 2012) under RCP 4.5 and RCP 8.5 scenarios (CO_2 concentration of 571 ppm) (Moss *et al.*, 2010). The five GCMs were selected to represent the uncertainty in projected temperature and rainfall changes based on five possible relative climate characteristics (cool/wet, cool/dry, hot/wet, hot/dry, and middle) (see Fig. 7).

In the creation of CMIP5 mean and variability change scenarios, we engaged AgMIP-R scripts for scenario generation (Hudson and Ruane, 2015). In the process, we assumed that solar radiation, winds, and relative humidity daily variables from the historical daily climate records are unchanged. We also ensured that vapour

	Cotton Season	Wheat Season	Annual
TMAX_BASELINE	40.2	27.2	33.1
RCP8.5_COOLWET_TMAX	41.1	28.2	34.2
RCP4.5_MIDDLE_TMAX	41.6	29.1	34.8
RCP4.5_COOLDRY_TMAX	41.7	29.0	34.9
RCP4.5_HOTWET_TMAX	42.8	29.5	35.5
RCP8.5_COOLDRY_TMAX	42.8	29.6	35.6
RCP4.5_HOTDRY_TMAX	42.7	29.8	35.6
RCP8.5_MIDDLE_TMAX	42.6	30.1	35.8
RCP4.5_COOLWET_TMAX	43.3	30.0	36.0
RCP8.5_HOTWET_TMAX	43.8	30.3	36.4
RCP8.5_HOTDRY_TMAX	43.7	30.9	36.7
TMIN_BASELINE	27.2	10.9	18.2
RCP4.5_COOLWET_TMIN	27.8	11.6	18.9
RCP4.5_COOLDRY_TMIN	28.7	12.6	19.8
RCP4.5_MIDDLE_TMIN	28.8	13.2	20.2
RCP8.5_COOLDRY_TMIN	29.6	13.6	20.8
RCP4.5_HOTWET_TMIN	30.3	13.1	20.8
RCP4.5_HOTDRY_TMIN	29.9	13.6	20.9
RCP8.5_MIDDLE_TMIN	29.8	13.8	21.0
RCP8.5_COOLWET_TMIN	30.2	13.4	21.0
RCP8.5_HOTWET_TMIN	31.4	13.7	21.6
RCP8.5_HOTDRY_TMIN	31.0	14.7	22.0
RCP8.5_HOTDRY_RAIN	571.2	274.8	1441.3
RCP4.5_HOTDRY_RAIN	771.7	306.2	1457.9
RCP4.5_MIDDLE_RAIN	885.9	578.6	1780.4
RCP8.5_COOLDRY_RAIN	1034.4	458.5	1808.1
RCP4.5_COOLDRY_RAIN	1119.4	376.6	1808.5
RAIN_BASELINE	1175.4	488.3	2000.4
RCP8.5_MIDDLE_RAIN	1196.7	617.0	2277.9
RCP4.5_HOTWET_RAIN	1408.6	508.5	2296.5
RCP8.5_COOLWET_RAIN	1637.7	417.5	2402.0
RCP4.5_COOLWET_RAIN	956.8	617.4	2444.9
RCP8.5_HOTWET_RAIN	1373.0	702.1	2448.0

Coolest – Warmest; Coolest – Warmest; Driest – Wettest

Fig. 7. Baseline and climate projections of cotton and wheat growing seasons for maximum temperature (TMAX) (°C), minimum temperature (TMIN) (°C), and precipitation (rain) (mm/year) averaged over all districts.

pressure, dew point temperatures, and relative humidity were physically consistent at time of maximum daily temperatures (this entails raising vapour pressure and T_{dew} as ΔT). Finally, we produced mean and variability change scenarios for all CMIP5 GCMs at the best calibrated site in each region, and then created future scenarios at every farm site using the 5-GCM subset to drive crop and livestock model simulations (Ahmad *et al.*, 2015) (see Fig. 8).

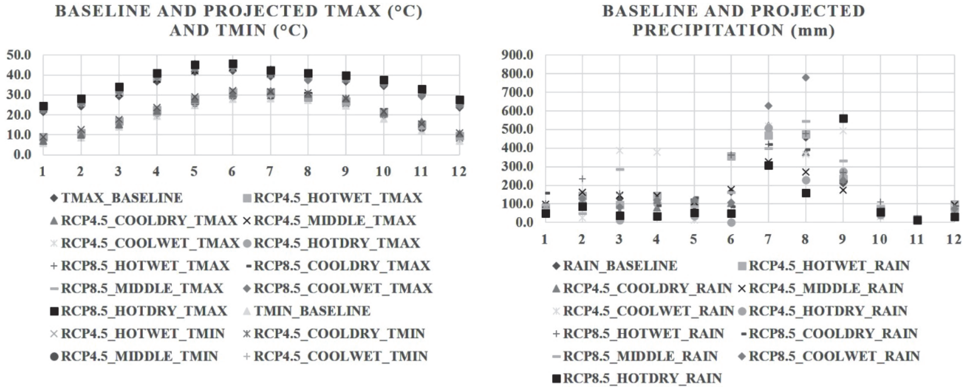


Fig. 8. Annual cycles of baseline and projected regional climate averaged over all districts.

Projected changes in future climate

The major projection of climate change in the target region complies with the global trend of increases in both maximum and minimum temperatures. However, there are highly heterogeneous change patterns observed in the projected precipitation regime owing to its high inter-annual variability in the region.

Temperature changes for the target region are projected to be highest under the GCMs with relatively hot/wet and hot/dry characteristics. For the cotton season, the highest changes are projected in the relatively hot/wet (hot/dry) climate with 3.6°C (3.5°C) increase in maximum temperature and 4.3°C (3.8°C) increase in minimum temperature, while in terms of wheat climate, the projected temperature increase is highest in the probable hot/dry climate with 3.7°C increase in maximum temperature and 3.8°C increase in minimum temperature under RCP 8.5 scenario. The highest projected average annual temperature increase is 3.6°C for maximum temperature and 3.8°C for minimum temperature under RCP 8.5 scenario.

The highest changes of the relatively hot/wet climate conditions in the future may be attributed to a significant increase in maximum temperature in May, June, and July of the cotton sowing season with an average projected increase of 3.9°C throughout the season. Projected changes under the relatively hot/dry conditions may be attributed to an average 3.8°C increase in May and June of the cotton growing season and an average 4.1°C increase in November, December, February, and March of the wheat growing season in terms of maximum temperature under the RCP 8.5 scenario.

However, in the minimum temperature regime, the highest changes under the relatively hot/wet conditions may be attributed to the average increase of 4.5°C in May, June, and July of the cotton growing season under the RCP 8.5 scenario. Moreover, in the minimum temperature regime, the relatively hot/dry conditions projected with highest changes may be attributed to significant average increases of 3.9°C in November, December, February, and March of the wheat growing season, and of 4.1°C in May and June of the cotton growing season under the RCP 8.5 projection period.

The precipitation projections depict high variability in all months of the cotton and wheat growing seasons over the region. In the projected cotton growing season under RCP 4.5, the greatest decreases in precipitation are seen under the relatively hot/dry climate with a significant decrease of 101 mm/month (approx. 404 mm/season absolute decrease) in the seasonal average. Under RCP 8.5, the projected decrease in the cotton growing season is again seen under the relatively hot/dry conditions with an even more significant 151 mm/month decrease (approx. 604 mm/season absolute decrease) over the season.

In the projected wheat growing season, a seasonal average decrease of 30 mm/month (182 mm/season absolute decrease) under RCP 4.5 and 36 mm/month (214 mm/season absolute decrease) under RCP 8.5 is seen under the relatively hot/dry climate conditions in the future. Annual precipitation decreases of 45 mm/month (543 mm/year absolute decrease in RCP 4.5) and 46 mm/month (560 mm/year absolute decrease in RCP 8.5) are also seen in the projected relatively hot/dry climate conditions over the region (see Fig. 9).

Median rainfall changes over the growing season of Southern Punjab in mid-century display a weakening of magnitude by up to 10% under RCP 4.5 and strengthening of it by up to 20% under RCP 8.5 scenario. Median of total rainfall changes over the growing season of the South Punjab region in mid-century display a slight decrease of up to 20 mm under RCP 4.5 and increase of up to 50 mm under the RCP 8.5 scenario. Median temperature changes over the growing season of Southern Punjab in mid-century display an increase in magnitude by up to 2°C under RCP 4.5 and by up to 3°C under RCP 8.5 (Fig. 10). Projected climate changes are much more pronounced in RCP 8.5 than in RCP 4.5.

Median changes in projected climate of target districts

To rule out blending of climate biases with climate changes, we took the median of projected changes presented by the five selected GCMs. The projected changes in maximum temperature are seen to affect the Multan district with the highest magnitude of up to 2.6°C under RCP 4.5 and up to 2.7°C under RCP 8.5 in the cotton growing season. For wheat growing season, Multan, Lodhran, and Rahim Yar Khan are affected with the highest magnitudes of 2.6°C under RCP 4.5, while under RCP 8.5 the highest changes are seen in Bahawalpur and Bahawalnagar with magnitudes of up to 3°C. On an annual basis, the Multan district is seen to project the highest changes with up to 2.7°C under RCP 4.5, whereas under RCP 8.5 Bahawalpur

