Chapter 22
Climate Resilient Cotton Production System: A Case Study in Pakistan

Muhammad Habib ur Rahman, Ishfaq Ahmad, Abdul Ghaffar, Ghulam Haider, Ashfaq Ahmad, Burhan Ahmad, Muhammad Tariq, Wajid Nasim, Ghulam Rasul, Shah Fahad, Shakeel Ahmad, and Gerrit Hoogenboom

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M. H. ur. Rahman (✉)
Department of Agronomy, Muhammad Nawaz Shareef University of Agriculture, Multan, Pakistan

Institute of Crop Science and Resource Conservation (INRES) Crop Science Group, University Bonn, Bonn, Germany
e-mail: habib.rahman@mnsuam.edu.pk

I. Ahmad
Centre for Climate Research and Development, COMSATS University, Islamabad, Pakistan

A. Ghaffar · G. Haider
Department of Agronomy, Muhammad Nawaz Shareef University of Agriculture, Multan, Pakistan

A. Ahmad
Climate Change, US-Pakistan Centre for Advanced Studies in Agriculture and Food Security, Department of Agronomy, University of Agriculture, Faisalabad, Pakistan

B. Ahmad
Pakistan Meteorological Department, Islamabad, Pakistan

M. Tariq
Central Cotton Research Institute, Multan, Pakistan

W. Nasim
Department of Agronomy, University College of Agriculture and Environmental Sciences, Islamia University of Bahawalpur, Bahawalpur, Pakistan

G. Rasul
Pakistan Meteorological Department, Islamabad, Pakistan

International Center for Integrated Mountain Development, Kathmandu, Nepal

S. Fahad
Department of Agriculture, University of Swabi, Swabi, Pakistan

College of Plant Science and Technology, Huazhong Agricultural University, Wuhan, People's Republic of China

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Abstract Cotton production is most vulnerable to climate change particularly in Pakistan, and sustainable cotton yield is critical to accomplish the future demand of the country. Climate change has negative impact on cotton production in major parts of the cotton-growing regions. It hampers not only the yield but also quality of fiber and has negative impact on socioeconomic conditions of farmers. Climate, crop, and economic multidisciplinary modeling approach are being used to assess the impact of climate change and development of adaptation strategies for sustainable cotton production. Climate change scenarios revealed the increase in both maximum and minimum temperature and uncertain rainfall patterns throughout the world and especially in dry and arid areas of the world like Pakistan. Rainfall would increase and decrease as projected by multi-GCMs and RCPs, and it is fact that these changes in climate would lead to negative effect on cotton crop production, and sustainable cotton production in the future is under threat due to climate variablity. Generally, mostly general circulation model (GCM) scenario projected the reduction in cotton yield as compared with the baseline during both timer periods and RCPs tested. Adaptation strategies can minimize the negative impact of climate change. So, changes in crop management practices (sowing, planting density, irrigation, and plant protection) may be good adaptation strategies for sustainable cotton production under changing climate scenarios of the world. Climate resilient cotton production system has potential to minimize the negative impacts of climate change on cotton crop by developing heat and drought resilient germplasm, mitigation technology to reduce GHG emission, and application of decision support system (DSS) and use of ICT-based technologies for sustainable cotton crop production. It is time to adopt climate, energy, and water smart cotton production technologies and practices for sustainable cotton production in the future.

Keywords Climate change · Phenology · Adaptation · Resilient · Sustainable · DSSAT

Abbreviations

AEZ	Arid irrigated zone
BVT	Bee vectoring technology
CO_2	Carbon dioxide
DSSAT	Decision Support System for Agrotechnology Transfer
GCMs	General circulation models
GHG	Greenhouse gas
GIS	Geographical information system

S. Ahmad
Department of Agronomy, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan, Pakistan

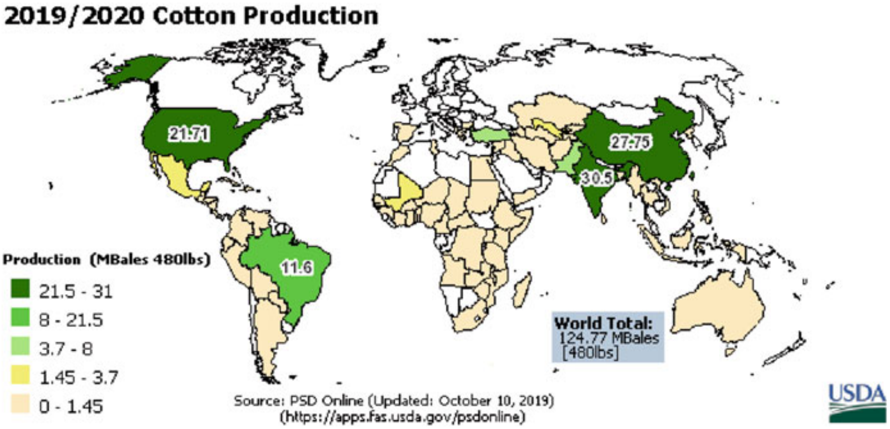
G. Hoogenboom
Agricultural and Biological Engineering Department, Institute for Sustainable Food Systems (ISFS), University of Florida, Gainesville, FL, USA

ICT	Information and communication technologies
IPM	Integrated pest management
RCPs	Representative concentration pathways
SR	Solar radiation

22.1 Introduction

22.1.1 Significance of Cotton Crop

Cotton, being a queen of the fiber, enjoys itself a predominant position among all other cash crops in the world (Usman et al. 2009; Ahmad et al. 2014, 2017a, 2018; Abbas and Ahmad 2018; Ahmad and Raza 2014; Ali et al. 2011, 2013a, b, 2014a, b). Cotton is the mostly used fiber across the globe and had significant contribution in textile industry of the world; therefore, its demand and consumption has been projected to increase then its production (USDA 2018). It can provide not only fiber for the textile industry but also contributes a major role in oil industries by providing oil-rich seed and protein. Total global cotton production worldwide in 2018 was 124 million bales. The United States, China, India, and Pakistan were the largest producers across the world and contribute more than half of the total production volume. Among the top exporter the United States was ranked first, exported 15.5 million bales around the world. Cotton production varied across the world due to differences in production potential mainly due to environmental and climatic factors (Fig. 22.1). Cotton production supports the world largest fiber and textile industry which includes textile mills, spindles, looms, knitwear units, garment units, ginners, and oil expellers. It is by all measures the world's most important economic sector with enormous forward and



Source: PSD Online (Updated: October 10, 2019)
(https://apps.fas.usda.gov/psdonline)

Fig. 22.1 Cotton production and areas across the world; regions have differences in production potential due to variations in environmental and climatic conditions backward linkages. Cotton yarn production from fiber is clustered in major cotton-growing countries including the USA, China, Pakistan, India, and Russia (3/4 yarn production is done in less developing countries of the world); yarn production in different regions and countries can be seen in the map of yarn production (Fig. 22.2). It is estimated in the 94th annual report “Cotton Outlook” of USDA that world’s cotton production will decline in 2018–2019 by 3.6% due to yield decline in cotton-producing countries (USDA 2018).

Cotton is already occupying about less than 3% of world’s agricultural land which is 36% of 10.3 billion hectare land suitable for agriculture on planet earth. Thus, according to an estimate, if the area occupied under cotton is 2.5% of total arable land, then it will be contributing 0.1–0.3% of global greenhouse gas emission (Cotton incorporated 2009; ITC 2011). It indicates that cotton is not the principal source of greenhouse gas emission. However, in-depth analysis of cotton production suggests that cotton at same time is a contributor and victim of global warming and climate change (ITC 2011; Amin et al. 2017, 2018; Khan et al. 2004; Rahman et al. 2018; Tariq et al. 2017, 2018). For instance, according to the estimates of different case studies, production-related GHG emission was estimated about 0.38–0.92 tons of carbon dioxide (CO_2) equivalents per bale of cotton. On the other hand, only ozone pollution out of several other environmental constraints for cotton was found to cause 23% yield loss in upland cotton (Grantz 2003).

Pakistan stands at fourth, third, and second position in terms of cotton production, largest producer of yarn, and largest exporter, respectively, across the world. It is fifth largest consumer of cotton yarn. Cotton and cotton products pay 1.6% in GDP while 55% contribution is country earning with respect to foreign exchange (GOP 2018). Cotton crop is being cultivated on an area of 3 million hectares which covers almost 15% area of the total area cultivated while almost 1.3 million farmers out of 5 million total farmers grow cotton crop. Cotton crop-growing areas and production in Pakistan (Punjab and Sindh) can be seen in cotton production map of Pakistan (Fig. 22.3) while Punjab is the major cotton-producing (74.7%) province in Pakistan. Cotton production is highly variable over the past years due to climatic variability, high climate extremes, weaker adaptive capacity of cotton growers to these climate extremes, high insect pest infestation, poor crop management practices, and policy challenges (Ashraf and Iftikhar 2013; Batool and Saeed 2017). Recently during 2015–2016 cotton production was roughly dropped by 38% in Punjab than the last years (6.3 million bales only as compared with the 10.3 million bales); it was mainly due to erratic and intense rainfall during monsoon, weed infestation, high insect pest infestation, and low-quality cotton seed (GOP 2016). Province-wise area and production of cotton crop is highlighted in the map (Fig. 22.3). Cotton crop being an ancient crop has a long history of its cultivation across the world. After wheat crop, it is the second largest cash crop on area basis in the country. It provides raw material for textile industry and it is an important source of foreign exchange earnings (GOP 2018).

Although Pakistan ranked fourth position in terms of cotton production in the world, still cotton crop is climate sensitive and suffered most due to environmental and climatic factors in the country. As it is depicted from several studies that cotton is the most vulnerable crop and its production would be reduced due to climate change (Rahman et al. 2018), it is clearly depicted from the ground facts that its

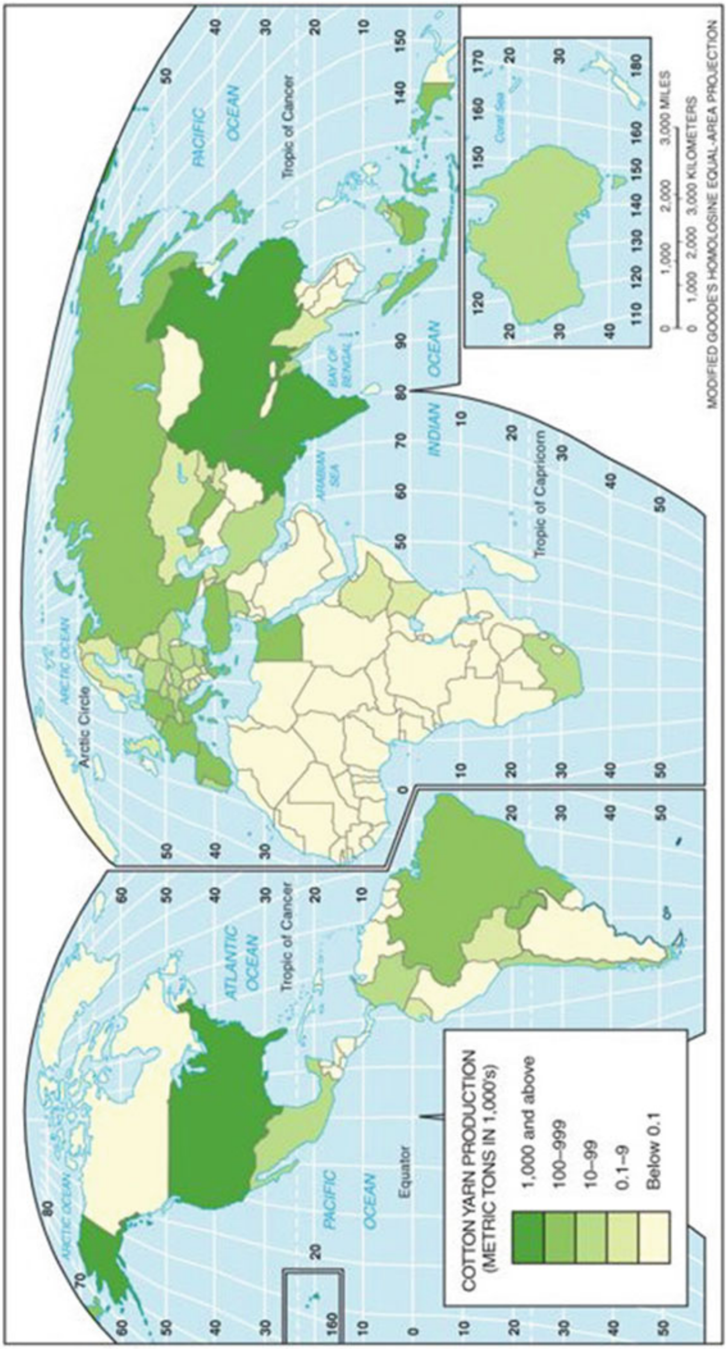


Fig. 22.2 Cotton yarn production (metric tons) in different areas of the world; cotton yarn production from fiber is clustered in major cotton-growing countries including the USA, China, Pakistan, India, and Russia (3/4 yarn production is done in less developing countries of the world)

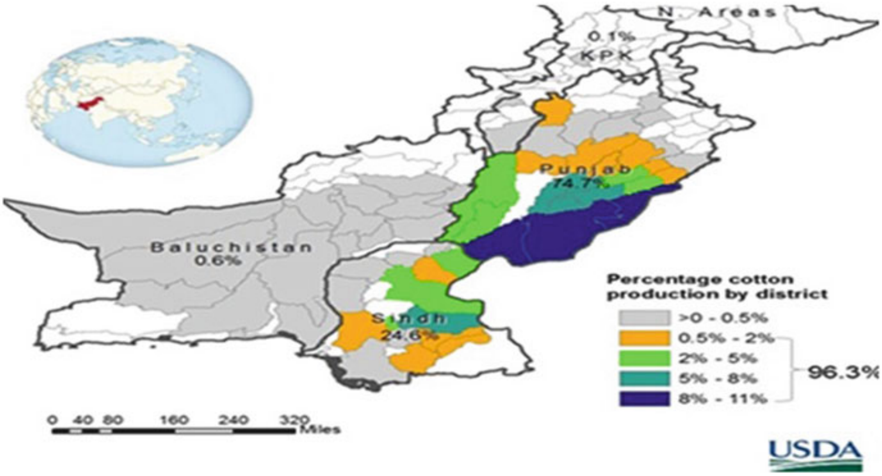


Fig. 22.3 Cotton areas and production in Pakistan (Punjab and Sindh); Punjab is the major cotton-producing province in Pakistan. District-wise area and production are highlighted in the map

production is variable among different years due to climate variability in the country. Future climate scenarios projected an increase in maximum and minimum temperature, rainfall variability, prevailing drought conditions, irrigation water shortage at farmer's field, and higher frequency and intensity of extreme weather events would severely damage the crop growth and a serious threat to sustainable cotton production (Ahmad et al. 2015; IPCC 2013a, b). Furthermore, future projections indicated that average increase in temperature in Pakistan is higher than the predictable global average temperature so cotton crop being grown during the summer is most vulnerable to climate change in Pakistan.