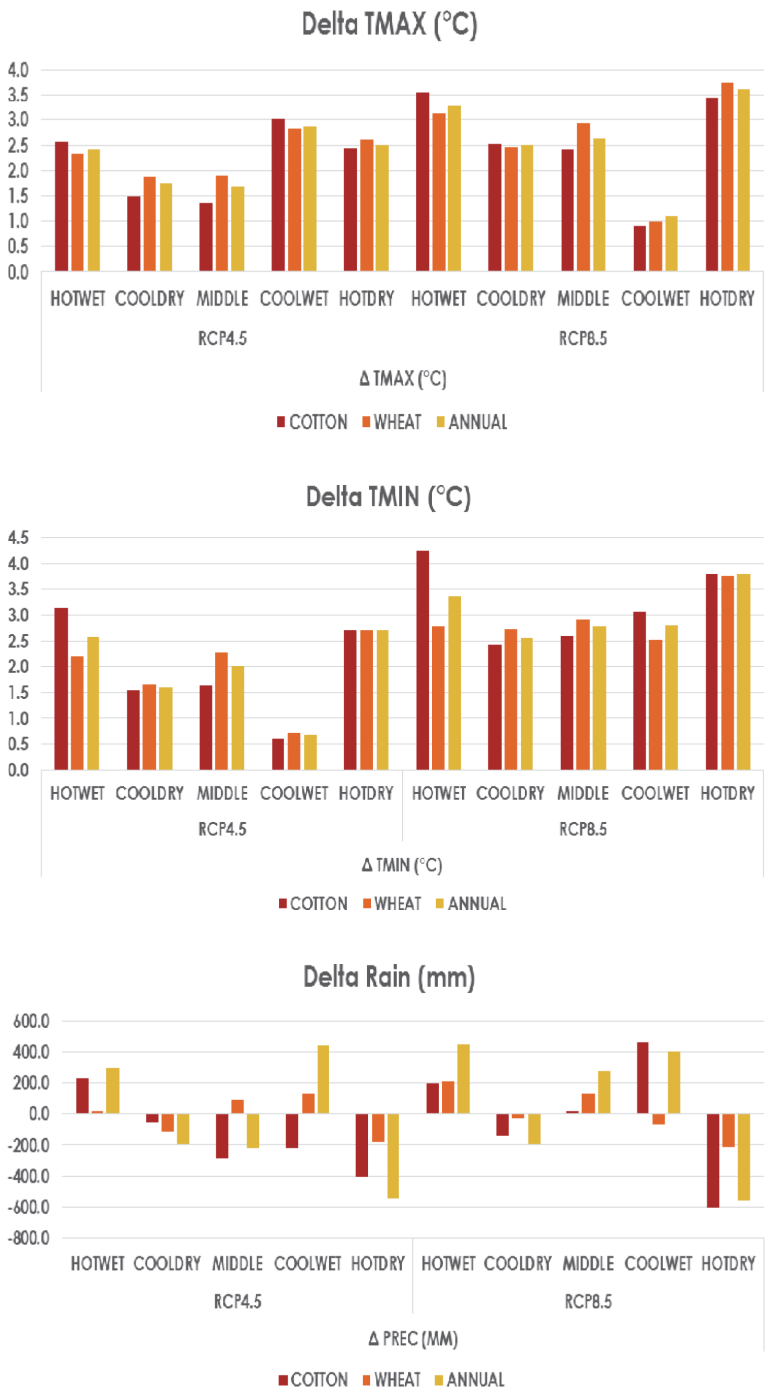
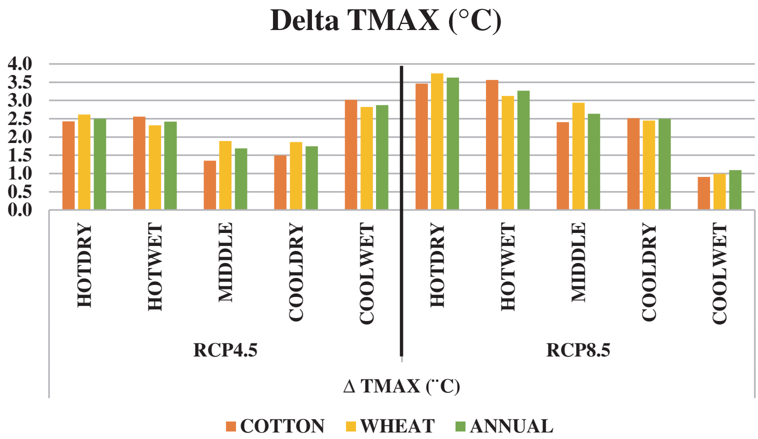
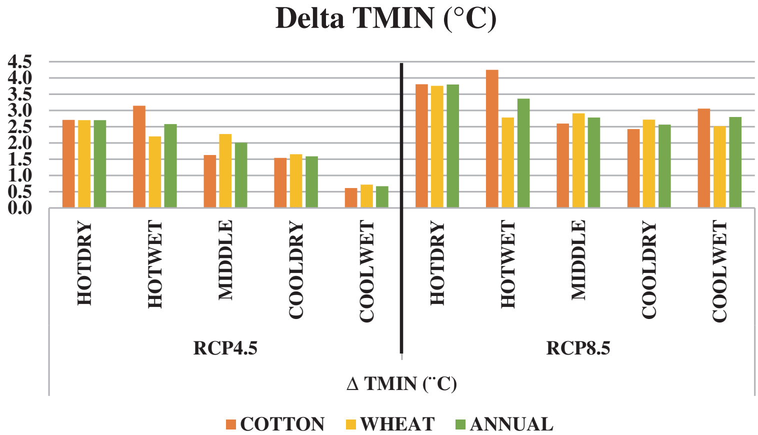


Fig. 9. Projected changes in regional climate averaged over all districts.





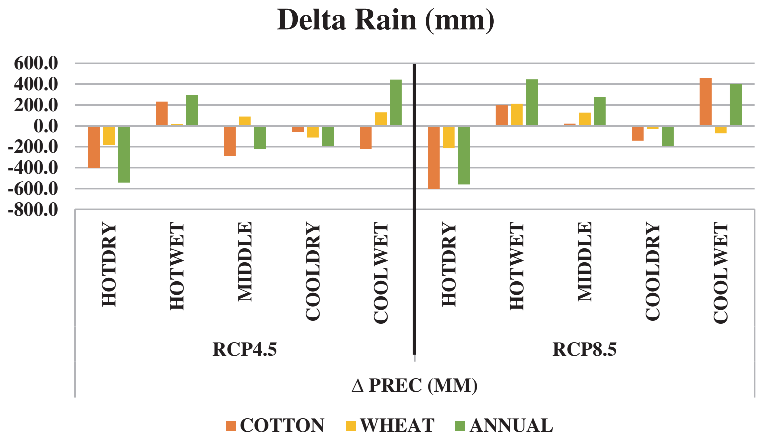


Fig. 9. (*Continued*)

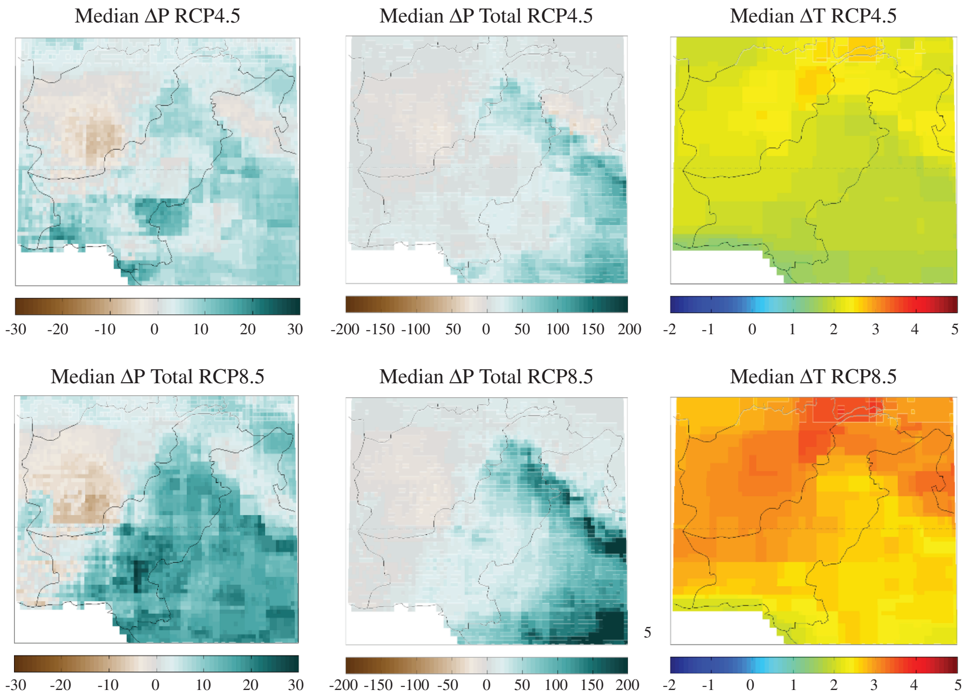


Fig. 10. Map of median annual temperature and precipitation projections for region across all GCMs.

and Bahawalnagar see the highest changes with magnitudes of up to 2.6°C. Changes in other variables may be seen in Table A.1 in the Appendix.

Socio-economic data

Survey data of cotton, wheat, and livestock were collected from the cotton–wheat cropping system of Punjab. Extensive farm surveys of 165 farms across five districts were conducted. The population is heterogeneous in nature; therefore, a stratified random sampling technique was used. The districts included Bahawalnagar, Bahawalpur, Lodhran, Multan, and Rahim Yar Khan. Two villages were selected randomly from each district. Each district was defined as a separate stratum, because of its own climatology and topography. From each stratum, at least 33 respondents (15 farms from each village) were chosen randomly so that the selected sample could be a true representation of the farming population. Survey data include crop management practices for cotton and wheat (sowing date, fertilizers, irrigation amount, and dates and harvest information), non-farm income, and other crops and livestock produced. Analysis was made on a per farm basis. The study sites are shown in Fig. 11.

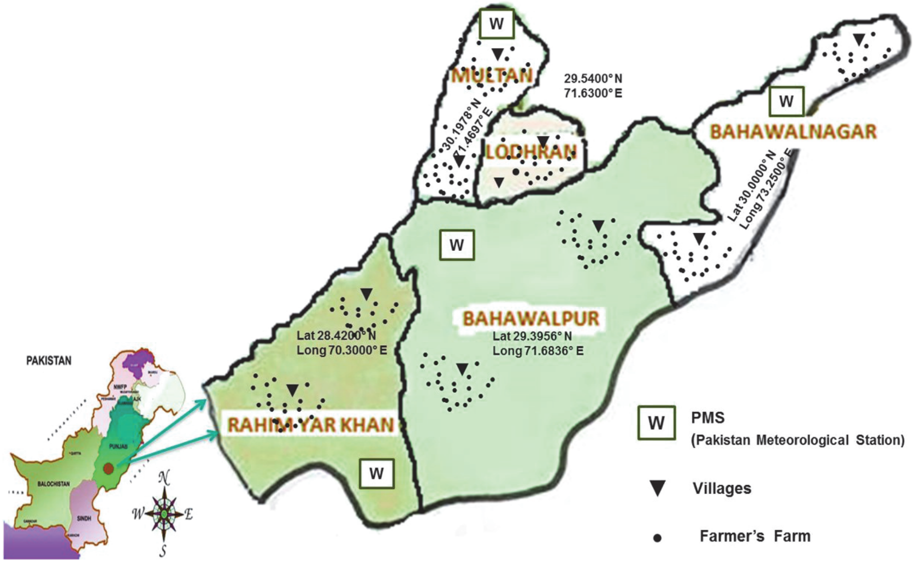


Fig. 11. Geographical location of the study site in Punjab, Pakistan.