Cotton production depends on environmental and climatic conditions of the region. Crop growth and development of crops is weather dependent and temperature has a significant role in crop development as it is also the most limiting crop-reducing factor especially in crop production (Hoogenboom 2000; Rahman et al. 2016). Cotton production was recorded highest during the years of 1991, 2004, and 2011 in the country while few years were known for the lower cotton production especially 1976, 1983, 1993, and 2015. Generally cotton crop has challenges for sustainable production due to changing in climatic conditions and especially due to climatic extremes. Major issues and challenges are becoming worse due to lacking in capacity of cotton growers to adopt the latest technologies and modern production practices as majority of the cotton growers in the country are still adopting conventional crop management practices and technologies (Makhdum et al. 2011; Zulfiqar et al. 2017). Higher fertilizer dose is being used at cotton field which leads to greenhouse gas (GHG) emission and especially contributes to CO_2 emission and global warming (Rasul et al. 2016). Conventional tillage practices are still being used at farmer field which also lead to more GHG emission. Lower use efficiency of water, fertilizer, radiation, and pesticides is the major challenge in current cotton cropping system and conventional cotton production leads to higher cost of production and lower resource use efficiencies (Raza and Ahmad 2015; Zulfiqar et al. 2017). Cotton production system is badly affected by climate change and is most vulnerable to climate extremes due to weaker adaptive capacity. Situation becomes worse as excessive irrigation water is being used along with intensive pesticide and fertilizer application to cotton crop in current cropping system (Rasul et al. 2012; Nazli et al. 2012; Zulfiqar et al. 2017). Current cropping system is most vulnerable to climate change especially in Pakistan and sustainable crop production is crucial to fulfill the future demand of the country (Rahman et al. 2018; Zhu et al. 2013).

22.1.2 Climate Change and Cotton Production

Changing climate is likely to upsurge the susceptibility of agriculture especially the cropping system (Ahmad et al. 2015) due to unexpected and extreme changes in climate especially increase in temperature and variability in rainfall patterns in the world (Rosenzweig et al. 2014; IPCC 2014a, b). There is explicit change in weather pattern of Pakistan (Ahmad et al. 2015). These changes have been amplified from last decades due to more emission of greenhouse gasses. Mean temperature is increasing 0.2–0.6 °C per decade in Pakistan (Ahmad et al. 2015) and night temperature is increasing more than day temperature. Climate change and variability has a severe impact on crop production and could also be the reason for shift in cropping system in different regions of the Punjab province (Ahmad et al. 2019). Climate being a critical factor in crop productivity across the globe as it effects the growth, development, phenological phases, and cotton yield, it has a significant role than other factors that contribute for crop production (Bradow and Davidonis 2000). Increase in temperature at any cotton growth phase may lead to a negative impact on cotton productivity, while cotton being a C_3 crop can get benefits from elevated CO_2 as fertilization.

However, combined effect of elevated temperature and CO_2 might have adverse effect on cotton production as elevated temperature has a prominent role (Singh et al. 2007). Expected variation in climate especially elevated temperature is estimated to have harmful effects on cotton crop and especially to cotton production (Ahmad et al. 2015; Rahman et al. 2016, 2017, 2018). Night temperature and especially elevated night temperature is more harmful for cotton crop as the specific difference between day and night temperature is crucial for optimum cotton production (Singh et al. 2007). Temperature and rainfall patterns affect the crop choice in different zones (Ghazala and Rasul 2009) and for sustainable cotton production, current spatial and temporal changes in rainfall and temperature need to be considered.

Climate change and variability has a severe impact on cotton production and is the major cause of shift in sowing time of cotton crop (Rahman et al. 2018). Variability in rainfall pattern and fluctuation in temperature have a negative impact on cotton crop growth, development, and production (Bange and Milroy 2004). Cotton crop is specific for temperature requirements at different growth phases (Ahmad et al. 2017a), physiological process, growth development and yield is dependent on climatic conditions (Singh et al. 2007). Temperature variation above and below normal conditions had a significant negative impact on cotton growth and ultimately cotton yield (Luo et al. 2014). Temperature stress at any crop growth phase leads to variability in cotton yield; higher day temperature followed by high night temperature may aggravate the harmful effect on cotton growth and yield. High temperature than normal leads to shorten growth phases, resulting in stunted growth and smaller boll which ultimately lead to lower cotton production (Reddy and Zhao 2005). Cotton yield was decreased up to 51% by increasing temperature from 28 to 32 °C in Indian Punjab which was assessed with the aid of crop models; cotton crop was severely damaged from sowing to anthesis phase (Wajid et al. 2014). Increase in summer temperature especially when exceeds to 45 °C in Punjab and Sindh provinces lead to sever reduction in seed cotton yield as boll development phases are most sensitive to heat stress (Rahman et al. 2004, 2018). As temperature is a critical factor in cotton production, especially boll setting and boll development phases are damaged significantly when maximum temperature during the day exceeds to 30 °C for only a period of 13 h (Reddy et al. 2002). Quality of cotton fiber is also affected by environmental factors and especially temperature and rainfall (Reddy et al. 2007). All quality parameters are negatively affected by environmental factors especially temperature and erratic and intense rainfall.

Elevated CO_2 alone has a positive impact on cotton crop growth, development, and yield due to CO_2 fertilization being a C_3 plant (Reddy et al. 2004). Increase in seed cotton yield of 5.5% by doubling the CO_2 at current temperature but 56% yield decrease only due to increase in maximum temperature while 28% reduction in seed cotton yield observed by the increment in minimum (night) temperature (Jalota et al. 2006). Elevated CO_2 has a positive effect on growth, development, biomass accumulation, and ultimately cotton yield because elevated CO_2 enhances photosynthesis efficiency by reducing stomatal conductance and transpiration (Reddy et al. 2007; Luo et al. 2016). As it is evident from various studies that interactive effect of increase in temperature, elevated CO_2, and variable rainfall patterns might possibly offset the optimistic effect of doubled concentration of carbon dioxide (Williams et al. 2015; Rahman et al. 2018). Intensive cotton production plans by changing in current production and cropping system through adopting the adaptation technologies/strategies could have potential to reduce the adverse effect of climate variability and sustainable cotton production would only be possible.

22.1.3 Climate of Cotton Zones in Pakistan

Climate is a prime factor that exerts major influence on vegetation, soil type, and water resources. Climate is the major driving force for crop production while cotton crop is very specific to its environmental requirements. Climate of cotton zone in Pakistan lies in arid to semiarid region in both provinces Sindh and Punjab. Cotton crop is suitable to this climatic region as it requires normally 4–5 months of uniform high temperature (28–43 °C) while optimum air temperature for its proper vegetative growth and development required 21–29 °C and reproductive growth phases required 27–31 °C temperature ranges (Singh et al. 2007; Bange et al. 2008; Rahman et al. 2018). Cotton crop requires minimum rainfall during its early growing periods while dry months are desirable for good-quality cotton production (Bange et al. 2008). Excessive and erratic rainfall at later growth stages/phases causes damages to crop and especially reproductive growth phases are severely damaged to excessive rainfall (Singh et al. 2007; Rahman et al. 2018). Drought conditions are already prevailed in this climatic zone while climatic conditions become worse in the future due to climate change and climate shift in the region. Irrigation water availability is more threaten and exacerbated in the cotton region due to being arid climate and cotton crop water requirement depends on irrigation water supply. Irrigation water availability in the cotton zones through the Indus basin would be unpredictable due to climatic variability in the country (IPCC 2014a, b). In the past few decades, cotton zone has experienced severe droughts and followed by devastating floods especially flood in 2010 which have contributed to low crop yield and especially the cotton crop being the main crop of this zone. Moreover, the mean temperature across the country has already been increased by 0.65 °C in the past 30 years (Ahmad et al. 2015). Future projections of climate change in cotton zone of Punjab showed the expected changes and increase of 1.2–1.8 °C during near term while higher increase (2.2–3.1 °C) of mean temperature is expected during second time period which is known as mid-century (2040–2069) under emission scenarios of RCP 4.5. Bigger changes and higher variations in climatic variables are expected under the GHG emission scenarios of RCP 8.5, as results showed that increase in mean temperature of 1.4–2.2 °C and 3.0–3.9 °C is projected for the time periods of near term and mid-century, respectively. Similarly, changes and variation in rainfall are projected ranged from −8% to 15% during the time period of near term and −5% to 17% change is projected under RCP 4.5 scenario during mid-century time period, while bigger changes and higher variations are projected for RCP 8.5, as it is expected that −8% to 22% and −2% to 20% ranges are anticipated for the time periods of near term and mid-century, respectively. Results of future projections about cotton yield and production revealed the reduction in seed cotton yield of 8% till 2039 while 20% decrease on an average basis is expected by 2069 under the lower emission scenario of RCP 4.5 as compared with the baseline yield. More variability is expected as likely higher increase in temperature and rainfall variability projected under RCP 8.5 scenario, results revealed that a reduction of 12% and 30% in mean seed yield on an average basis under RCP 8.5 (Rahman et al. 2018). Temperatures are also expected to increase more in winter than in summer which is more dangerous to crops and heat waves during cotton season are the threats to sustainable cotton production. Rainfall projections are more uncertain and less clear due to uncertainties in the model structure (Collins et al. 2013; Rahman et al. 2018). Impact of climate change on cotton yield may vary across different regions in the country and it will be significant without proper adaptation technologies/strategies for cotton crop.

Future projections across Pakistan (a) and especially in Punjab (b) and cotton zones represent the increase in the average annual mean temperature (Fig. 22.4), by 2050, revealed the threat to sustainable cotton production in the country. Similarly projected changes in annual precipitation across Pakistan (a) and Punjab (b) by 2050 represented the variability in rainfall and uncertainty especially in cotton zone.

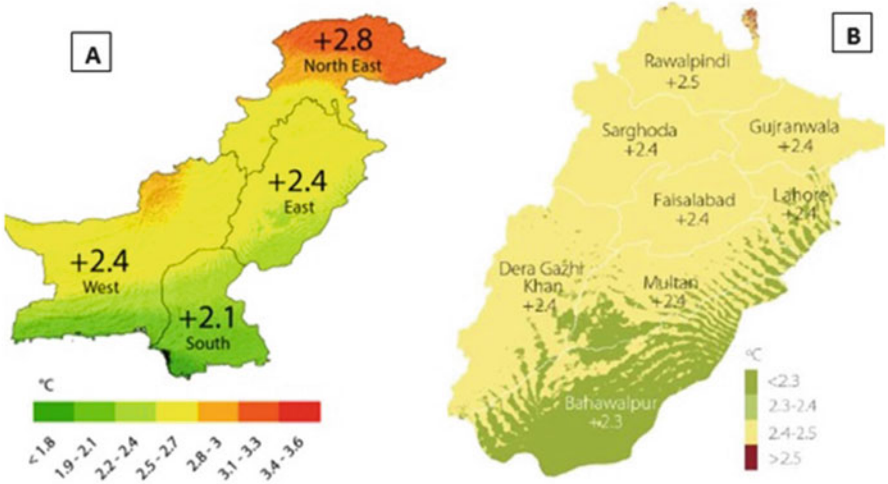


Fig. 22.4 Projected changes in temperature across Pakistan (**a**) and Punjab (**b**) by 2050 represent the increase in the average annual mean temperature especially cotton zone in Pakistan

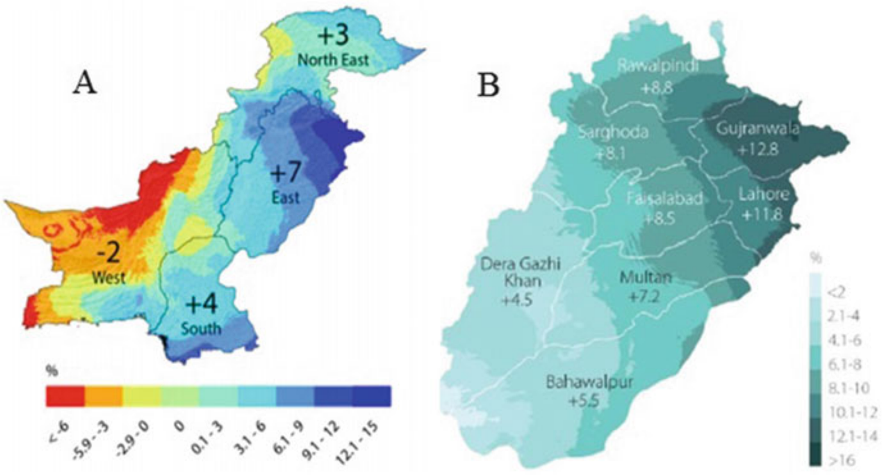


Fig. 22.5 Projected changes in annual precipitation across Pakistan (**a**) and Punjab (**b**) by 2050 represent the variability in rainfall and uncertainty especially in cotton zone. Generally maps depict both increase and decrease in annual rainfall across Pakistan

Generally maps depict both increase and decrease in annual rainfall across Pakistan and Punjab (Fig. 22.5). Variation in maximum and minimum temperature and ranges of Punjab in Kharif season (30-year mean), both temperature ranges are quite high in cotton zone 37–40 °C and 25–29 °C (Fig. 22.6). Similarly, rainfall variability is depicted clearly from the map while rainfall amount is less than 350 mm as it is in arid region (Fig. 22.7).