Regional Integrated Assessment

Two crop models, DSSAT and APSIM, were calibrated with the optimum sowing date for three cultivars of cotton and wheat using two years of experimental data. Both models simulate crop phenology, growth, and yield over time (Jones *et al.*, 2003; Innes *et al.*, 2015). After calibration and evaluation of three cultivars with the experimental dataset, both crop models were evaluated at the farm level. Crop management data, including sowing date, fertilizer, irrigation, initial conditions, soil moisture, and organic amendments were used as inputs to the crop models. One average input farm was selected to evaluate the sensitivity of crop models. The economic analysis was conducted using the TOA-MD impact assessment model (Antle, Sottovogel and Valdivia, 2014).

The Regional Integrated Assessment (RIA) was carried out using AgMIP IT tools (ADA, QuadUI, and ACMOUI) (Rosenzweig and Hillel, 2015). The following simulations were carried out to evaluate the impact of climate change on the cotton–wheat farming system (Table 5).

Carbon, temperature, water, and nitrogen analysis

The sensitivity of DSSAT and APSIM models to variations in climate was tested systematically by modifying CO_2, temperature, and precipitation values of baseline weather data as described in Ruane *et al.* (2014). The changes were applied to all 365 days of every year of historical time period. The CO_2 concentrations tested were

Table 5. Climate change analysis for integrated assessment in cotton–wheat cropping system of Punjab, Pakistan.

Crop Model Simulations	Identifier	Core Questions
Historical data, current management	CM1	Q1 = CM2/CM1
Current climate, current management	CM2	Q2 = CM3/CM1
Current climate, current management, plus adaptation	CM3	Q3 = CM5/CM4
Current climate, future RAPs	CM4	Q4 = CM6/CM5
Climate change, future RAPs	CM5	
Climate change, future RAPs, plus adaptation	CM6	

Source: Rosenzweig and Hillel, 2015.

360, 450, 540, 630, and 720 ppm (at 90 ppm intervals) at 30 and 180 kg N ha^{-1}. The observed daily temperatures (minimum and maximum) were modified by −2°C, ambient, +2°C, +4°C, +6°C, and +8°C. The daily precipitation was adjusted between 25%, 50%, 75%, 100%, 125%, 150%, 175%, and 200% of ambient. Nitrogen fertilization was changed by 0, 30, 60, 90, 120, 150, and 180 kg N ha^{-1} at 30 kg intervals.

Farmer field evaluation

The crop growth models DSSAT and APSIM were run with observed weather data of the cropping year, e.g., 2012–2013, and the results were compared to assess the accuracy of models using statistical indices including root mean square error (RMSE). There was good agreement between predicted and observed farmer cotton field yield, with RMSEs of 748 and 969 kg ha^{-1} for DSSAT and APSIM, respectively (Fig. 12). The RMSEs of wheat for DSSAT and APSIM were 899.29 and 816.95 kg ha^{-1}, respectively (Fig. 13).

The main factors driving differences in observed and simulated wheat were attributed to the differences in soil profiles (15 were used) and different management practices of the various farms. The difference between simulated and observed yields was lower for those farmers whose management practices followed the Govt. of Pakistan's recommendations (Government of Pakistan, 2019). Planting time, plant population, number of irrigation applications, irrigation at critical stages, fertilizer application dates, application at crop critical stages, weed management, and disease control were better in the case of progressive farmers' fields and in those cases the crop models simulated almost the same yield as observed.

Carbon Dioxide, Temperature, Water, and Nitrogen Analysis

The responses of DSSAT and APSIM were evaluated with changing levels of CO_2, temperatures, rainfall, and fertilizers for the cotton crop. The crop models showed

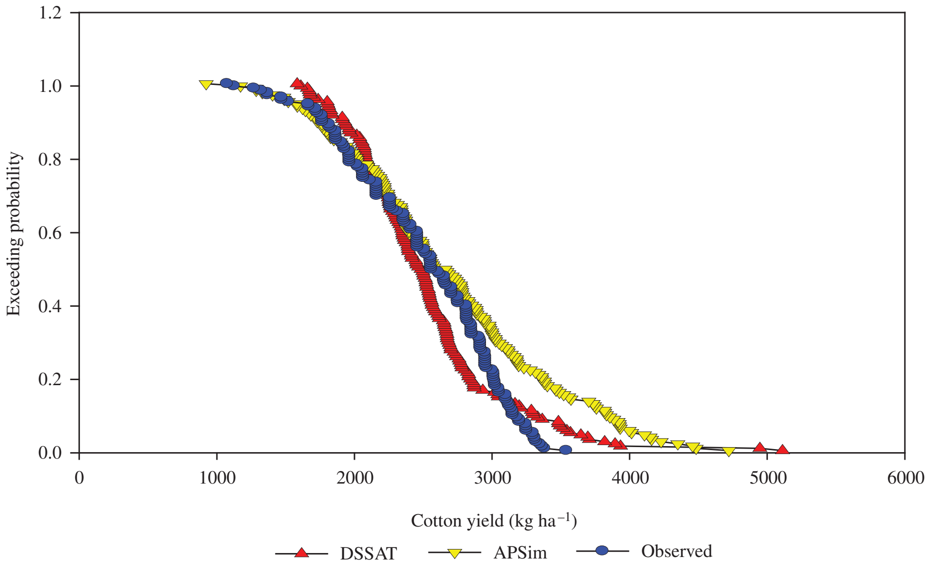


Fig. 12. Exceedance probability of cotton yield on farmer fields for DSSAT and APSIM compared to observed.

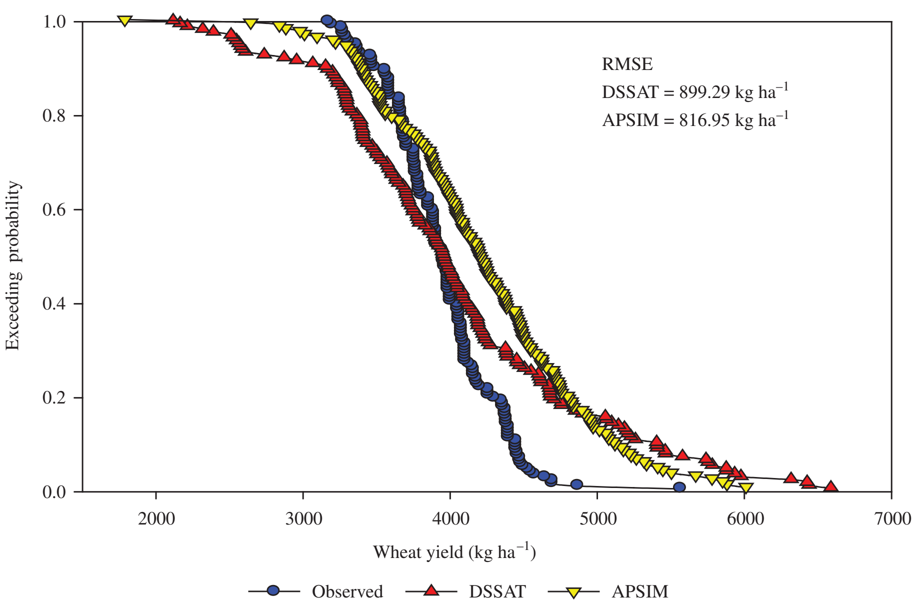


Fig. 13. Exceedance probability of wheat yield on farmer fields for DSSAT and APSIM compared to observed.

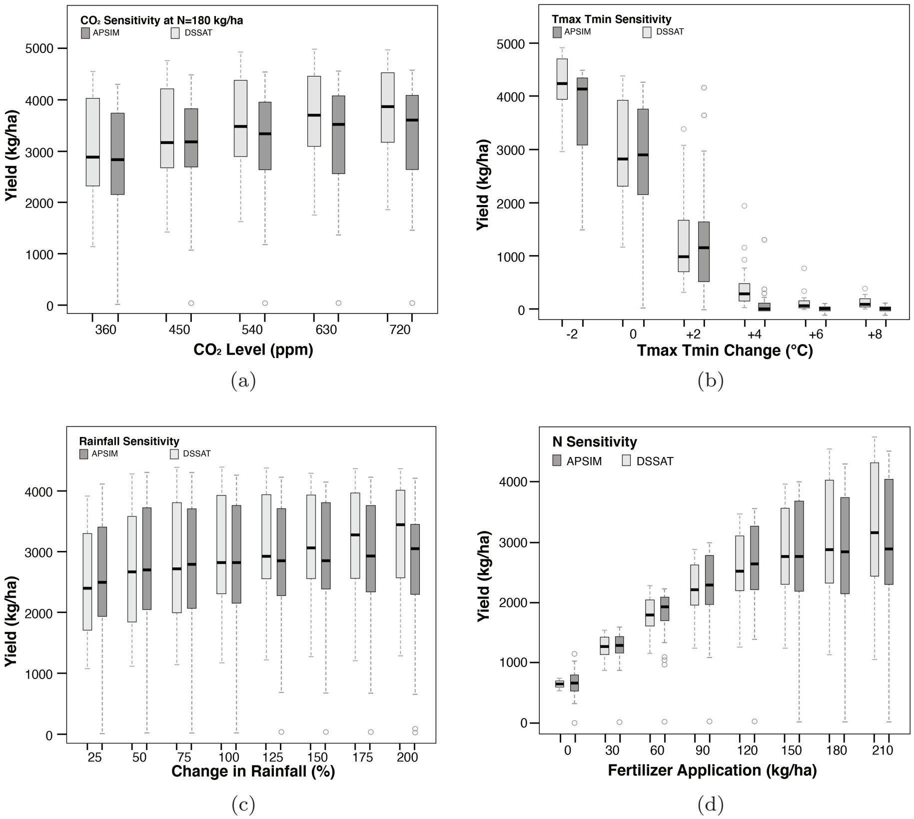


Fig. 14. The DSSAT and APSIM responses to change in (a) CO_2 concentration, (b) temperature, (c) rainfall, and (d) fertilizers on cotton yield.

lower response to increasing levels of CO_2 from 360 to 720 ppm at 180 kg ha^{-1}; however, the APSIM model is less sensitive to CO_2 compared to DSSAT (Fig. 14a). Both models showed a greater response to increasing levels of temperatures. The highest yield was observed at the lowest temperature of $-2°$C, while yield decreased as temperature increased by 2°C. The higher yield at low temperature could be due to increased growing period. The cotton crop failed when temperature was increased from 2°C to 8°C (Fig. 14b).