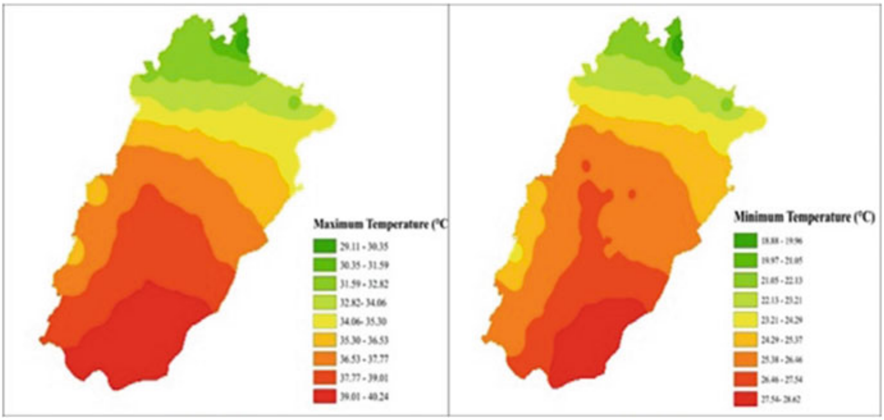


Fig. 22.6 Maximum and minimum temperature variation of Punjab in Kharif season (30-year mean); both temperature ranges are quite high in cotton zone

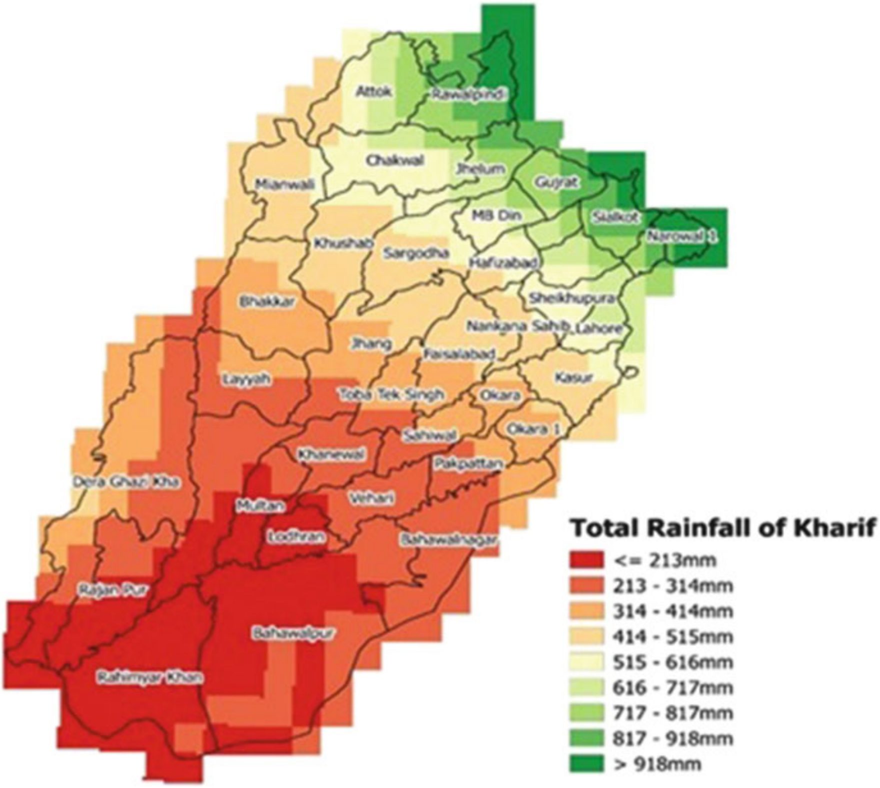


Fig. 22.7 Average (2000–2017) seasonal rainfall distribution across the Punjab during cotton growing seasons

22.1.4 Agrometeorology and Climate Norms for Cotton Crop

Cotton crop is very specific in terms of agrometeorology; specific ranges of weather variables are required for successful cotton production. Although all-weather variables are crucial and play an important role in cotton production, temperature and rainfall variability have significant contribution in successful cotton production. As temperature is considered as the most critical factor for cotton growth and development, optimum temperature of 33 °C is required for efficient growth and development as it is the temperature that promotes the photosynthesis and ultimately cotton growth. Although increasing temperature above optimum leads to lower growth, temperature above 36 °C significantly reduced the flower and boll retention (Singh et al. 2007). Optimum thermal range of 23–32 °C is considered as most suitable for physiological process occurring in cotton plants and this optimum thermal range is also considered as optimal range for growth and development of cotton (Cottee et al. 2010). Temperature has a major role to determine the phenological phases especially initiation and ending of different growth phases and generally whole growth of cotton crop is totally dependent on temperature for being thermo period sensitive (Luo et al. 2014). Cotton crop is very specific for temperature ranges, as it requires uniformly high temperature of 28–43 °C for 4–5 months during its crop growth period. Vegetative growth period required mean air temperature of 21–29 °C while reproductive phases also required very specific for temperature; optimum air temperature for majority of reproductive phases is 27–32 °C (Reddy et al. 2007). Cotton requires 8–9 mean hours daily for optimum growth and development and mean relative humidity almost about 70%, while during boll development relative humidity should be less than 70% and minimum 8 sunshine hours per day are required for the development of a good fiber (Reddy et al. 2004). Optimum temperature for majority of physiological growth and development phases is ranged 25–33 °C; however as temperature increased more than 33 °C, all physiological processes especially photosynthesis in cotton are being reduced and generally cotton growth and development badly affected when temperature increased from 42 °C (Singh et al. 2007). A temperature of 33 °C is reported as optimal temperature for efficient growth and development of cotton plants while above 36 °C temperature is reported as detrimental for reproductive phases which especially cause significant reduction in flower and boll retention (Reddy et al. 2004). Minimum temperature below 15 °C retards the crop growth and reduces the square formation and boll development (Bange and Milroy 2004).

Cotton crop is specific for its temperature ranges for the initiation and competition of each phase and crop requires specific thermal time (Reddy et al. 2007) and critical growth phases of cotton crop are adversely affected by climate extremes especially high temperature stress at reproductive phases (Rahman et al. 2016). Cotton is photoperiod-sensitive crop while it is perennial and indeterminate in terms of morphology (Bange et al. 2008). Accumulated degree days above a specific temperature threshold are deliberated as a good appraisal to see the temperature effect on specific growth phases of cotton crop (Wajid et al. 2014; Rahman et al. 2016).

Sowing time of cotton crop and even each growth phase initiation and completion total depends on temperature. Temperature is a critical factor that defines the sowing of a crop while climatic attributes describe the optimum sowing time in any region and it is crucial for the sustainable cotton production specially the current environmental and climatic challenges to achieve the potential (Singh et al. 2007). Cotton crop seedlings are also temperature sensitive as cold temperature stress results in poor crop stand and delay in developmental and phenological phases, poor physiological growth attributes, and less productivity (Constable and Bange 2006; Conaty et al. 2012). Cold shock due to chilling temperature at early growth phases leads to slow down the growth process and late developmental phases showed that temperature has a significant role at any stage of cotton crop development. A significant difference in day and night temperature is also crucial for optimum cotton growth and lower night (>20 °C) temperature particularly during boll development phases leads to stunted boll growth and poor cotton yield (Bange and Milroy 2004). Studies on sowing time and cotton crop performance at different growth phases are well documented in Rahman et al. (2016). Sowing of cotton crop at optimum time can only harvest peak solar radiation and optimal cotton crop norms can be exposed for better production, while late sowing has to face the sub- and super-optimal climatic conditions at critical growth phases especially heat stress and drought conditions prevails at reproductive phases leads to flower and boll shedding and ultimately lower cotton production (Arshad et al. 2007; Rahman et al. 2004, 2016, 2017, 2018). Late sowing has also faced the high-temperature stress while optimal temperature ranges for physiological and metabolic processes from 23 to 32 °C, and super-optimal temperature leads to short reproductive phases than the early or normal sowing and ultimately resulted in poor production (Pettigrew and Johnson 2005; Conaty et al. 2012). Sowing at right time produced more yield due to better boll retention and more growing period for reproductive phases and timely completion of each phenophase (Rahman et al. 2016).

Although cotton crop requires irrigation amount of 650–750 mm depending on sowing time, as early sowing cotton needs more irrigation water, cotton crop requires minimum rainfall and it is adopted in arid climatic zones just like arid region of Punjab and Sindh provinces. Heavy rainfall especially erratic and intense is more dangerous to cotton crop during either vegetative or reproductive phases. Dry growing season is good for the production of quality fiber as rainfall during later growth phases may cause squares and boll shedding while opened boll is dangerously affected by erratic and intense rainfall especially in terms of cotton quality (Vara Prasad et al. 2005; Singh et al. 2007). High rainfall leads to high humidity which provides the favorable climatic conditions for many of the insect pest and diseases. Excessive rainfall promotes the top growth, more biomass, and lower yield as it is an indeterminate crop so balanced fertilizer and irrigation management are crucial. Best suitable areas for cotton on the basis of environmental conditions like soil (texture, EC, and fertility), climate (minimum and maximum temperature and rainfall), and irrigation water availability and moisture index were assessed and found that cotton crop is most suitable in the lower areas of Punjab province like Khanewal, Vehari, Multan, Muzaffargarh, Bahawalpur, Bahawalnagar, etc.

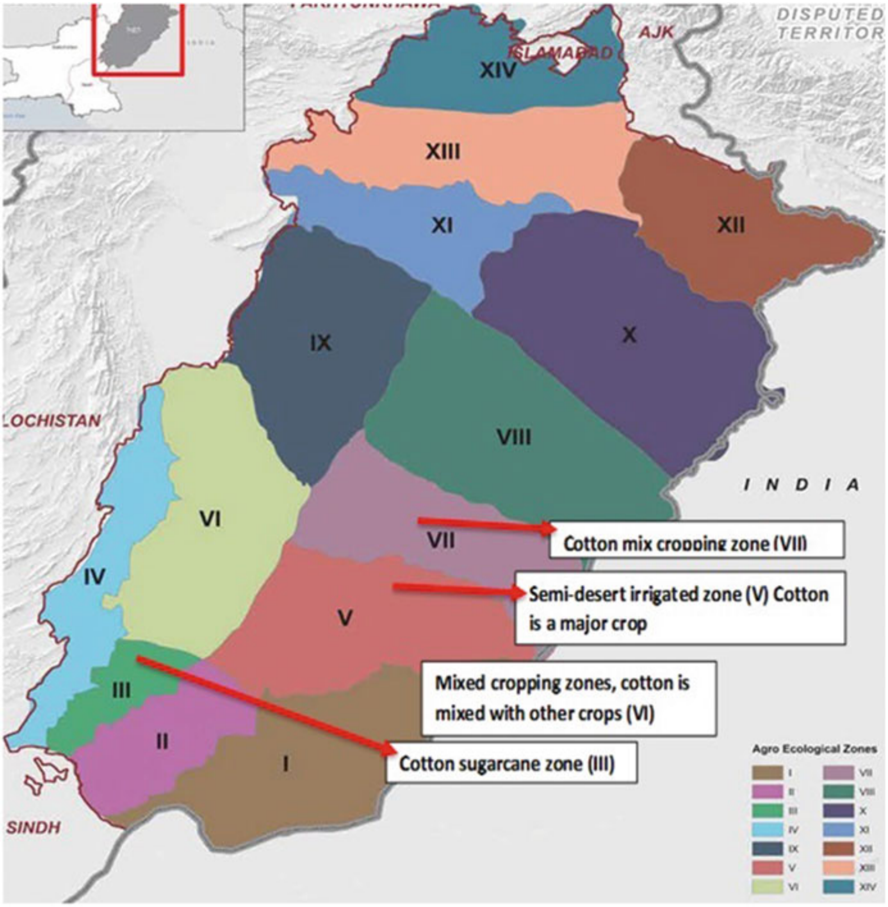


Fig. 22.8 Map of Punjab represents the suitability areas for cotton crop; there are two major zones that belong to cotton crop. There are 14 agroecological zones in Punjab which are recently redefined by UAF, PMAS Arid Agriculture University, MNS-UAM, and FAO-Pakistan (Source: FAO-Pakistan)

(Figs. 22.8 and 22.9). Area's of Indus River, the Indus basin and delta, and northern and southern irrigated plains where cotton is the main and dominant crop while recently developed AEZs showed that highest yield areas in cotton zone are arid irrigated zone (AEZs-II), cotton-sugarcane zone (III), and cotton mix cropping zone (VII) in Punjab-Pakistan. These zones are found in four divisions (Sahiwal, Multan, D.G. Khan, and Bahawalpur). The soil in these AEZ is sandy loamy and the temperature for crop production ranges from maximum 30.7 °C to minimum 17.7 °C. Based on economic suitability, Rajanpur is highly suitable for cotton production with a net return of Rs. 13,487 per hectare, followed by Rahim Yar Khan and Bahawalpur with net returns of Rs. 13,089 and Rs. 12,905 per hectare, respectively.