The crop models showed lower sensitivity to increasing amounts of rainfall. The lowest increase in yield was recorded when rainfall increased from 25% to 150%; however, further increases in rainfall from 150% to 200% caused reductions in yield (Fig. 14c). The cotton crop is sensitive to water: thus high rainfall caused waterlogged conditions that affect cotton growth and yield.

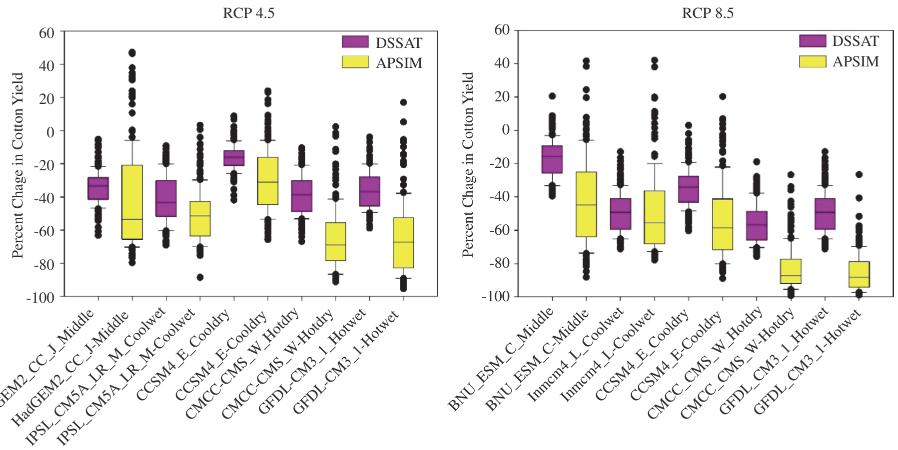
Increases in nitrogen fertilizers resulted in increases in yields by both crop models up to 150 kg ha^{-1}; further increase in nitrogen did not increase yields (Fig. 14d).

Impact of Climate Change on Current and Future Cotton Production Systems

Impacts of climate change on current agricultural production system

Greater yield reductions would be expected in mid-century due to climatic uncertainty, increases in temperature, and lower rainfall under the RCP4.5 scenario. There would be 31% and 51% mean seed cotton yield (SCY) reduction in mid-century (2040–2069) compared to the baseline as simulated by DSSAT and APSIM, respectively, using the RCP 4.5 scenario. However, this reduction will differ for different GCMs. The DSSAT-simulated reduction in yield ranging from −13% (cool/dry) to −40% (hot/dry), while in APSIM this reduction ranged from −29% (cool/dry) to −67% (hot/dry). Greater reduction in the hot/dry scenario is due to greater increase in temperature (2.4°C in TMAX and 2.7°C in TMIN). Uncertain and very low rainfall (−54 in PREC mm) during the cotton growing season will also play a crucial role (Fig. 15a).

Temperature rise has a negative impact on cotton growth and yield. Greater SCY reduction would be expected in mid-century due to greater increases in temperature and lower rainfall in the RCP8.5 scenario. There would be 30% and 62% mean SCY reduction in mid-century (2040–2069) compared to the baseline as simulated by DSSAT and APSIM, respectively, using RCP8.5. However, this reduction will differ for different GCMs. The DSSAT-simulated reduction in yield ranged from −7% (cool/wet) to −53% (hot/dry), while in APSIM the reduction ranged from −43% (middle) to −81% (hot/dry). These GCMs projected much hotter and drier



(a) (b)

Fig. 15. Percent change in seed cotton yield (SCY) in response to changing climate scenarios under RCPs 4.5 and 8.5 (Q1).

conditions, with greater increases in temperature (3.5°C in TMAX and 3.8°C in TMIN). Uncertain and very low rainfall −151 in ΔPREC (mm) during the cotton growing season would also play a crucial role.

Potential adaptation in current farming system under current climate

Increase in nitrogen fertilization (kg ha^{-1}) by 10% and change in planting geometry (increase in row spacing) by 15% were used as adaptations/interventions under current climate. The impact of these interventions and adaptations is presented in Fig. 16. The increase in SCY is 2.8% and 7.1% for DSSAT and APSIM, respectively.

Climate change impacts on future cotton production system without adaptation

A sustainable RAP (RAP 4) was developed during the consultative sessions with scientists and stakeholders. Soil degradation (5% increase), ground surface water (10% decrease), and modification in virtual cultivar could be options to minimize the effects of climate change on cotton productivity. Enhancement in genetic potential of cultivars would also be crucial for sustainable cotton production; heat-, drought-, and waterlogging-tolerant genotypes would be an important part of agricultural development. Both crop models were run with sustainable cropping systems and it was noted that the DSSAT-simulated reduction in SCY ranged from −13.95% to −36.21%, while in APSIM this reduction ranged from −28.31% to −64.24%. The climate scenario used was an increase in temperature (2.6 in TMAX and 3.1 in TMIN)

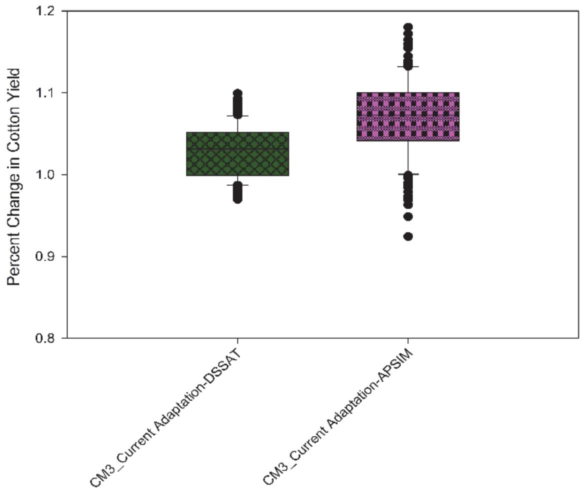


Fig. 16. Impact of current climate adaptations on cotton yield (Q2).

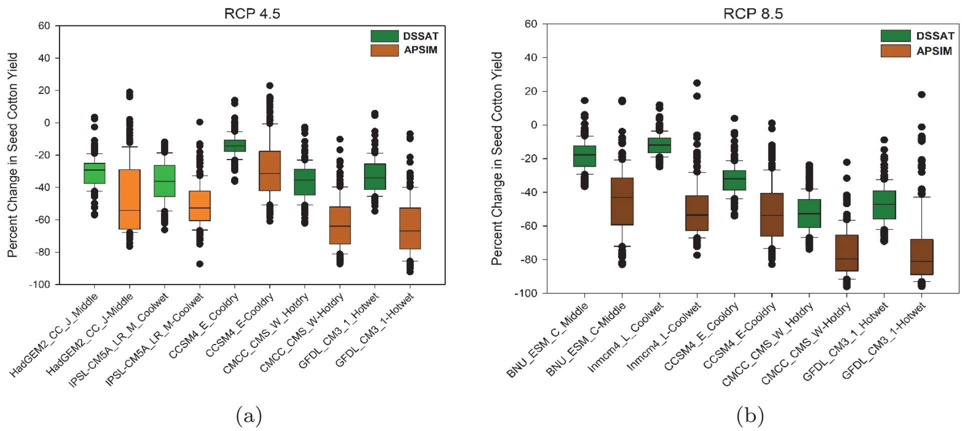


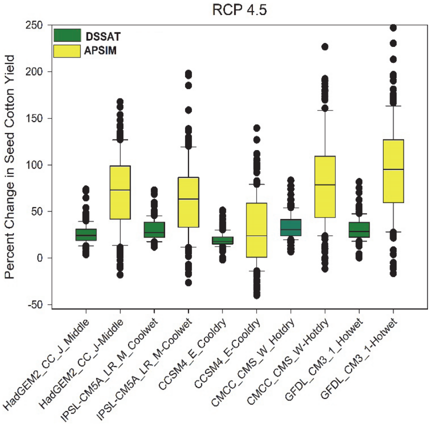
Fig. 17. Percent change in seed cotton yield (SCY) on future production system (Q3).

and very low rainfall −100.9 Δ PREC (mm) during the cotton growing season (Fig. 17a).

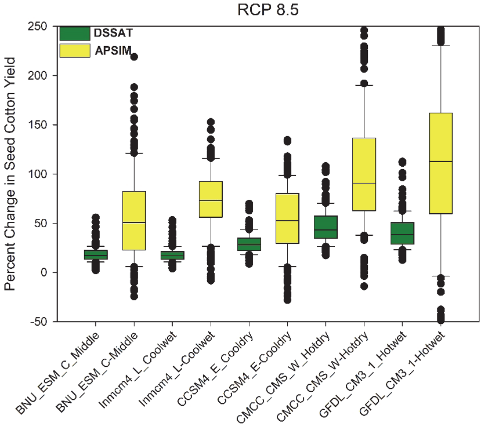
An unsustainable agricultural development pathway (RAP5) was developed during consultative sessions with scientists and other stakeholders. Soil degradation (10% increase), ground surface water (10% decrease), balanced use of fertilizer (8% increase), and modification in virtual cultivar could be the possible options to minimize the effects of climate variables on cotton productivity. Enhancement in genetic potential of cultivars would also be crucial for sustainable cotton production; heat-, drought-, and waterlogging-tolerant genotypes would also be good adaptations in future uncertain climate. DSSAT and APSIM were run with RAP 5 without adaptation and it was noted that the DSSAT-simulated reduction in SCY ranged from −11.50% to −52.29%, while in APSIM this reduction ranged from −44.83% to −72.76%. The climate scenario used was an increase in temperature (3.5 in TMAX°C while 3.8 in TMIN°C) and very low rainfall −151 Δ PREC (mm) during the cotton growing season (Fig. 17b).