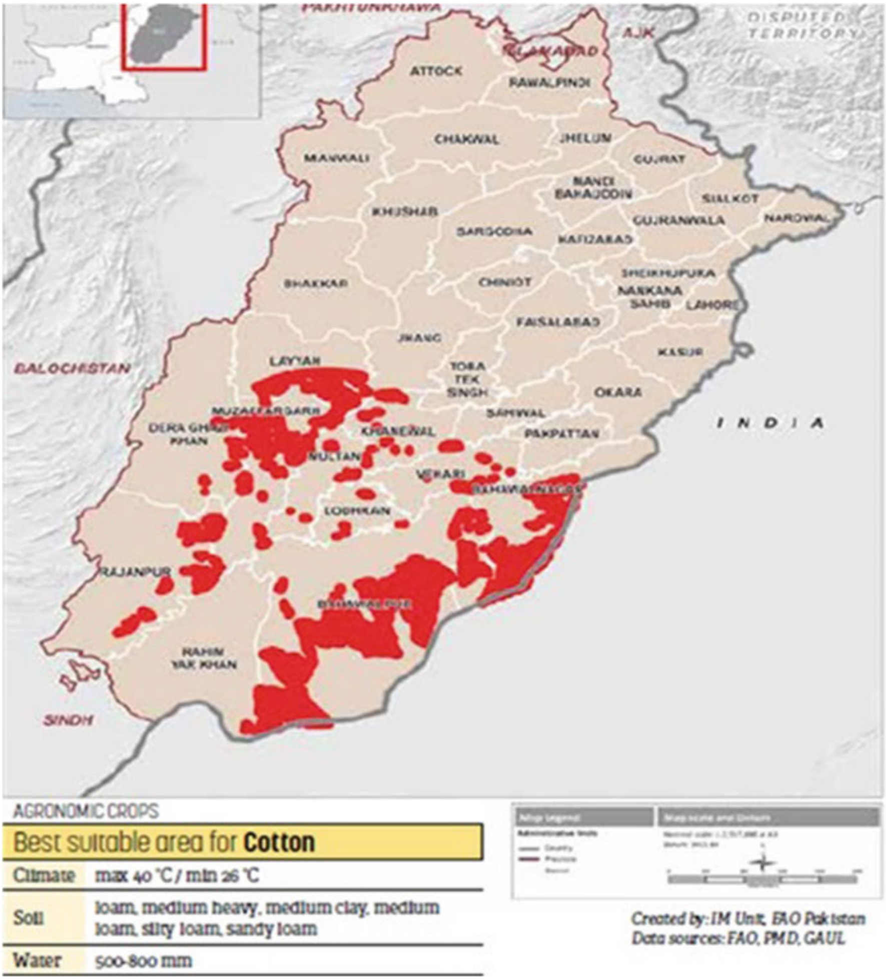


Fig. 22.9 Cotton crop suitability map in Punjab on the basis of crop norms especially maximum temperature, minimum temperature, rainfall, soil texture, soil EC, and moisture index. Crop suitability map represents that south Punjab is only suitable for cotton crop in Punjab; South Punjab is the main contributor region in cotton production (Source: FAO-Pakistan)

22.2 Climate Change Scenarios for Cotton Season in Pakistan

22.2.1 General Circulation Models (GCMs) and Representative Concentration Pathways (RCPs)

Representative concentration pathways (RCPs) basically represent the concentration of greenhouse gasses as it is adopted in fifth assessment report by IPCC. Two concentration pathways (RCP 4.5 and RCP 8.5) of greenhouse gases were adopted in this study; basically these RCPs depend on the prediction data of how much greenhouse gases are emitted from all sources/contributor throughout the years in the future. RCPs represent the radioactive forcing values due to GHGs in the year 2100 (2.6, 4.5, 6.0, and 8.5 W m^{-2}, respectively) relative to pre-industrial levels (Van Vuuren et al. 2011). RCPs represent the possible changes in GHG emissions and concentration in the atmosphere as a result of anthropogenic activities. RCP 4.5 is a mild behavior scenario of GHG emission and it is projected that emission will be at peak around 2040 and then it will decline while RCP 8.5 scenario represents the continued emission of GHGs and its radioactive forcing throughout the twenty first century (IPCC 2014a, b). Generally, RCPs also depend on certain assumptions about socioeconomic scenarios which provide flexible description of future scenarios.

22.2.2 Methodology for Climate Change Scenario Generation

Measured historic weather data (1980–2010) of weather variables, i.e., rainfall, relative humidity, both minimum and maximum temperature, solar radiation (SR), vapor pressure, and surface wind, was used for the generation of multi-GCM (29) future data for different time periods [near term (2010–2039) and mid-century (2040–2069)] in multiple combination with RCPs (4.5 and 8.5) by adopting the protocols mentioned in Ruane et al. (2015b). Historic weather data was declared as baseline in this study. Delta scenario method was adopted, while “R” software was used to run the scripts for the generation of future climate scenarios by adopting the methodology proposed by AgMIP (2013a, b) and Ruane et al. (2013). Data of climate change scenarios for future time periods by using two RCPs of 4.5 and 8.5 with latest and available 29 GCMs were downscaled for cotton zone in Pakistan. Standard procedure and protocols were adopted as described in Ruane et al. (2015a). CO_2 concentration of 390 ppm was adopted and used as baseline in this study while for future climate CO_2 was used as follows: during near term 423 and 432 ppm for RCP 4.5 and RCP 8.5, respectively, and during mid-century time period 499 and 571 ppm for RCP 4.5 and RCP 8.5, respectively (Rosenzweig et al. 2014). Comprehensive explanation about RCPs, GCMs, and CO_2 concentrations can be seen in AgMIP (2014) and Rahman et al. (2018).

22.2.3 Climate Change Scenarios in Near Term (2010–2039) and Mid-century (2040–2069)

22.2.3.1 Future Climate Scenarios During Near Term (2010–2039)

General circulation models (GCMs) were categorized into different groups (hot dry, hot wet, moderate, moderate dry, cool dry, cool wet, moderate wet, very hot, and dry scenarios) due to variation in mean temperature and rainfall during cotton growing season. Classification of GCMs generally represents the behavior of each GCM on the basis of changes and variation in temperature and precipitation. Baseline seasonal mean temperature (April to October) and rainfall are 31.92 °C and 165 mm, respectively, while changes are computed as variation and differences between baseline and future temperature and precipitation. Generally, there would be increase in seasonal mean temperature and variability in precipitation patterns that are projected by all GCMs and RCPs during all-studied time periods in the cotton zone of Pakistan. Mean ensemble of 29 GCMs showed that RCP 4.5 scenario is relatively moderate while RCP 8.5 scenario showed harsh behavior as higher increase in seasonal mean temperature of 2.01 and 3.86 °C (relative to baseline) is projected than RCP 4.5 (1.80 and 3.41 °C) for the time period of 2040 and 2069, respectively (Figs. 22.10 and 22.11). Mean increase of 4.3% and reduction of 3.9% relative to baseline is projected in seasonal rainfall during cotton growing season for RCP 4.5 scenario for the time period of 2040 and 2069, respectively (Fig. 22.12). Likewise, mean ensemble of 29 GCMs showed the reduction of 5% and 7% for the time period of 2040 and 2069, respectively, in emission scenario of RCP 8.5; largely RCP 8.5 scenario is related with significant variation both in precipitation and temperature than RCP 4.5 scenario (Fig. 22.13).

Different GCMs showed variation due to differences in behavior while GCMs have been categorized into different groups on the basis of variation in temperature and precipitation. Generally smaller changes relative to baseline during cotton growing season would range from 0.65 °C (HADGEM2-CC) to 3.46 °C (MIROC-ESM), during near-term time period, whereas the significant higher deviation/changes are observed in INMCM4 (1.82 °C) and MIROC-ESM (5.89 °C) under RCP 4.5 emission scenario than baseline for mid-century time periods (Fig. 22.10). Changes in mean seasonal temperature ranged from 0.72 °C (HADGEM2-ES) to 2.82 °C (MIROC-ESM) in near-term time period while higher changes ranged from 2.40 °C (INMCM4) to 6.06 °C (MIROC-ESM) in RCP 8.5 till 2069 time period (Fig. 22.11). Major and significant changes/variation under RCP 8.5 scenario revealed the harsh behavior. Individual response of GCM and division into different categories on the basis of variation and deviation from baseline can be observed in Figs. 22.10 and 22.11 with respect to changes in mean seasonal temperature. It is projected clearly from the response of each GCM that there would be more increase in minimum temperature as compared with the maximum temperature for the studied time periods which is more detrimental to cotton growth and development and especially cotton production.

Maximum consensus of GCMs about changes in seasonal temperature, mild scenarios, worse and worst scenarios, and hotter GCMs is deliberated in details in Figs. 22.10 and 22.11. Results of GCMs for maximum consensus under RCP 4.5 projected that there would be an increase in seasonal average temperature of 1.4–1.86 °C and 2.8–3.4 °C for 2040 and 2069 time spans, respectively (Fig. 22.10). MIROC-ESM found the hottest one among all GCMs under studied time periods (2040 and 2069 time spans) for the RCP 4.5 emission scenario. Similarly, maximum consensus about increase in mean maximum temperature in

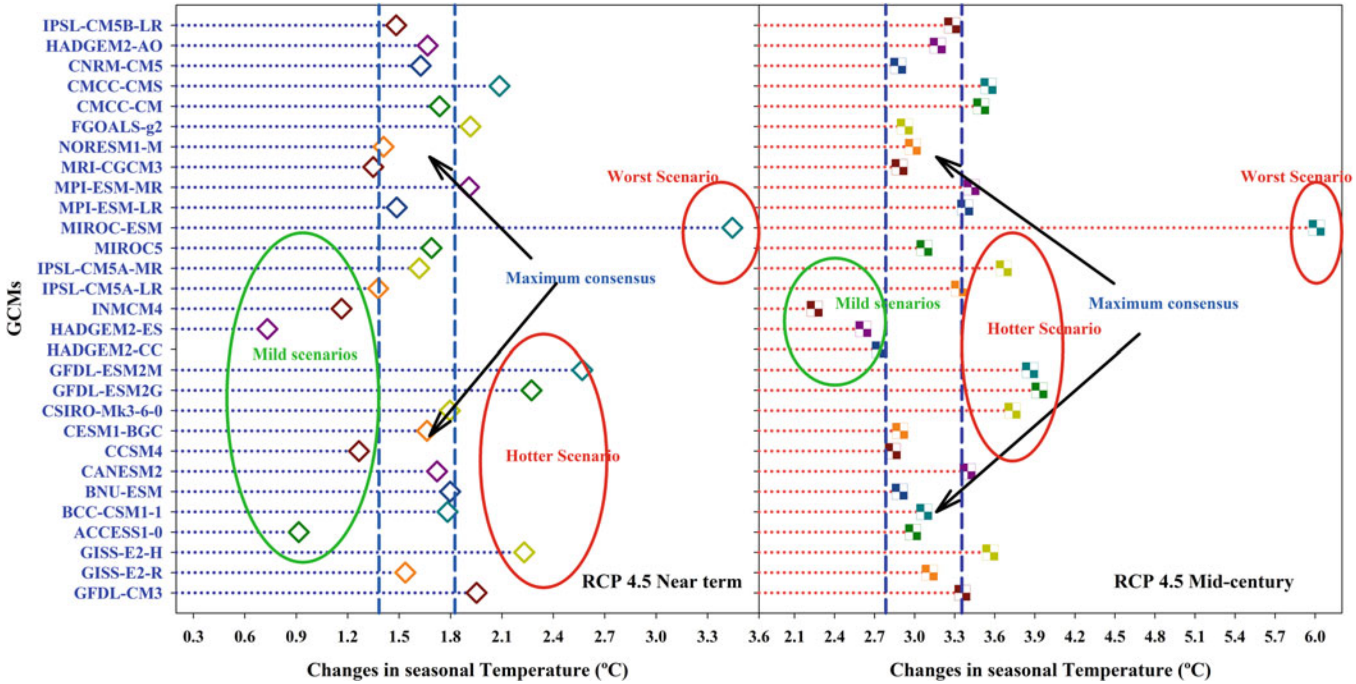


Fig. 22.10 GCM evaluation and categorization on the basis of changes in mean seasonal temperature (°C) during cotton growing season as projected by climate models (GCMs) relative to baseline period (1980–2010) under GHG emission scenario of *RCP 4.5* during *near term (2010–2039)* and *mid-century (2040–2069)* time periods, respectively. Maximum consensus developed by the climate models (GCMs) in both time periods is shown by the vertical blue dotted lines. Green and red circles represent the mild and hotter scenarios, respectively, while hottest and worst scenario is shown by MIROC-ESM in both time periods (near term and mid-century)