Benefits of future climate change adaptation in cotton

Enhancement in genetic potential of cultivars would be crucial for sustainable cotton production; heat-, drought-, and waterlogging-tolerant genotypes would be good adaptations in future uncertain climate. The adaptation strategies were tested under both RAPs. Under the Sustainable development RAP, DSSAT simulated an increase in SCY ranging from 19.70% to 33.90%, while in APSIM this increase would range from 30.21% to 96.47%. The climate scenario used projected an increase in temperature (2.6 in TMAX °C while 3.1 in TMIN °C) and very low rainfall −100 Δ PREC (mm) during the cotton-growing season. This proved to be a good



(a)



(b)

Fig. 18. Percent change in yield in the future cotton–wheat system due to climate change adaptations (Q4) under (a) RCP4.5 and (b) RCP8.5.

adaptation strategy with the ability to compensate for the projected shortage of water and unexpected rainfall (Fig. 18a).

The Unsustainable Development Pathway (RAP5 with adaptation) included enhancement in genetic potential of cultivars for sustainable cotton production: heat, drought and water logging-tolerant genotypes would be good adaptations in the future uncertain climate. The adaption strategy was tested with APSIM and DSSAT. Results with DSSAT show an increase in SCY ranging from 18.27 to 47.07%, while in APSIM this increase ranged from 53.68 to 108.96%. The climate scenario for these simulations was an increase in temperature (3.6 in TMAX°C, while 4.3 in TMIN°C) and moderate rainfall 49.4 Δ PREC (mm) during the cotton growing season (Fig. 18b).

Livestock

Climate change impacts on livestock

Climate change may have substantial effects on the global livestock sector (Thornton and Gerber, 2010). Livestock production systems will be affected in many ways and changes in productivity are inevitable. Increasing climate variability will increase livestock production risks and reduce the ability of farmers to manage these risks. In the case of livestock, the impact of climate change is especially significant in extreme hot and cold weather. The majority of farmers do not have proper shelters for livestock, so vulnerability is high in extreme climatic conditions.

Table 6. Effect of climate risk on livestock production.

Effects	Changes in livestock	References
Heat stress	Production of milk, mortality, loss of reproductive capacity	(Baumgard and Rhoads Jr, 2013)
Water scarcity and drought	Production of milk, mortality, loss of reproductive capacity	(Nardone *et al*., 2010)
Quality and quantity of feed	Milk and meat production, loss of reproductive capacity	(Craine *et al*., 2010)
Floods	Mortality, post-flood water-borne infections	(Jabbar, 1990)

Table 7. Projected milk yield reduction due to climate change.

	Global Circulation Model (GCM) Scenarios				
Activities	**Middle**	**Hot/Dry**	**Cool/Dry**	**Hot/Wet**	**Cool/Wet**
Milk reduction in percentage	−20	−30	−15	−25	−10

Source: Based on review of literature and RAPs.

Livestock may be influenced by climate change directly or indirectly through a variety of key processes (Table 6). There is 20%–30% increase in the maintenance energy requirement and heat stress combined with dry matter intake decreased by 10%–20% in the commercial dairy herds under climate change conditions (Chase, 2006). The physiological change regarding milk synthesis during heat stress may be due to hepatic glucose preferentially used for processes other than milk synthesis (Baumgard *et al*., 2011). Climatic factors, e.g., temperature, precipitation, and severity of extreme events, affect livestock and crop yield (Thornton *et al*., 2008). Climate change will have severely deleterious impacts on livestock in many parts of the tropics and subtropics, even for small increases in the average temperature. We have incorporated a factor for milk reduction in all analyses based on expert opinion supported by existing literature (Table 7).

Economics of climate change impacts and adaptation on cotton–wheat cropping system

Climate change has extensive impacts on agricultural systems, food security, and biological networks. Pakistan is challenged by increasing climate change risks due to its hazard-prone agro-geo climatic position, overexploitation of its agricultural economy, and prevalent poverty. This part of the RIA aims to estimate the socio-economic impacts of climate change on current and future agricultural production systems of Punjab, Pakistan.

The TOA-MD is used for the climate change impact assessment (Antle, 2011). The TOA-MD model represents the whole farm production system and considers the farm population instead of individual farmers. The model is designed to be used for multidisciplinary research and it is feasible, less costly in terms of data collection and computation, and user friendly (Antle and Valdivia, 2015).

The TOA-MD is used to access the socio-economic impacts of climate change on farming communities in the cotton–wheat cropping system of Pakistan. First, a comprehensive survey was conducted in the cotton–wheat cropping system through a well-structured questionnaire. Data were collected from 165 farms across five districts. The survey calculated mean, variances, and within- and between-system correlations.

The model was set up with two configurations: System 1 is calculated from survey data characterizes the 'current' or base production system and System 2 uses simulated yields from crop models to represent the climate impacted system or the adapted system to climate change. Vulnerability, poverty, net returns, and per capita income (PCI) with and without climate change are calculated by TOA-MD for current and future agricultural production systems. For future agricultural production systems, RAPs were formulated. Cost factors, future prices, household size, and farm size were formulated for the RAPs by expert opinion and results from the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model (Fig. 19).

Sensitivity analysis for prices was added by incorporating low and high price ranges for globally traded commodities in the analysis. To calculate the benefits of adaptations in current and future periods, adaptation packages were formulated by drawing upon existing literature, expert opinion, and research. The output of adaptation benefits was assessed in the form of adoption rate, change in net farm returns, and poverty rates. A sensitivity analysis for benefits of future adaptations regarding the cotton crop was also done.

Caveats associated with the regional integrated analysis include the lack of representation of major flooding events, such as the major inundation in Pakistan in 2011.

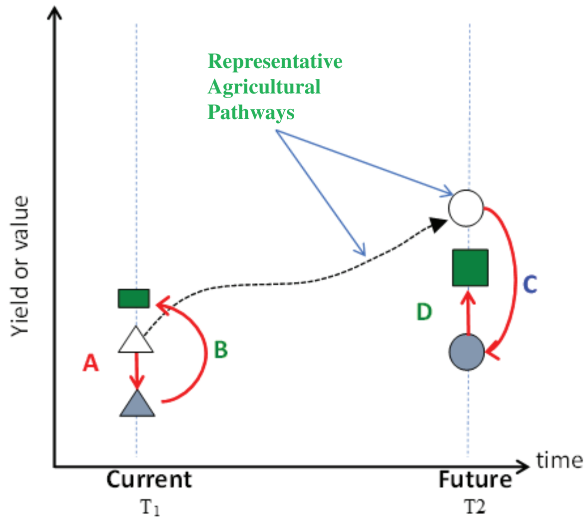


Fig. 19. Framework for climate change impact assessment and adaptation benefits (Antle *et al.*, 2015).

Impacts of climate change on current agricultural production system

This analysis is based on a multidisciplinary approach to assess the threats and weigh solutions for a changing climate. An integrated assessment was made to estimate the impacts of climate change on crop yields and the resulting effects on socio-economic trends to project a clear picture of agricultural production systems in Punjab, Pakistan in the coming decades.

Climate results show that there would be increase in mean maximum temperature of 2.5°C and 3.6°C and in mean minimum temperature of 2.7°C and 3.8°C under RCP 4.5 and RCP 8.5, respectively, for mid-century (2040–2069) in the cotton–wheat cropping area. Decrease in rainfall would be about 33% and 52% during the cotton growing season and 36% and 42% during the wheat growing season under RCPs 4.5 and 8.5, respectively, for the mid-century with the hot/dry climate scenario.

The yield reduction of the cotton crop is 51% under APSIM and 31% under DSSAT for RCP 4.5, while for RCP8.5 the yield reduction is on an average 62% and 30% for APSIM and DSSAT, respectively. The yield of wheat is reduced by 5% and 4% under APSIM and DSSAT, respectively, under RCP4.5, whereas it declines by 4% and 2% for APSIM and DSSAT, respectively, under RCP8.5. RCP4.5 was less negative in the projected upper and lower limits of temperature increase and rainfall variability. In the cases of hot/dry and hot/wet weather conditions, yields were decreased over current in both crop models.

The results of the impacts analysis in Tables A.3 and A.4 (see Appendix) for the current system showed that there would be significant negative impacts on current and future cotton production as cotton is highly sensitive to climate variations. The mean net economic impacts are negative under both RCPs. The results utilizing APSIM model crop simulations show that at the aggregate level 66 to 87% households would be vulnerable to climate change under RCP4.5, while vulnerability would be 75 to 93% under RCP 8.5. With DSSAT crop model results 60 to 80% of households would be vulnerable under mild climatic conditions while vulnerability would be 62 to 88% under harsh climatic scenarios. The APSIM crop model results lead to larger negative economic impacts than DSSAT; on the other hand, there is a significant difference between mild and harsh climatic scenarios. Net impacts overall show that there will be negative impacts of changing climatic conditions on the cotton–wheat cropping system.

In this study, observed mean yield for wheat is 12,780 kg per farm and for cotton 8748.6 kg per farm. The results showed that cotton is highly sensitive to climate change in Pakistan as its current yield declines in the range of 13% to 65% due to climate change under RCP 4.5. Wheat yield is also sensitive to climatic variation; its yield also shows mild benefits resulting from increased CO_2 concentrations. The majority of farmers would lose from CC, ranging between 60% and 87% under RCP 4.5. Net farm returns decline substantially from initial 685,660.8 PKR rupees per farm. This would increase farm poverty due to climate change. The simulations showed that poverty will be increased due to climate change under all GCMs, RCPs, and crop models as net returns are negative; PCI is also decreasing, mainly due to adverse impacts on cotton (Fig. 20).

Climate change had relatively larger impacts on the current agricultural production system than on the future farming systems; percentage of vulnerability, net economic impacts, and poverty due to climate change are larger under the current agricultural production system. It is suggested that adaptation and mitigation strategies must be explored and practiced limiting potential climate change damages in Pakistan.

Potential adaptation in the current system under current climate

The proposed management interventions have an overall positive impact on farm net returns and per capita income. The results with APSIM crop model simulations show that adoption rate is projected at 56%, which will increase the mean net revenue and per capita income by 14%. Increased returns and PCI will ultimately reduce the farm level poverty by 76% in the cotton–wheat cropping system compared to the present. Net returns and PCI would be increased by 16% in the cotton–wheat cropping system utilizing the DSSAT crop model; these higher returns will reduce poverty by 85%. The potential adoption rate is 59% with the DSSAT crop model crop yield changes.