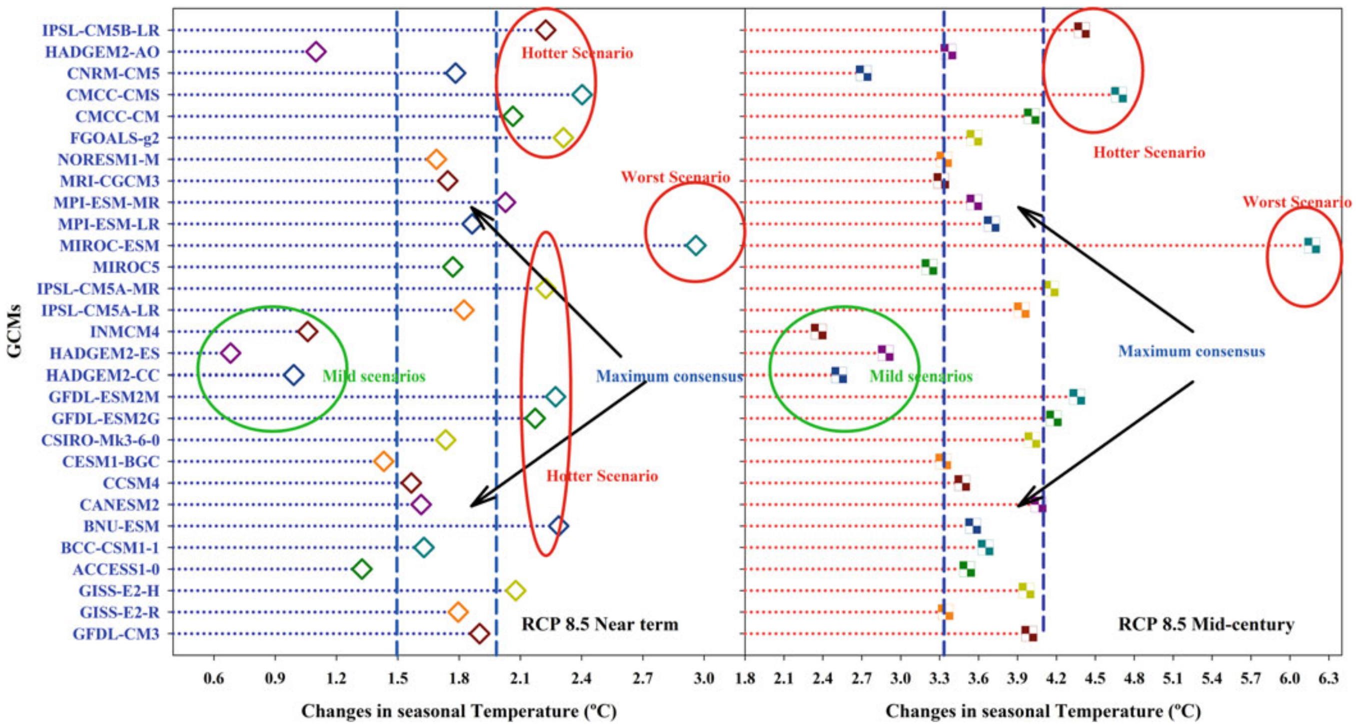


Fig. 22.11 GCM evaluation and categorization on the basis of changes in mean seasonal temperature (°C) during cotton growing season as projected by climate models (GCMs) relative to baseline period (1980–2010) under GHG emission scenario of *RCP 8.5* during *near term (2010–2039)* and *mid-century (2040–2069)* time periods, respectively. Maximum consensus developed by the climate models (GCMs) in both time periods is shown by the vertical blue dotted lines. Green and red circles represent the mild and hotter scenarios, respectively, while hottest and worst scenario is shown by MIROC-ESM in both time periods (near term and mid-century)

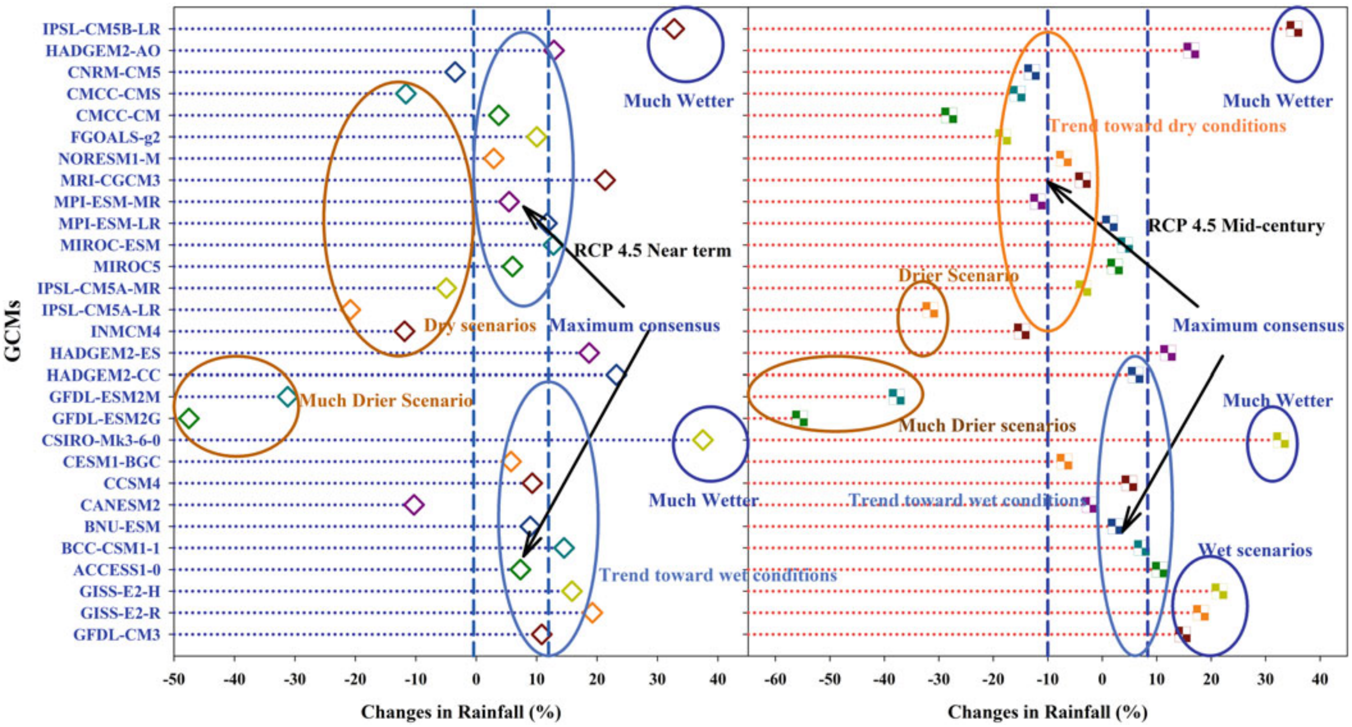


Fig. 22.12 GCM evaluation and categorization (dry, much drier, maximum consensus, wet, and much wetter scenarios) on the basis of changes in total seasonal rainfall (mm) during cotton growing season as projected by climate models (GCMs) relative to baseline period (1980–2010) under GHG emission scenario of *RCP 4.5* during *near term (2010–2039)* and *mid-century (2040–2069)* time periods, respectively. Maximum consensus developed by the climate models (GCMs) in both time periods is shown by the vertical blue dotted lines. Different color circles represent the dry, much drier, wet, and much wetter scenarios in both time periods (near term and mid-century)

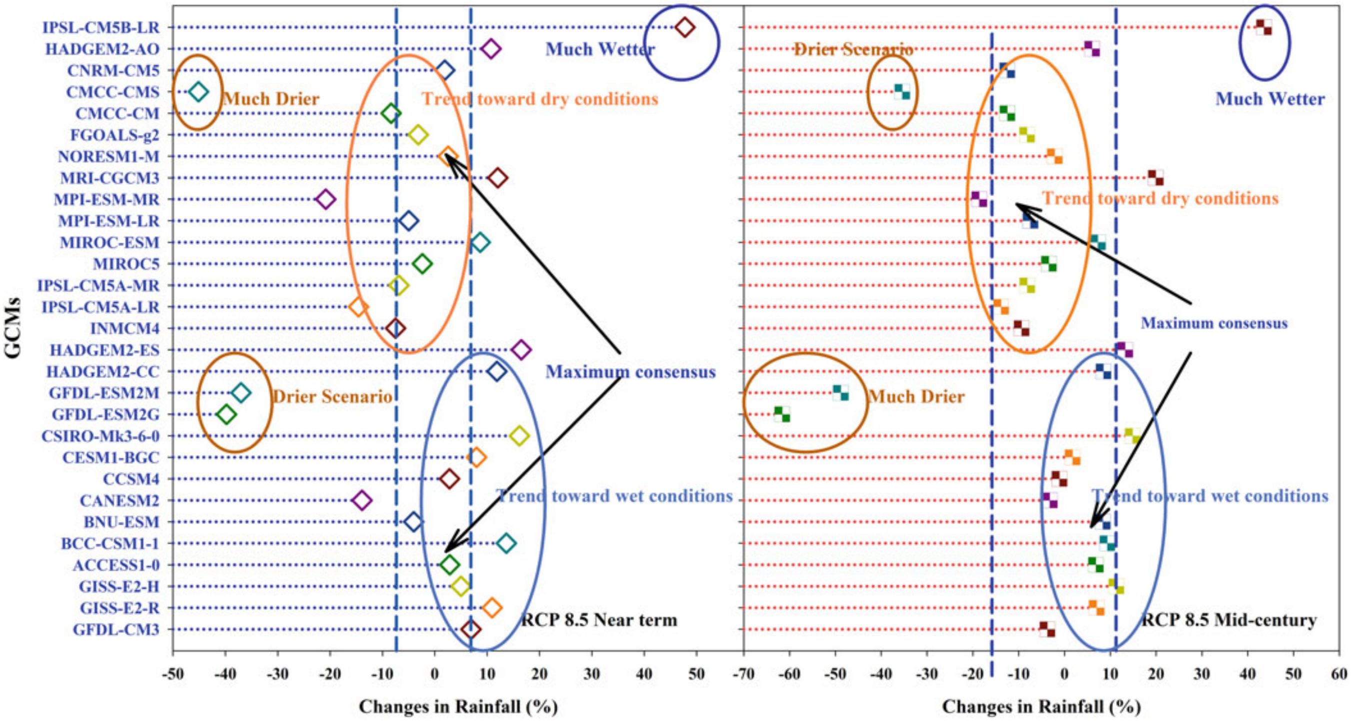


Fig. 22.13 GCM evaluation and categorization (dry, much drier, maximum consensus, wet, and much wetter scenarios) on the basis of changes in total seasonal rainfall (mm) during cotton growing season as projected by climate models (GCMs) relative to baseline period (1980–2010) under GHG emission scenario of *RCP 8.5* during *near term (2010–2039)* and *mid-century (2040–2069)* time periods, respectively. Maximum consensus developed by the climate models (GCMs) in both time periods is shown by the vertical blue dotted lines. Different color circles represent the dry, much drier, wet, and much wetter scenarios in both time periods (near term and mid-century)

RCP 8.5 scenario would range from 1.5 to 2 °C and 3.3 to 4.1 °C relative to baseline for 2040 and 2069 time spans, respectively (Fig. 22.11).

Climate scenarios about precipitation revealed that seasonal changes and variation in rainfall patterns during cotton season are more uncertain. Results of maximum consensuses for rainfall showed the smaller increase in rainfall amount relative to baseline. Changes in rainfall would range from 0% to 10% and −10% to 8.5% for 2040 and 2069 time periods under RCP 4.5 (Fig. 22.12). Mostly, climate models revealed the trend of increasing rainfall while fewer models showed the decreasing tendency of rainfall in under RCP 4.5 scenario during cotton growing season but it seems most uncertain patterns. Significant reduction in rainfall amount is clearly depicted under RCP 8.5 scenario for both time periods; it is projected that change in rainfall would range from −9% to 8% and −18% to 11% for the time periods of 2040 and 2069, respectively (Fig. 22.13).

There are few GCMs as well that are declared as drier than seasonal baseline but highest reduction is observed for the GFDL-ESM2G under both emission scenarios (RCP 4.5 and RCP 8.5) in both time periods of 2050 and 2069. There are few GCMs like IPSL-CM5B-LR that was found wet and hot in both timer periods and RCPs as compared with other GCMs. There are some worst-case scenarios as well where higher increase in temperature and reduction in precipitation are projected. Furthermore few models were also found wetter and much wetter and some may declare as dry and drier but one thing is common among all GCMs and studied RCP scenarios that rainfall patterns are more uncertain and cotton crop is very specific for its irrigation water demand. Some GCMs showed less uncertain and showed stable behavior during both time periods under both RCPs, namely, CCSM4, HadGEM2-CC, HadGEM2-ES, INMCM4, CanESM2, CNRM-CM5, ACCESS1-0, BNU-ESM, and MIROC5. These GCMs are recommended and can be applied for the assessment of climate change impacts for other crops in Pakistan. Generally climate models are uncertain, climate change impact assessment studies about crops especially for cotton crop should rely on more than one climate models as uncertainties are common in emission scenarios (Rahman et al. 2018). It is recommended across the globe about modeling studies to use multi-models for climate change as it can provide more consistent result about decision management especially in agriculture sector as it is more risky than others (Asseng et al. 2013; Rosenzweig et al. 2014; Rahman et al. 2018).

22.3 Impact of Climate Change on Cotton Production

22.3.1 Climate Change Impact Assessment for Cotton Crop During Near Term (2010–2039)

Cotton crop is very sensitive for its climatic requirements and slight variation may lead to changes in growth and development and ultimately lead to reduction in production. Weather variables especially temperature and rainfall have a significant role for cotton production and variation or change in these factors may lead to severe reduction in cotton production. High temperature above normal which is required for optimum growth and development of cotton crop speeds up the phenological phases and had a negative impact on vegetative and especially reproductive growth phases of cotton and ultimately reduces the cotton production. Sustainable cotton production becomes more sensitive especially in arid climate where rainfall variability and high temperature are already a severe threat to cotton crop. Generally, mostly GCM scenario projected the reduction in cotton yield as compared with the baseline during both time periods and RCPs tested.

Seed cotton yield would reduce but an important contribution of variation existed in yield (−2.7% to −49%) among studied GCMs under RCP 4.5 during near term; similarly yield reduction ranges from −3% to −32% under scenario of RCP 8.5 during near term although less uncertainty was found among GCMs under RCP 8.5 scenario. Generally, less seed cotton yield reduction is observed under RCP 4.5 but few GCMs are more uncertain (Figs. 22.14 and 22.15). Although all GCMs showed the reduction in cotton crop yield in Pakistan during near term, there are few worse-case scenarios as well that showed the higher reduction in cotton yield because those are found hotter and variable in term of rainfall. Drier GCMs and hottest at the same time are found worst-case scenarios for cotton production as heat and drought conditions are more detrimental to cotton crop. Overall mean ensemble of 29 GCMs showed the reduction of 10% and 17% in seed cotton yield in Pakistan under GHG emission scenarios of RCP 4.5 and RCP 8.5, respectively, during near term. More reduction in cotton yield is expected due to higher increase in mean seasonal temperature and significant amount of rainfall variability during cotton growing season in Pakistan. Drier conditions with below potential evapotranspiration and especially high night temperature lead to more reduction in cotton yield in worst-case scenarios of GCMs during near term (Figs. 22.14 and 22.15).

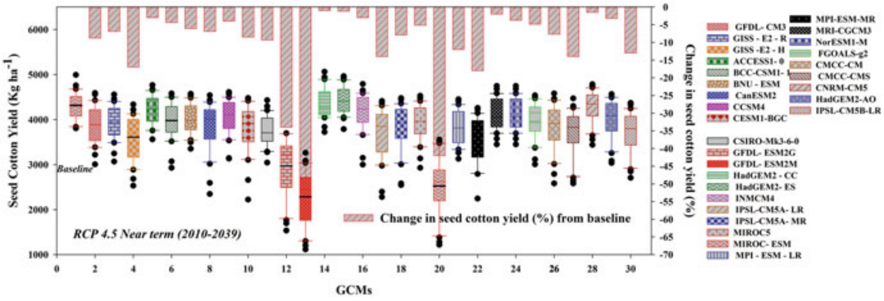


Fig. 22.14 Mean seed cotton yield of cultivars and yield gained/lost as compared with baseline (historic) simulated by CSM-CROPGRO-Cotton based on 29 GCMs under RCP 4.5 for near term of the twenty first century (2010–2039). Black dots at both ends of box plots represent the lowest and highest SCY points in different growing years. Changes in mean seed cotton yield (%) of each GCM depict by the bar graphs against each GCM

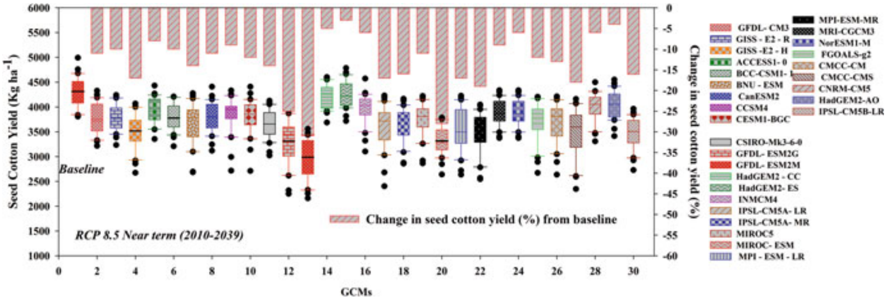


Fig. 22.15 Mean seed cotton yield of cultivars and yield gained/lost as compared with baseline (historic) simulated by CSM-CROPGRO-Cotton based on 29 GCMs under RCP 8.5 for near term of the twenty first century (2010–2039). Black dots at both ends of box plots represent the lowest and highest SCY points in different growing years. Changes in mean seed cotton yield (%) of each GCM depict by the bar graphs against each GCM

22.3.2 Climate Change Impact Assessment for Cotton Crop During Mid-century (2040–2069)

Significantly higher losses of cotton yield are projected for the time period of 2040–2060 for both RCP 4.5 and RCP 8.5 but especially higher reduction is expected in RCP 8.5 due to worst scenarios of increasing temperature both maximum and due to more increase in minimum temperature accompanied by higher rainfall variability and especially the drier conditions during cotton growth especially at reproductive phases. It is projected that there would be a decrease of 25% and 39% (mean ensemble of 29 GCMs) in cotton yield under RCP 4.5 and RCP 8.5, respectively, during mid-century as compared with the seasonal average baseline cotton yield (3919 kg ha^{-1}). Variation in the yield of cotton crop would range from −5% to −57% and −7% to −72% under RCP 4.5 and 8.5 scenarios, respectively, during mid-century in Pakistan (Figs. 22.16 and 22.17). Major reduction in cotton yield is attributed for the same GCMs as observed during the near-term time period for both RCP 4.5 and RCP 8.5 emission scenarios. Similar causes as mentioned and discussed in previous section like higher increase in night temperature accompanied with drier conditions, heat stress during reproductive growth phases of cotton, and rainfall variability may be the significant contributor in lower cotton yield production under future climate scenarios of Pakistan.

More seed cotton yield reduction is projected for CMCC-CMS, IPSL-CM5B-LR, GISS-E2-H, GFDL-ESM2M, and GFDL-ESM2G and GFDL-ESM2M and GFDL-ESM2G are hotter and drier while HADGEM2-ES and HADGEM2-CC are milder and wet which leads to lower reduction in cotton yield. High variation was found among GCMs for cotton yield but normally ten GCMs, including MIROC-ESM, GFDL-ESM2G, GFDL-ESM2M, IPSL-CM5A-LR, CMCC-CMS, GFDL-CM, CSIRO-MK3-6-0, MPI-ESM-MR, CANESM2, and IPSL-CM5A-MR, projected significant variation in climatic variables especially temperature and rainfall, while mild behavior is projected by the four GCMs, namely, HADGEM2-CC, INMCM4,

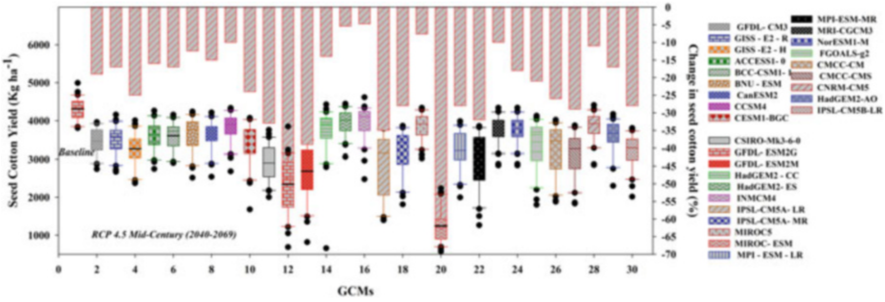


Fig. 22.16 Mean seed cotton yield of cultivars and yield lost as compared with baseline (historic) simulated by CSM-CROPGRO-Cotton based on 29 GCMs under RCP 4.5 for mid of the twenty first century (2040–2069). Black dots at both ends of box plots represent the lowest and highest SCY points in different growing years. Changes in mean seed cotton yield (%) of each GCM depict by the bar graphs against each GCM

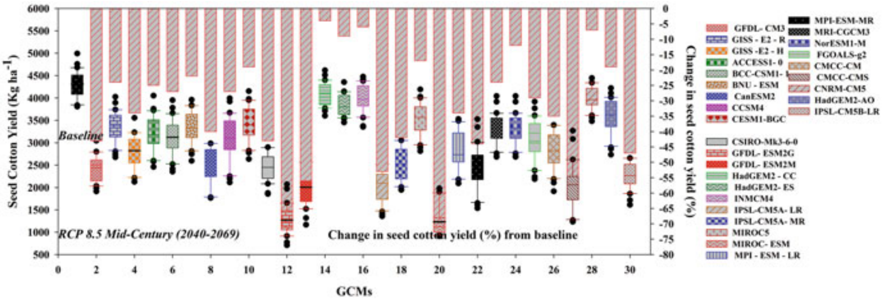


Fig. 22.17 Mean seed cotton yield of cultivars and yield lost as compared with baseline (historic) simulated by CSM-CROPGRO-Cotton based on 29 GCMs under RCP 8.5 for mid of the twenty first century (2040–2069). Black dots at both ends of box plots represent the lowest and highest SCY points in different growing years. Changes in mean seed cotton yield (%) of each GCM depict by the bar graphs against each GCM

HADGEM2-ES, and CNRM-CM5, than all other studied GCMs and generally speaking changes overall are moderate (Figs. 22.14, 22.15, 22.16, and 22.17). Few GCMs are found hotter and drier as well like GFDL-ESM2G and GFDL-ESM2M but few others (HADGEM2-ES, HADGEM2-CC, and INMCM4) are, although hot, have wet conditions during cotton growing seasons which lead to lower reduction of cotton yield in these GCMs during both studied time periods.

22.4 Adaptation Technology Development for Sustainable Cotton Production Under Climate Change Scenarios

Climate change has negative effects on growth and yield of cotton. Extreme temperatures and uncertain rainfall patterns decrease the seed cotton yield by reducing the length of growing periods. To ensure the high yield under changing climate, adaptation measures are necessary to address the current and future threats of climate change. Crop management options, development of climate resilient cultivars, and ICT-based technologies could have potential as adaptation strategies in context of changing climate.

22.4.1 Management Strategies

Modification in production technology of cotton is important for confronting the risk associated with climate change. Different management strategies as shown in Table 22.1 could be useful for mitigating the negative effects of climate change on cotton.

Adjustment of sowing dates is very important and associated with growing season length. Too early and late sowing of cotton reduced the yield by increasing the chances of inset attack due to unfavorable weather conditions. Late sowing delay flowering and boll development which occur in cooler environment that leads to decrease in the yield (Braunack et al. 2012). Sowing of cotton crop at optimum time increased the yield by increasing growing season length. The number of plants m^{-2} is very less than the recommended at farm field level; few plants are unable to germinate that causes the reduction in yield. High plant population also decreases the yield due to decrease in boll size and increases fruit shedding. So, maintenance of optimum plant population increased the yield.

Application of slow release (coated) and balanced use of fertilizers (NPK) increased the efficiency and meet the nutritional requirement of crop that lead to increase in the yield. Future scenarios of irrigation water showed that per capita availability of water would be reduced in the future due to climate change and less water would be available for crop production (Ahmad et al. 2019). Efficient methods such as drip irrigation in cotton reduced the losses and provide water directly to root

Table 22.1 Crop management strategies as adaptation for cotton under climate change

Adaptations	References
Adjustment of sowing dates	Huang (2016)
Optimum plant population	Wrather et al. (2008)
Precise application of nutrients (balanced use of fertilizers, slow released fertilizers)	Wrather et al. (2008)
Efficient water technologies (drip irrigation)	Bhaskar et al. (2005)
Integrated pest and disease management	Hillocks (2005)
Drainage of water during excess rainfall	Manik et al. (2019)
Reducing post-harvest losses (mechanical picking)	Muthamilselvan et al. (2007)

zone of crop which prevent from drought or severe water stress. Insect pest and disease attack on cotton causes the huge reduction in yield of cotton.

Integrated pest management (IPM) eliminated the use of pesticides and minimized the toxicity of chemical due to the use of cultural and biological methods for pest control. Insect pest and disease will become more problematic due to climate change (Petzoldt and Seaman 2006). IPM would be useful strategy for control of insets pest and diseases. Some practices adopted in IPM method are timely removal of weeds and removal of alternate host plants and cotton sticks from the field. Animals like sheep and goats are allowed to feed after last picking. Bee vectoring technology (BVT) is part of IPM which is a biological control of pest and leads to heather and stronger plants (Arora et al. 2011). As far as water is concerned, cotton is sensitive to stagnant water. Excess water promotes the fruit shedding in cotton due to inadequate aeration in the root zone. Removal of excess water from the field by making drain at low end of the field is a useful strategy for cotton especially during monsoon season (Muthamilselvan et al. 2007; Perumal et al. 2006). Cotton is an indeterminate crop and picking of cotton is done 3–5 times at final stages. Manual picking of cotton is labor intensive and cost accounts for 30–35% of total cultivation. It also increased the post-harvest losses due to picking of immature boll. Mechanical picking of cotton reduced the total cost and post-harvest losses.