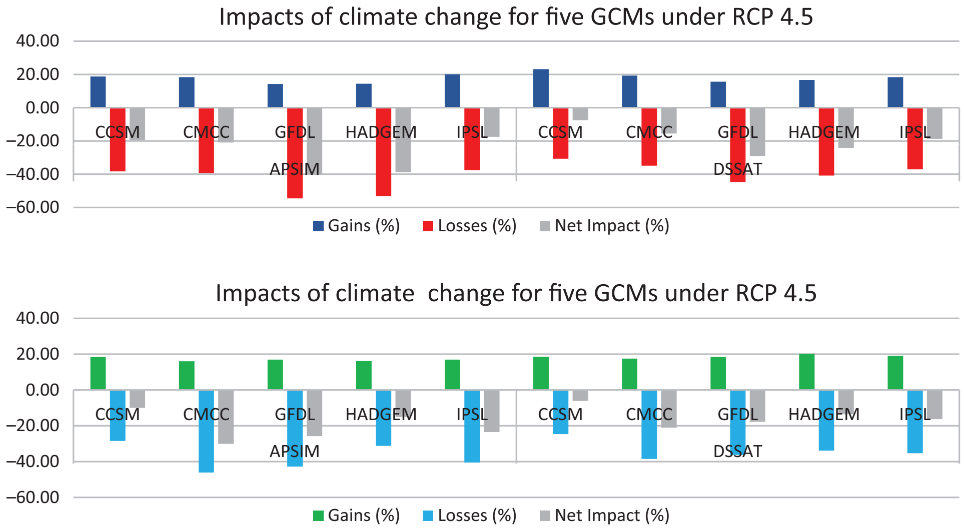


Fig. 20. Aggregated net economic impacts for the five GCM climate change scenarios under RCPs 4.5 and 8.5 with DSSAT and APSIM for simulated yields in the future agricultural production system of Punjab.

Vulnerability of future system to climate changes

The impact analysis presented in Tables A.5–A.8 (see Appendix) projects serious future challenges to the cotton crop as cotton yield declined sharply in both crop models. The analysis in the future was made under the two development pathways (RAPs) and under different price assumptions for the key crops. The analysis showed that cotton is highly vulnerable to climate change and sensitive to both high temperature and variation in rainfall pattern. Due to these variations, farmers start producing other crops and take up orchard farming.

Wheat is a staple food that is important in terms of food security. Wheat yield changes from 3 to −9 kg per farm in APSIM and 0.4 to −8 in DSSAT. Mean change in output of the cotton crop ranges between −24 and −64 kg per farm in case of APSIM and between −14 and −36% in DSSAT. Farming households in the cotton–wheat cropping system are highly vulnerable to climatic variations. Approximately 59% to 87% of households are vulnerable utilizing APSIM and 53% to 74% utilizing the DSSAT crop model simulations for the sustainable development pathway with high prices (Figs. 21 and 22).

Climate change vulnerability is relatively high when prices are high, whereas for the sustainable development pathway (RAP 4) climate change vulnerability is relatively less compared to the unsustainable development pathway (RAP 5). Losses are higher in APSIM than in DSSAT as the relative yields of cotton are lower in

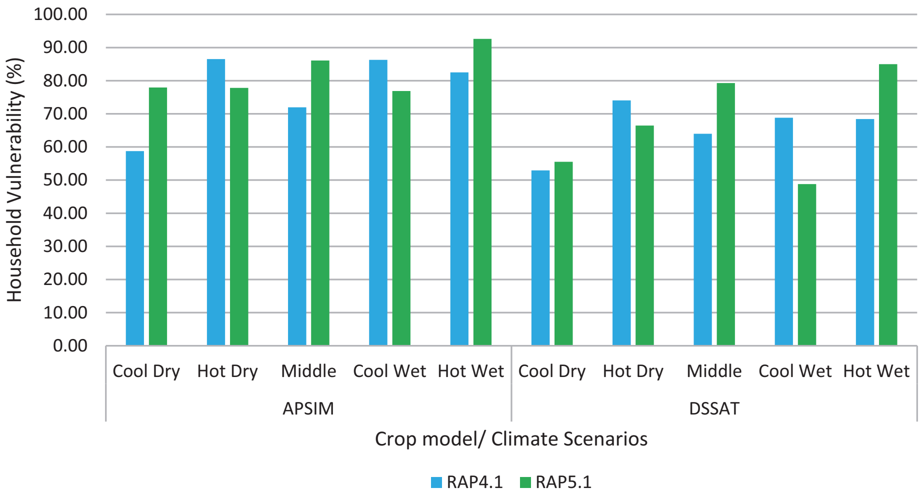


Fig. 21. Comparison of proportion of vulnerable households for sustainable and unsustainable development pathways with high prices.

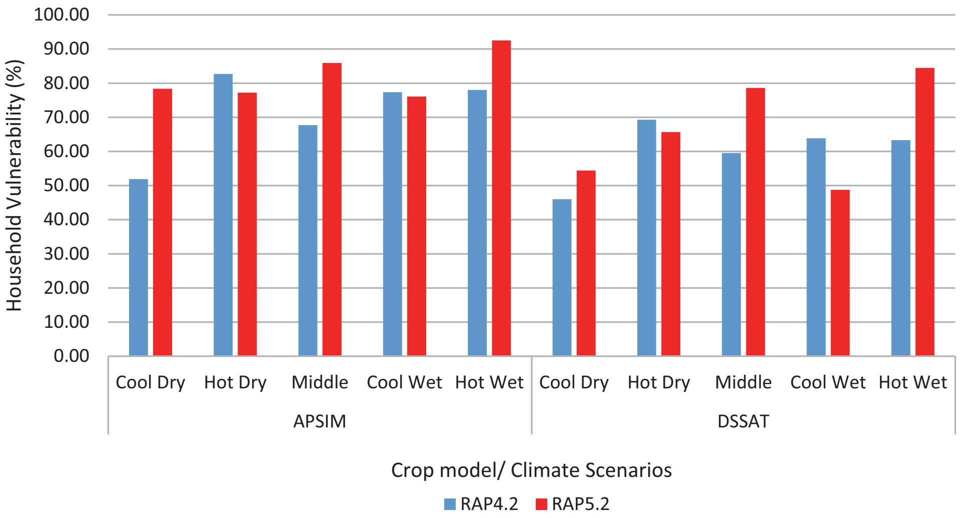


Fig. 22. Comparison of proportion of vulnerable households for sustainable and unsustainable development pathways with low prices.

the APSIM crop model. The APSIM crop model is relatively more sensitive than DSSAT and shows higher cotton crop losses than DSSAT. Poverty rates would be increased due to climate change and net farm returns and PCI would also decline for all GCMs for DSSAT and APSIM.

Potential adaptation in the future system under climate change

Results show an increase in net returns due to adaptation that will increase PCI and reduce poverty compared to a future without adaptation. Planned and unplanned adaptations to climate vulnerability in agricultural systems can maintain ecosystem balance and minimize economic losses. Policies for development must have synergistic effects with climate change to ensure the adaptive capacity of the nation. To minimize climate losses there can be adaptation strategies on the farm level, as well as on the national policy level. To assess the benefits of adaptation, the adaptation packages were formulated through a continuous engagement process with researchers, farmers, and policy makers to combat current and future climatic vulnerabilities.

For current and future climatic vulnerabilities, different short-term and long-term adaptation packages were compiled in which biophysical, socio-economic, and policy parameters were assessed. Important adaptation parameters for the future were genetic improvements, drought-resistant and heat-tolerant varieties, deep tillage, soil and water conservation practices, construction of water storage, efficient irrigation systems, crop diversification, agricultural insurance, and farm mechanization (e.g., mechanical pickers for cotton).

The adoption rate under sustainable development ranges between 23% and 67% under high price scenarios and 33% to 49% for low price scenarios. Percentage change in net economic returns under sustainable development pathways ranges between 4% and 27% in high price scenarios and 12% to 19% in low price scenarios. Likewise, under sustainable development pathways PCI would increase by 4% to 21% under high prices and 12% to 18% under low prices. Adoption rate under unsustainable development pathways ranges from 53% to 62% and 35% to 47% for high and low prices, respectively. Unsustainable development pathways exhibit an increase in net economic returns ranging from 17% to 23% and 11% to 17% under high and low prices, respectively. Reduction in poverty for unsustainable development ranges from 45% to 51% and 24% to 57% under low and high prices, respectively. See Tables A.9–A.12 in the Appendix.

Conclusions and Next Steps

Climate change is a great threat for current agricultural production systems in Pakistan. Cotton and wheat are important cash crops and support the agro-based Pakistan economy. Climate change is projected to bring an increase in mean maximum temperature of 2.5°C to 3.6°C and mean minimum temperature of 2.7°C to 3.8°C by mid-century in Punjab, Pakistan. Decrease in rainfall would be about 33% to 52% during the cotton growing season and 36% to 42% during the wheat growing season with hot/dry conditions. Reductions in cotton yield of 7% to 42% and wheat yield of 2% to 4.5% would result. The cotton crop is relatively more sensitive to climate change than wheat. Wheat is benefited by future increases in CO_2 concentrations but harmed by rising temperature.

Economic results show that there would be drastic impacts on farm income due to the increase in temperature and humidity in the cotton–wheat cropping system. Seventy-eight percent of households are vulnerable to climate change, with simulated increases of 69% in farm poverty through reductions of 27% net returns in the current cotton–wheat cropping system.

These crop yield reductions can be minimized by management interventions on farms that increase sowing density and fertilizer application in cotton and change the sowing dates and fertilizer application methods in wheat. Those would increase net returns by 15% and reduce poverty. In the future agriculture production system, 71% on average farm households were vulnerable to future pathways, out of which 69% were vulnerable in case of Sustainable Development Pathways (RAP4) (under RCP4.5), while 74% were in Unsustainable Pathways (RAP5) (under RCP8.5). Poverty would increase by 53% due to a 19% decrease in net farm returns.

The proposed adaptation package includes increase in sowing density, balanced use of fertilizer, and improved genetic cultivars. The adoption rate of this adaptation package is projected to be 56% and it reduces farm poverty levels, on average, by 36%. While the analysis shows that the adaptation strategy help to offset the negative impacts of climate change, they are not enough. There is still a considerable proportion of farms that would remain vulnerable to climate change and under high poverty rates. Further analysis that include different strategies coupled with policy interventions or different land use should be examined. The AgMIP Regional Integrated Assessment has the tools and methods to extend the current analysis and therefore contribute with supporting policy decision-making with science-based information.

Acknowledgments

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Appendix

Table A.1. Selected GCMs under characteristic climate conditions.

	Crops Season Cool/Wet	Cotton/Wheat JJASONDJFMA Hot/Wet	Middle	Cool/Dry	Hot/Dry
RCP 4.5	M	1	J	E	W
RCP 8.5	L	1	C	E	W

Table A.2. Median changes in projected climate for all districts.

Station	Latitude	Longitude	Cotton	Wheat	Annual	Cotton	Wheat	Annual	Cotton	Wheat	Annual
			TMAX (°C) RCP 4.5			TMIN (°C) RCP 4.5			RAIN (mm) RCP 4.5		
Multan	30.2	71.5	2.7	2.5	2.7	1.7	2.2	1.9	−18.4	−3.6	−5.7
Bahawalpur	29.3	71.7	2.4	2.5	2.5	1.9	2.3	2.2	−16.6	11.3	−9.3
Bahwalnagar	30.0	73.3	2.2	1.9	1.8	1.5	1.8	1.8	−20.8	−22.9	−10.1
Lodhran	29.5	71.6	2.4	2.5	2.5	1.5	2.2	1.9	−20.8	15.6	−11.4
Rahim Yar Khan	28.4	70.3	2.4	2.5	2.5	1.9	2.3	2.2	−9.7	13.7	−8.3
			TMAX (°C) RCP 8.5			TMIN (°C) RCP 8.5			RAIN (mm) RCP 8.5		
Multan	30.19	71.5	2.6	2.9	2.6	3.3	3.2	3.1	1.5	−17.2	17.2
Bahawalpur	29.34	71.7	2.5	3.0	2.6	3.0	2.7	2.8	1.3	0.3	9.5
Bahwalnagar	29.99	73.3	2.5	3.0	2.6	3.0	2.7	2.8	1.2	−2.0	9.4
Lodhran	29.53	71.6	2.5	2.9	2.6	3.0	2.7	3.1	3.3	0.3	18.1
Rahim Yar Khan	28.42	70.3	2.5	2.9	2.6	3.0	2.7	3.1	1.6	−9.0	12.6

Table A.3. Climate sensitivity of current cotton–wheat cropping system of Punjab, Pakistan under RCP 4.5.

	Hot/Dry		Hot/Wet		Middle		Cool/Dry		Cool/Wet	
Aggregated Results	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**
Observed mean output of wheat (kg/farm)	12,780	12,780	12,780	12,780	12,780	12,780	12,780	12,780	12,780	12,780
Mean change in output of wheat (%)	−14	−10	−0.4	−6	−2	2	1	−2	−11	5
Observed mean output of cotton (kg/farm)	8478	8478	8478	8478	8478	8478	8478	8478	8478	8478
Mean change in output of cotton (kg/farm)	−67	−40	−65	−32	−44	−31	−30	−13	−51	−39
Vulnerable households (%)	87	80	83	77	77	71	66	60	82	75
Gains (% mean net returns)	17	18	18	19	17	21	19	19	17	20
Losses (% mean net returns)	−47	−39	−43	−37	−32	−34	−30	−25	−41	−36
Observed net returns without CC (Rs./farm)	685,660	685,660	685,660	685,660	685,660	685,660	685,660	685,660	685,660	685,660
Projected net returns with CC (Rs./farm)	421,212	494,940	456,605	522,788	549,397	560,313	593,081	628,536	474,071	536,140
Observed PCI* without CC (Rs.)	133,503	133,504	133,504	133,504	133,504	133,503	133,504	133,504	133,504	133,504
Projected PCI with CC (Rs.)	82,501	98,493	88,265	103,274	105,600	110,132	114,439	122,463	93,581	106,611
Observed poverty rate without CC (%)	8	8	8	8	8	8	8	8	8	8
Projected poverty rate with CC (%)	18	12	16	12	13	11	10	9	14	11

Note: *Per capita income (PCI) is the average income of the households that measures the income earned per person in the cotton–wheat cropping system in one year.

Table A.4. Climate sensitivity of current cotton–wheat cropping system of Punjab, Pakistan under RCP 8.5.

	Hot/Dry		Hot/Wet		Middle		Cool/Dry		Cool/Wet	
Aggregated Results	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**
Observed mean output of wheat (kg/farm)	12,780	12,780	12,780	12,780	12,780	12,780	12,780	12,780	12,780	12,780
Mean change in output of wheat (%)	−12	−14	−0.3	−7	−13	+2	−0.2	−4	+2	+9
Observed mean output of cotton (kg/farm)	8478	8478	8478	8478	8478	8478	8478	8478	8478	8478
Mean change in output of cotton (kg/farm)	−81	−53	−82	−46	−44	−14	−54	−31	−50	−8
Vulnerable households (%)	79	74	93	88	93	84	78	62	75	78
Gains (% mean net returns)	18	19	14	16	14	17	19	23	20	18
Losses (% mean net returns)	−39	−35	−55	−45	−53	−41	−38	−31	−38	−37
Observed net returns without CC (Rs./farm)	685,660	685,660	685,660	685,660	685,660	685,660	685,660	685,660	685,660	685,660
Projected net returns with CC (Rs./farm)	497,863	542,481	342,871	429,503	353,581	469,069	508,827	615,502	527,457	515,331
Observed PCI* without CC (Rs.)	133,503	133,504	133,504	133,504	133,504	133,503	133,504	133,504	133,504	133,504
Projected PCI with CC (Rs.)	96,578	106,942	68,388	85,850	70,268	93,124	98,843	120,657	101,991	101,480
Observed poverty rate without CC (%)	8	8	8	8	8	8	8	8	8	8
Projected poverty rate with CC (%)	14	11	25	16	24	14	14	10	13	13

Note: *Per capita income (PCI) is the average income of the households that measures the income earned per person in the cotton–wheat cropping system in one year.

Table A.5. Climate change impacts in future cotton–wheat cropping system in Punjab, Pakistan under sustainable development with high prices.

	Hot/Dry		Hot/Wet		Middle		Cool/Dry		Cool/Wet	
Aggregated Results	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**
Projected mean output of wheat (kg/farm)	16,082	16,082	16,082	16,082	16,082	16,082	16,082	16,082	16,082	16,082
Mean change in output of wheat (%)	3	−2	2	−5	−2	−3	−9	−8	−8	0.4
Projected mean output of cotton (kg/farm)	10,464	10,464	10,464	10,464	10,464	10,464	10,464	10,464	10,464	10,464
Mean change in output of cotton (%)	−28	−14	−64	−32	−46	−36	−62	−36	−51	−36
Vulnerable households (%)	87	74	83	68	72	64	59	53	86	69
Gains (% mean net returns)	15	18	16	19	19	21	23	25	15	19
Losses (% mean net returns)	−41	−32	−38	−30	−33	−29	−28	−26	−43	−30
Projected net returns without CC (Rs./farm)	112,4581	112,4581	112,4581	112,4581	112,4581	112,4581	112,4581	112,4581	112,4581	112,4581
Projected net returns with CC (Rs./farm)	748,126	909,099	800,148	962,799	920,265	100,0511	105,0896	109,9414.2	721,551	958,682
Projected PCI* without CC (Rs.)	172,081	172,081	172,081	172,081	172,081	172,081	172,081	172,081	172,081	172,081
Projected PCI with CC (Rs.)	114,748	140,156	120,924	147,549	139,586	153,757	158,768	168,057	115,180	148,807
Projected poverty rate without CC (%)	6	6	6	6	6	6	6	6	6	6
Projected poverty rate with CC (%)	12	9	11	8	9	8	8	7	15	8

Note: *Per capita income (PCI) is the average income of the households that measures the income earned per person in the cotton–wheat cropping system in one year.

Table A.6. Climate change impacts in future cotton–wheat cropping system in Punjab, Pakistan under sustainable development with low prices.

	Hot/Dry		**Hot/Wet**		**Middle**		**Cool/Dry**		**Cool/Wet**	
Aggregated Results	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**
Projected mean output of wheat (kg/farm)	16,082	16,082	16,082	16,082	16,082	16,082	16,082	16,082	16,082	16,082
Mean change in output of wheat (%)	3	−2	2	−5	−2	−3	−9	−8	−8	0.4
Projected mean output of cotton (kg/farm)	10,464	10,464	10,464	10,464	10,464	10,464	10,464	10,464	10,464	10,464
Mean change in output of cotton (%)	−28	−14	−64	−32	−46	−36	−62	−36	−51	−36
Vulnerable households (%)	83	69	78	63	68	60	52	46	77	64
Gains (% mean net returns)	17	20	18	22	21	23	27	28	18	22
Losses (% mean net returns)	−40	−32	−37	−30	−33	−30	−28	−26	−36	−30
Projected net returns without CC (Rs./farm)	771,055	771,055	771,055	771,055	771,055	771,055	771,055	771,055	771,055	771,055
Projected net returns with CC (Rs./farm)	535,153	648,852	574,961	687,674	653,678	710,266	764,282	797,551	592,029	685,217
Projected PCI* without CC (Rs.)	118,974	118,974	118,974	118,974	118,974	118,974	118,974	118,974	118,974	118,974
Projected PCI with CC (Rs.)	83,368	101,184	88,291	106,539	100,533	110,334	116,440	122,740	92,942	107,450
Projected poverty rate without CC (%)	11	11	11	11	11	11	11	11	11	11
Projected poverty rate with CC (%)	19	13	18	13	14	12	12	11	15	12

Note: *Per capita income (PCI) is the average income of the households that measures the income earned per person in the cotton–wheat cropping system in one year.

Table A.7. Climate change impacts in future cotton–wheat cropping system in Punjab, Pakistan under unsustainable development with high prices.