22.4.2 Heat and Drought Resilient Germplasm Development

Heat and drought stress caused the physiological and chemical changes in cotton which affected the growth and yield. Generally, heat and drought conditions restricted the root growth, plant height, boll development, and fiber quality. However, photosynthetic activity, stomatal conductance, and water potential are also decreased (Chastain et al. 2016). Therefore, it is necessary to develop heat- and drought-tolerant mechanism in cotton to avoid multiple stresses and to survive under harsh environment.

Future rise in temperature would reduce the phenological events such as days to flowering and maturity. Regaining the phenological event under high temperature through breeding could be best strategy in developing heat-tolerant cultivars (Ahmad et al. 2017a). For example, a study was conducted for the development of climate resilient cultivars of cotton in Pakistan using Decision Support System for Agrotechnology Transfer (DSSAT). Future rise in maximum temperature of 3.6 °C and minimum temperature of 3.8 °C was used in a model. Impact of rise in temperature decreased the days to anthesis by 10%, maturity by 20%, and yield by 60%. Genetic coefficients of cotton in DSSAT were adjusted to regain the phenology and yield. The time required for the cultivar to reach a final pod was decreased by 30% and fraction of daily growth which is portioned to seed and shell was increased by 10%. Other phenology-related traits were also adjusted to get the climate resilient cultivar of cotton (Ahmad et al. 2017b). Drought-tolerant cultivars could be developed through selection of potential traits, which can enhance the performance under water deficit condition. Several traits exist that are associated with drought tolerance such as leaf conductance, leaf water potential, rolling, osmotic adjustment, and extraction of soil water (Turner 1979; Woodfin et al. 1979). However, plant breeder can use different techniques for the evaluation of these traits to develop drought-tolerant cultivars. The development of heat and drought tolerant can offset the yield losses and sustain the productivity under changing climate scenarios.

22.4.3 Application of Decision Support System for Sustainable Cotton Production

Decision support system (DSS) is computer-based system that helps in decision-making. DSS addresses the issues related to efficient agronomic practices, conservation, nutrient management, insect pest, and disease management which would be useful in adapting the environmental vulnerabilities. Nutrients could be managed through DSS. Fertilizers are very expensive and huge losses were observed during application at farm level, which reduced the yield. In the future due to rise in temperature, fertilizer losses would be increased through volatilization. So DSS has been designed for the recommendation of optimum doses of fertilizer to crops. For example, CROPGRO simulates the yield of cotton by the integrating soil, water, genetics, and environment system (Hoogenboom 2000; Rahman et al. 2017). It helps in simulating the nitrogen balance and optimization of fertilizer in cotton (Wang et al. 2013). Haifa Nutri-Net is another DSS that assists the growers in nutrient and irrigation management under changing climate (Achilea et al. 2005). Planning Land Applications of Nutrients for Efficiency and the Environment (PLANET) is another system which provides the best management practices for crops and recommends the fertilizer application based on previous crop (Gibbons et al. 2005).

Insects and pests can be managed through DSS to increase the production under changing climate. For example, CLIMEX model is used to examine the insect and pest distribution. It has been used by more than 20 countries for insect and pest management (Walker and White 2001). Another model SOPRA is also used for monitoring and management of pest population (Mir and Quadri 2009). DSS has been used for water management and timely estimation of drought for cotton (Loi and Tangtham 2005). For climate change adaptations, climate forecasting is necessary because it provides the scientific bases. Decision Support System for Agrotechnology Transfer (DSSAT) has been designed to assess the climate impacts (Jones et al. 2000); another model on geographical information system (GIS) and remote sensing based has been developed to estimate the risk associated with climate. Forecasting of climate based on DSS helps in adjustment of crops in different climatic conditions.

22.4.4 *Use of ICT for Better Cotton Production Under Climate Change*

Information and communication technologies (ICT) play a key role for adapting climate change. The main steps for the development of adaptations through ICT are given in Fig. 22.18. Similar steps were described by Sala (2009). The first step of adaptation is the observation on how the climatic variations are occurring on a specific site. Observation could be carried out by different tools like sensor-based networks and remote sensing techniques. The collected data on climatic impacts on cotton are stored and digitized for communication of different institutes. After the data is analyzed for planning, for this purpose computer-based models are used for decision-making. GIS can facilitate in development of adaptation measures based on observation for stakeholders. The developed adaptation is implemented to farmers for decision-making as shown in step 3 in Fig. 22.18. The tools useful for implementation and management are forecasting and early warning system. Capacity

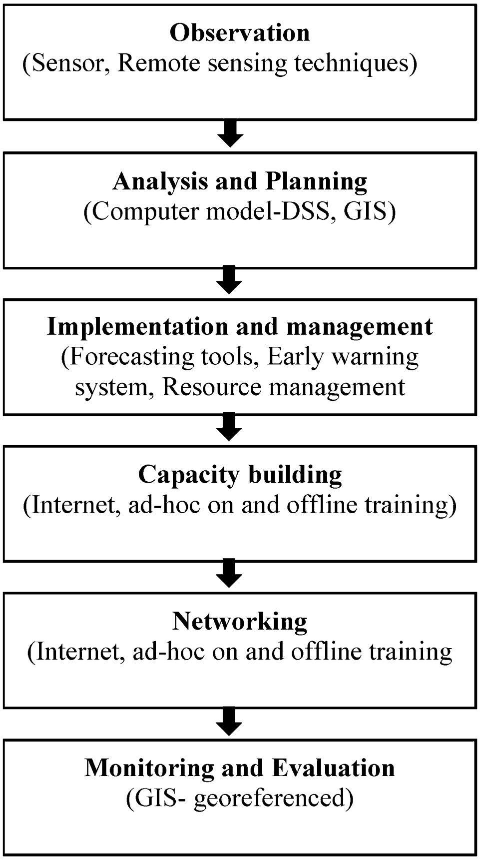


Fig. 22.18 ICT-based steps for the development of adaptation strategies for sustainable cotton production to mitigate the negative impact of climate change

building on climate adaptation can be employed for the awareness of farmers in cotton zones. Training, seminars, and workshops could be conducted using ad hoc on and offline system. The final step is networking in which data is stored and retried for comparing the information with other knowledge partner in different areas for precise decision. The final stage of adaptation through ICT is monitoring and evaluation, which could be done using GIS tools. It allows geo-reference information and support for monitoring and evaluation of developed adaptations strategies.

22.4.5 Potential Options of Climate Resilient Cotton Production

These are the few options that may have potential to develop climate resilient cotton production:

1. Improving resource use efficiency (water, fertilizers, agrochemicals).
2. Changing from conventional to good agricultural practices.
3. Carbon sequestration as a climate change mitigation strategy.
4. Breeding heat and drought climate resilient varieties with high resource use efficiency.
5. Optimizing sowing dates to harvest the maximum solar radiation and optimum climate norms.
6. Reduced tillage operations for the low emission of GHGs.
7. Prolonging soil cover to control weeds and enhance water use efficiency and water productivity.
8. Increasing plant density.
9. Introduction of carbon pricing policy.
10. Developing energy efficient technologies.
11. Improving soil organic matter.
12. Promotion of biodiversity.
13. Improvement in agriculture extension services (farmer education).
14. Climate smart village development for the promotion of climate resilient cropping system.

22.4.6 Strategies/Technologies for Climate Smart Cotton Production

Climate smart technologies and practices are the need of the time to develop climate smart cotton production system as climate smart agriculture (CSA) tackles with three important pillars as: (1) sustainably increasing agricultural productivity and income to meet national food security, (2) adapting and building resilience in agricultural systems to climate change, and (3) reducing and/or removing greenhouse gas emissions or increasing carbon sequestration (FAO 2013, 2017). Practices and technologies in agriculture are deliberated as smart especially in terms of climate that have potential and assist to achieve at least one component of CSA. Climate smart agriculture system generally improves the resource use efficiency and increased resilience and productivity by reducing greenhouse gas emissions. Climate smart cotton production system has technologies and strategies to increase sustainable cotton production, farm income, and livelihood, improves water and fertilizer use efficiency and develops resilience to climate variability, and generally lowers the emission of GHG emission due to different poor management practices (FAO 2010, 2012, 2016). Vulnerability of cotton production system due to climate extremes can be minimized significantly by adopting CSA technologies and practices and hence it revealed the potential (FAO 2010). Few studies on climate smart cotton showed that new practices and technologies and especially adaption in current cotton system will strengthen the sustainable cotton production by improving resource use efficiency (Ashraf and Iftikhar 2013; Pasha 2015; Imran et al. 2018; Rahman et al. 2018).

Carbon, energy, water, and knowledge smart climate agricultural technologies and practices are now being adopted and need to be adopt for cotton production system as well because cotton is most sensitive to any stress (Imran et al. 2018). CSA practices and technologies are also being adopted by even small landholders (Khatri-Chhetri et al. 2017) in Punjab especially in cotton belt which will improve cotton production, WUE, and NUE and ultimately improve the efficiency of key inputs in cotton-based cropping system. Cotton production can be improved by adopting CSA practices like sowing on raised bed or ridges as has potential to save water and high efficiency and it enhances nutrients uptake and transport (Khatri-Chhetri et al. 2016; Imran et al. 2018). Sowing on beds also ensures good crop stand and optimum plant population as planting density is the key contributor in cotton yield. It also improves germination and crop stand under unfavorable environmental conditions and it also saves crop for waterlogging situation in case of erratic and intense rainfall during monsoon. Climate resilient genotype development which can withstand at high temperature and drought conditions is also among top agenda of CSA, as climate smart varieties have potential to minimize the negative impact of climate change and survive even under unfavorable climatic conditions (Rane and Nagarajan 2004). Currently genotypes being cultivated at farmer's field have lack of sustainability and most vulnerable to climate extremes and only survive for few years and lose potential quickly and cause cotton yield stagnation (Rahman et al. 2016). Water-saving technologies especially high irrigation efficiency system have potential and especially drip irrigation is being adopted as CSA practice for cotton crop to save irrigation water by reducing surface water losses and it has also potential to improve nutrient use efficiency (Watto and Mugera 2015; Dağdelen et al. 2009; Manpreet et al. 2007). Cotton crop yield is improved by adopting drip irrigation through saving water and good crop stand which ultimately lead to better crop production by avoiding environmental stress. It has been observed that application of climate smart practices and technologies considerably reduces the adverse effects of climate change and improves cotton yield and production and ultimately better livelihood of farmers at grassroots scale. There is a need of the time to adopt climate smart cotton production system for the sustainable cotton production under climate change scenarios.

22.5 Conclusions

Current agriculture production systems are most vulnerable to climate change; climate extremes and climate variability are threats to sustainable crop production across the world to fulfill the needs of ever-increasing population. Food and fiber security is under threat due to environmental challenges and especially current cotton-based cropping system and cotton crop is most sensitive to climate extremes and environmental stress. Cotton crop is a significant cash crop, it has a prominent role in cropping system and support the GDP. Climate change is expected to enhance the vulnerability of cotton crop as there is significant shift in seasons and increase in the number of climate extreme events across the world. Climate change scenarios revealed the increase in both maximum and minimum temperature and uncertain rainfall patterns throughout the world and especially in dry and arid areas of the world. Rainfall would increase and decrease as projected by multi-GCMs and RCPs and it is fact that these changes in climate would lead to negative effect on cotton crop production and sustainable cotton production in the future is under threat. Weather plays a crucial role as it determines the initiation and ending period of phenological stages during crop growing cycle. Climate change has a negative impact on cotton production in major parts of the cotton-growing regions. It not only hampers the yield but quality of fiber and has a negative impact on socioeconomic conditions of farmers. Climate, crop, and economic multidisciplinary modeling approach are being used to assess the impact of climate change and adaptation strategy development for sustainable cotton production. Changes in crop management practices (sowing, planting density, irrigation, plant protection) may be good adaptation strategies for sustainable cotton production under changing climate scenarios of the world. Climate resilient cotton production system has potential to cope with the negative impacts on cotton crop by developing heat and drought resilient germplasm, mitigation technology to reduce GHG emission, and application of decision support system and use of ICT-based technologies for sustainable cotton crop production. It is time to adopt climate, energy, and water smart cotton production technologies and practices for sustainable cotton production in the future.