	Hot/Dry		Hot/Wet		Middle		Cool/Dry		Cool/Wet	
Aggregated Results	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**
Projected mean output of wheat (kg/farm)	12,298	12,298	12,298	12,298	12,298	12,298	12,298	12,298	12,298	12,298
Mean change in output of wheat (%)	−11	−10	−17	−7	−17	−14	−8	−6	−9	−11
Projected mean output of cotton (kg/farm)	8002	8002	8002	8002	8002	8002	8002	8002	8002	8002
Mean change in output of cotton (%)	−75	−47	−45	−18	−76	−52	−52	−31	−50	−11
Vulnerable households (%)	93	85	86	79	78	56	78	67	77	49
Gains (% mean net returns)	14	16	16	17	17	24	17	20	18	26
Losses (% mean net returns)	−50	−39	−46	−35	−35	−27	−36	−30	−35	−25
Projected net returns without CC (Rs./farm)	923,457	923,457	923,457	923,457	923,457	923,457	923,457	923,457	923,457	923,457
Projected net returns with CC (Rs./farm)	500,288	636,958	577,074	697,181	705,545	883,411	700,116	804,853	712,500	931,248
Projected PCI* without CC (Rs.)	131,964	131,964	131,964	131,964	131,964	131,964	131,964	131,964	131,964	131,964
Projected PCI with CC (Rs.)	72,598	92,580	81,308	10,0381	100,730	127,132	99,396	115,326	101,332	132,809
Projected poverty rate without CC (%)	9	9	9	9	9	9	9	9	9	9
Projected poverty rate with CC (%)	24	15	22	13	13	9	14	11	13	9

Note: *Per capita income (PCI) is the average income of the households that measures the income earned per person in the cotton–wheat cropping system in one year.

Table A.8. Climate change impacts in future cotton–wheat cropping system in Punjab, Pakistan under unsustainable development with low prices.

	Hot/Dry		Hot/Wet		Middle		Cool/Dry		Cool/Wet	
Aggregated Results	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**
Projected mean output of wheat (kg/farm)	12,298	12,298	12,298	12,298	12,298	12,298	12,298	12,298	12,298	12,298
Mean change in output of wheat (%)	−11	−10	−17	−7	−17	−14	−8	−6	−9	−11
Projected mean output of cotton (kg/farm)	8002	8002	8002	8002	8002	8002	8002	8002	8002	8002
Mean change in output of cotton (%)	−75	−47	−45	−18	−76	−52	−52	−31	−50	−11
Vulnerable households (%)	93	85	86	79	78	54	77	66	76	49
Gains (% mean net returns)	14	16	16	17	17	26	18	21	18	27
Losses (% mean net returns)	−50	−39	−45	−36	−36	−29	−36	−30	−35	−26
Projected net returns without CC (Rs./farm)	591,617	591,617	591,617	591,617	591,617	591,617	591,617	591,617	591,617	591,617
Projected net returns with CC (Rs./farm)	321,960	408,437	373,351	447,799	447,874	569,364	451,077	516,886	460,236	597,193
Projected PCI* without CC (Rs.)	85,555	85,555	85,555	85,555	85,555	85,555	85,555	85,555	85,555	85,555
Projected PCI with CC (Rs.)	48,000	60,593	54,012	65,690	65,229	82,739	65,277	75,145	66,709	86,178
Projected poverty rate without CC (%)	16	16	16	16	16	16	16	16	16	16
Projected poverty rate with CC (%)	47	31	42	27	28	20	28	22	27	18

Note: *Per capita income (PCI) is the average income of the households that measures the income earned per person in the cotton–wheat cropping system in one year.

Table A.9. Benefits of future climate change adaptation in cotton–wheat cropping system of Punjab, Pakistan under sustainable development with high prices.

	Hot/Dry		Hot/Wet		Middle		Cool/Dry		Cool/Wet	
Aggregated Results	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**
Projected mean output of wheat* (kg/farm)	16,082	14,709	16,347	15,361	15,858	15,759	16,536	15,831	13,541	16,250
Mean change in output of wheat (%)	−12	20	9	18	3	12	−4	−15	8	11
Projected mean output of cotton** (kg/farm)	10,464.2	6693.1	3768.8	7048.6	5634.5	7353.4	7516	9025.5	5162.5	6682.9
Mean change in output of cotton (%)	84	39	96	31	71	26	30	20	63	30
Adoption rate (%)	24	72	67	70	69	66	58	66	76	67
Projected net returns without CC (Rs./farm)	11,24,556	909,088	770,872	962,796	920,296	10,00,460	1037,545	10,99,404	721,453	958,634
Projected net returns with CC (Rs./farm)	11,76,239	11,99,727	978,354	12,47,243	11,73,652	12,60,955	12,38,155	13,78,007	10,31,559	12,22,055
Projected PCI*** without CC (Rs.)	172,603	140,576	117,115	147,993	140,001	154,238	156,878	168,559	115,561	149,267
Projected PCI with CC (Rs.)	180,478	183,666	147,960	190,396	179,450	193,609	188,332	210,279	160,095	188,949
Projected poverty rate without CC (%)	6	9	12	8	9	8	8	7	15	8
Projected poverty rate with CC (%)	4	4	6	4	4	4	4	4	5	4

Note: *The projected yields of wheat were calculated from simulations of APSIM and DSSAT and they vary in all climate scenarios.
**The projected yields of cotton were calculated from simulations of APSIM and DSSAT and they vary in all climate scenarios.
***Per capita income (PCI) is the average income of the households that measures the income earned per person in the cotton–wheat cropping system in one year.

Table A.10. Benefits of future climate change adaptation in cotton–wheat cropping system of Punjab, Pakistan under sustainable development with low prices.

	Hot/Dry		Hot/Wet		Middle		Cool/Dry		Cool/Wet	
Aggregated Results	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**
Projected mean output of wheat* (kg/farm)	16,082	14,709	16,347	15,361	15,858	15,759	16,536	15,831	13,541	16,250
Mean change in output of wheat (%)	−12	20	9	18	3	12	−4	−15	8	11
Projected mean output of cotton** (kg/farm)	10,464	6693	3768	7048	5634	7353	7516	9025	5162	6682
Mean change in output of cotton (%)	84	39	96	31	71	26	30	20	63	30
Adoption rate (%)	47	60	48	51	49	48	39	47	48	49
Projected net returns without CC (Rs./farm)	535,246	648,931	575,044	687,763	653,783	710,325	764,408	797,646	592,091	685,272
Projected net returns with CC (Rs./farm)	626,036	834,299	677,063	831,919	778,443	844,072	860,503	937,901	700,582	820,487
Projected PCI*** without CC (Rs.)	83,618	101,493	88,563	106,867	100,835	110,688	116,793	123,120	93,228	107,791
Projected PCI with CC (Rs.)	97,391	128,824	103,773	128,297	120,409	130,832	131,866	144,097	109,779	128,077
Projected poverty rate without CC (%)	19	14	18	13	14	1	11	10	15	12
Projected poverty rate with CC (%)	14	9	13	10	10	9	9	8	11	9

Note: *The projected yields of wheat were calculated from simulations of APSIM and DSSAT and it varies in all climate scenarios.
**The projected yields of cotton were calculated from simulations of APSIM and DSSAT and it varies in all climate scenarios.
***Per capita income (PCI) is the average income of the households that measures the income earned per person in the cotton–wheat cropping system in one year.

Table A.11. Benefits of future climate change adaptation in cotton–wheat cropping system of Punjab, Pakistan under unsustainable development with high prices.

	Hot/Dry		Hot/Wet		Middle		Cool/Dry		Cool/Wet	
Aggregated Results	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**
Projected mean output of wheat* (kg/farm)	10,126	10,540	11,265	11,019	10,162	11,423	11,324	11,484	11,182	11,619
Mean change in output of wheat (%)	−11	23	−6	13	−6	17	−16	27	1	10
Projected mean output of cotton** (kg/farm)	1985	3839	2119	4280	4442	6617	3830	5459	4023	7093
Mean change in output of cotton (%)	109	41	58	19	54	30	104	47	74	18
Adoption rate (%)	60.9	76.8	53.8	73.7	65	64	63.3	70.3	73.9	62.9
Projected net returns without CC (Rs./farm)	500,302	636,961	577,099	697,186	705,554	883,408	700,133	804,858	712,514	931,247
Projected net returns with CC (Rs./farm)	611,443	885,133	676,980	936,540	881,995	10,96,404	853,349	10,40,005	946,536	11,47,264
Projected PCI*** without CC (Rs.)	72,610	92,593	81,324	100,396	100,746	127,149	99,413	115,343	101,348	132,828
Projected PCI with CC (Rs.)	89,089	126,266	96,129	132,995	127,159	156,827	121,836	147,533	134,827	162,924
Projected poverty rate without CC (%)	24	15	22	13	13	9	13	10	13	9
Projected poverty rate with CC (%)	14	7	12	7	7	5	7	6	6	5

Note: *The projected yields of wheat were calculated from simulations of APSIM and DSSAT and it varies in all climate scenarios.
**The projected yields of cotton were calculated from simulations of APSIM and DSSAT and it varies in all climate scenarios.
***Per capita income (PCI) is the average income of the households that measures the income earned per person in the cotton–wheat cropping system in one year.

Table A.12. Benefits of future climate change adaptation in cotton-wheat cropping system of Punjab, Pakistan under unsustainable development with low prices.

	Hot/Dry		**Hot/Wet**		**Middle**		**Cool/Dry**		**Cool/Wet**	
Aggregated Results	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**
Projected mean output of wheat* (kg/farm)	10,126	10,540	11,265	11,019	10,162	11,423	11,324	11,484	11,182	11,619.1
Mean change in output of wheat (%)	−11	23	−6	13	−6	17	−16	27	1	10
Projected mean output of cotton** (kg/farm)	1985	3839	2119	4280	4442	6617	3830	5459	4023	7093
Mean change in output of cotton (%)	109	41	58	19	54	30	104	47	74	18
Adoption rate (%)	87	52	35	50	41	40	40	46	48	47
Projected net returns without CC (Rs./farm)	32,4005	410,473	375,641	4499,39	449,755	571,569	451,087	519,058	462,383	599,290
Projected net returns with CC (Rs./farm)	523,569	519,054	417,429	553,960	522,074	661,078	513,625	619,192	552,265	705,192
Projected PCI*** without CC (Rs.)	48,291	60,892	54,342	66,004	65,505	83,061	65,288	75,461	67,025	86,487
Projected PCI with CC (Rs.)	75,845	75,508	60,570	80,085	76,386	95,569	74,519	89,126	79,848	101,181
Projected poverty rate without CC (%)	46.4	30.8	41.5	26.9	27.8	19.2	28.2	21.4	26.8	17.4
Projected poverty rate with CC (%)	19.9	23.5	33.8	21.0	22.0	15.5	22.5	17.0	20.3	13.1

Note: *The projected yields of wheat were calculated from simulations of APSIM and DSSAT and it varies in all climate scenarios.
**The projected yields of cotton were calculated from simulations of APSIM and DSSAT and it varies in all climate scenarios.
***Per capita income (PCI) is the average income of the households that measures the income earned per person in the cotton–wheat cropping system in one year.

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