References

Abbas Q, Ahmad S (2018) Effect of different sowing times and cultivars on cotton fiber quality under stable cotton-wheat cropping system in southern Punjab, Pakistan. Pak J Life Soc Sci 16:77–84

Achilea O, Ronen E, Elharrar G (2005) Haifa Nurti-Net–a comprehensive crop Nutrition software, operated over the web. EFITA/WCCA, pp 25–28

AgMIP (2013a) Guide for running AgMIP climate scenario generation tools with R in windows. AgMIP. http://www.agmip.org/wp-content/uploads/2013/10/Guide-forRunning-AgMIP-Climate-Scenario-Generation-with-R-v2.3.pdf

AgMIP (2013b) The coordinated climate-crop modeling project C3MP: an initiative of the agricultural model inter comparison and improvement project. C3MP protocols and procedures. AgMIP. http://research.agmip.org/download/attachments/1998899/C3MP+Protocols+v2.pdf

AgMIP (2014) Guide for regional integrated assessments: handbook of methods and procedures, Version 5.1. AgMIP. http://www.agmip.org/wpcontent/uploads/2013/06/AgMIPRegional%20Research-Team-Handbook-v4.2.pdf

Ahmad S, Raza I (2014) Optimization of management practices to improve cotton fiber quality under irrigated arid environment. J Food Agric Environ 2(2):609–613

Ahmad S, Raza I, Ali H, Shahzad AN, Atiq-ur-Rehman, Sarwar N (2014) Response of cotton crop to exogenous application of glycinebetaine under sufficient and scarce water conditions. Braz J Bot 37(4):407–415

Ahmad A, Ashfaq M, Rasul G, Wajid SA, Khaliq T, Rasul F, Saeed U, Rahman MH, Hussain J, Baig IA, Naqvi SAA, Bokhari SAA, Ahmad S, Naseem W, Hoogenboom G, Valdivia R (2015) Impact of climate change on the rice–wheat cropping system of Pakistan. In: Rosenzweig C, Hillel D (eds) Handbook of climate change and agro ecosystems: the agricultural model inter comparison and improvement project integrated crop and economic assessments, Part 2. Imperial College Press, London

Ahmad S, Abbas Q, Abbas G, Fatima Z, Atique-ur-Rehman, Naz S, Younis H, Khan RJ, Nasim W, Habib ur Rehman M, Ahmad A, Rasul G, Khan MA, Hasanuzzaman M (2017a) Quantification of climate warming and crop management impacts on cotton phenology. Plants 6(1):E7. https://doi.org/10.3390/plants6010007

Ahmad A, Ashfaq M, Rasul G, Wajid SA, Khaliq T, Rasul F, Saeed U, Ahmad I, Nasir J, Baig IA (2017b) AgMIP-Pakistan RRT final report. Agric Model Intercomp Improv Proj. 1–76

Ahmad S, Iqbal M, Muhammad T, Mehmood A, Ahmad S, Hasanuzzaman M (2018) Cotton productivity enhanced through transplanting and early sowing. Acta Sci Biol Sci 40:e34610

Ahmad I, Wajid SA, Ahmad A, Cheema MJM, Judge J (2019) Optimizing irrigation and nitrogen requirements for maize through empirical modeling in semi-arid environment. Environ Sci Pollut Res Int 26(2):1227–1237

Ali H, Afzal MN, Ahmad F, Ahmad S, Akhtar M, Atif R (2011) Effect of sowing dates, plant spacing and nitrogen application on growth and productivity on cotton crop. Int J Sci Eng Res 2 (9):1–6

Ali H, Abid SA, Ahmad S, Sarwar N, Arooj M, Mahmood A, Shahzad AN (2013a) Integrated weed management in cotton cultivated in the alternate-furrow planting system. J Food Agric Environ 11(3&4):1664–1669

Ali H, Abid SA, Ahmad S, Sarwar N, Arooj M, Mahmood A, Shahzad AN (2013b) Impact of integrated weed management on flat-sown cotton (*Gossypium hirsutum* L.). J Anim Plant Sci 23 (4):1185–1192

Ali H, Hameed RA, Ahmad S, Shahzad AN, Sarwar N (2014a) Efficacy of different techniques of nitrogen application on American cotton under semi-arid conditions. J Food Agric Environ 12 (1):157–160

Ali H, Hussain GS, Hussain S, Shahzad AN, Ahmad S, Javeed HMR, Sarwar N (2014b) Early sowing reduces cotton leaf curl virus occurrence and improves cotton productivity. Cer Agron Moldova XLVII(4):71–81

Amin A, Nasim W, Mubeen M, Nadeem M, Ali L, Hammad HM, Sultana SR, Jabran K, Habib ur Rehman M, Ahmad S, Awais M, Rasool A, Fahad S, Saud S, Shah AN, Ihsan Z, Ali S, Bajwa AA, Hakeem KR, Ameen A, Amanullah, Rehman HU, Alghabar F, Jatoi GH, Akram M, Khan A, Islam F, Ata-Ul-Karim ST, Rehmani MIA, Hussain S, Razaq M, Fathi A (2017) Optimizing the phosphorus use in cotton by using CSM-CROPGRO-cotton model for semi-arid climate of Vehari-Punjab, Pakistan. Environ Sci Pollut Res 24(6):5811–5823

Amin A, Nasim W, Mubeen M, Ahmad A, Nadeem M, Urich P, Fahad S, Ahmad S, Wajid A, Tabassum F, Hammad HM, Sultana SR, Anwar S, Baloch SK, Wahid A, Wilkerson CJ, Hoogenboom G (2018) Simulated CSM-CROPGRO-cotton yield under projected future climate by SimCLIM for southern Punjab. Pak Agric Syst 167:213–222

Arora R, Jindal V, Rathore P, Kumar R, Singh V, Bajaj L (2011) Integrated pest management of cotton in Punjab, India. Radcliffe's IPM world Textb., St. Paul University, Minnesota. http://www.ipmworld.umn.edu/chapters/Arora.html

Arshad M, Wajid A, Maqsood M, Hussain K, Aslam M, Ibrahim M (2007) Response of growth, yield and quality of different cotton cultivars to sowing dates. Pak J Agric Sci 44:208–212

Ashraf S, Iftikhar M (2013) Mitigation and adaptation strategies for climate variability: a case of cotton growers in the Punjab, Pakistan. Int J Agric Ext 1(1):30–35

Asseng S, Ewert F, Rosenzweig C, Jones JW, Hatfield JL, Ruane AC, Boote KJ, Thorburn PJ, Rötter RP, Cammarano D, Brisson N, Basso B, Martre P, Aggarwal PK, Angulo C, Bertuzzi P, Biernath C, Challinor AJ, Doltra J, Gayler S, Goldberg R, Grant R, Heng L, Hooker J, Hunt LA, Ingwersen J, Izaurralde RC, Kersebaum KC, Müller C, Kumar NS, Nendel C, O'Leary G, Olesen JE, Osborne TM, Palosuo T, Priesack E, Ripoche D, Semenov MA, Shcherbak I, Steduto P, Stöckle C, Stratonovitch P, Streck T, Supit I, Tao F, Travasso M, Waha K, Wallach D, White JW, Williams JR, Wolf J (2013) Uncertainty insimulating wheat yields under climate change. Nat Clim Chang 3:827–832

Bange MP, Milroy SP (2004) Impact of short term exposure to cold temperatures on early development of cotton (*Gossypium hirsutum* L.). Aust J Agric Res 55:655–664

Bange MP, Caton SJ, Milroy SP (2008) Managing yields of high fruit retention in transgenic cotton (*Gossypium hirsutum* L.) using sowing date. Aust J Agric Res 59:733–741

Batool S, Saeed F (2017) Mapping the cotton value chain in Pakistan: a preliminary assessment for identification of climate vulnerabilities & pathways to adaptation. Sustainable Development Policy Institute, Islamabad, Pakistan, pp 1–60

Bhaskar KS, Rao MRK, Mendhe PN, Suryavanshi MR (2005) Micro irrigation management in cotton. CICR Technical Bulletin No. 31. Cent. Inst. Cott. Res., Nagpur, India

Bradow JM, Davidonis GH (2000) Quantitation of fiber quality and the cotton production-processing interface: a physiologist's perspective. J Cotton Sci 4:34–64

Braunack MV, Bange MP, Johnston DB (2012) Can planting date and cultivar selection improve resource use efficiency of cotton systems? Field Crop Res 137:1–11

Chastain DR, Snider JL, Choinski JS, Collins GD, Perry CD, Whitaker J, Grey TL, Sorensen RB, van Iersel M, Byrd SA, Porter W (2016) Leaf ontogeny strongly influences photosynthetic tolerance to drought and high temperature in Gossypium hirsutum. J Plant Physiol 199:18–28

Collins M, Knutti R, Arblaster J, Dufresne JL, Fichefet T, Friedlingstein P, Gao X, Gutowski WJ, Johns T, Krinner G, Shongwe M, Tebaldi C, Weaver AJ, Wehner M (2013) Long term climate change: projections, commitments and irreversibility. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change. The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp 1029–1036. https://doi.org/10.1017/CBO9781107415324.024

Conaty WC, Burke JJ, Mahan JR, Neilsen JE, Sutton BG (2012) Determining the optimum plant temperature of cotton physiology and yield to improve plant-based irrigation scheduling. Crop Sci 52:1828–1836

Constable GA, Bange MP (2006) What is cotton's sustainable yield potential? Aust Cotton Grower 26:6–10

Cottee NS, Tan DKY, Bange MP, Cothren JT, Campbell LC (2010) Multi-level determination of heat tolerance in cotton (*Gossypium hirsutum* L.) under field conditions. Crop Sci 50:2553–2564

Cotton Incorporated (2009) Summary of life cycle inventory data for cotton (field to bale – version 1.12 July 2009). Cary, NC, Cotton Incorporated, p 31

Dağdelen N, Başal H, Yılmaz E, Gürbüz T, Akcay S (2009) Different drip irrigation regimes affect cotton yield, water use efficiency and fiber quality in western Turkey. Agric Water Manag 96 (1):111–120

FAO (2010) "Climate-smart" agriculture policies, practices and financing for food security, adaptation and mitigation. Food and Agriculture Organization of the United State of America (FAO), Rome, Italy, pp 1–49. http://www.fao.org/docrep/013/i1881e/i1881e00.htm. Accessed 21 Dec 2018

FAO (2013) Climate smart agriculture sourcebook. Food and Agriculture Organization of the United Nations (FAO), Rome. http://www.fao.org/docrep/018/i3325e/i3325e.pdf

FAO (2017) FAOSTAT Pakistan. Food and Agriculture Organization of the United Nations (FAO), Rome. http://www.fao.org/faostat/en

FAO (Food and Agriculture Organisation of the United Nations) (2012) The state of food and agriculture - investing in agriculture for a better future. FAO, Rome, Italy

FAO (Food and Agriculture Organisation of the United Nations) (2016) AQUASTAT website. http://www.fao.org/nr/water/aquastat/main/index.stm

Ghazala N, Rasul G (2009) Water requirement of wheat crop in Pakistan. Pak J Meteorol 6 (11):89–97

Gibbons MM, Fawcett CP, Warings RJ, Dearne K, Dampney P, Richardson SJ (2005) PLANET nutrient management decision support system–a standard approach to fertilizer recommendations. EFITA/WCCA, pp 25–28

GOP (2016) Final crop estimates. 2016, Crop Reporting Service, Governmement of Punjab, Lahore. http://crs.agripunjab.gov.pk

GOP (Government of Punjab) (2018) Cotton under drip irrigation system - a case study. Directorate General Agriculture (Water Managment), Government of Punjab, Lahore. http://ofwm.agripunjab.gov.pk

Grantz DA (2003) Ozone impacts on cotton: towards an integrated mechanism. Environ Pollut 126:331–344

Hillocks RJ (2005) Integrated management of insect pests, diseases and weeds of cotton in Africa. Integr Pest Manag Rev 1:31–47

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

Huang J (2016) Different sowing dates affected cotton yield and yield components. Int J Plant Prod 10:63–84

Imran MA, Ali A, Ashfaq M, Hassan S, Culas R, Ma C (2018) Impact of climate smart agriculture (CSA) practices on cotton production and livelihood of farmers in Punjab. Pak Sustain 10:2101. https://doi.org/10.3390/su10062101

IPCC (2013a) Summary for policymakers. In: Climate change 2013. The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change, p 33. https://doi.org/10.1017/CBO9781107415324

IPCC (2013b) Summary for policymakers. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. IPCC, Cambridge, UK. http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WGIAR5_SPM_brochure_en.pdf

IPCC (2014a) Climate change 2014. Synthesis report summary chapter for policymakers 31. IPCC. https://doi.org/10.1017/CBO9781107415324

IPCC (2014b) Summary for policymakers. In: C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White Editor. Climate change 2014: impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of working group II to the fifth assessment report of the Intergovernmental Panel on Climate Change, 2014, IPCC: Cambridge, UK. 1–32. http://ipcc-wg2.gov/AR5/images/uploads/WG2AR5_SPM_FINAL.pdf

ITC (2011) Trade map. International Trade Centre, Switzerland. http://www.trademap.org/

Jalota SK, Sood A, Chahal GBS, Choudhary BU (2006) Crop water productivity of cotton (*Gossypium hirsutum* L.) – wheat (*Triticum aestivum* L.) system as influenced by deficit irrigation, soil texture and precipitation. Agric Water Manag 84:137–146

Jones JW, Hansen JW, Royce FS, Messina CD (2000) Potential benefits of climate forecasting to agriculture. Agric Ecosyst Environ 82:169–184

Khan MB, Khaliq A, Ahmad S (2004) Performance of mashbean intercropped in cotton planted in different planting patterns. J Res (Sci) 15(2):191–197

Khatri-Chhetri A, Aryal JP, Sapkota TB, Khurana R (2016) Economic benefits of climate-smart agricultural practices to smallholder farmers in the Indo-Gangetic Plains of India. Curr Sci 110:1251–1256

Khatri-Chhetri A, Aggarwal PK, Joshi PK, Vyas S (2017) Farmers' prioritization of climate-smart agriculture (CSA) technologies. Agric Syst 151:184–191

Loi NK, Tangtham N (2005) Decision support system (DSS) for sustainable watershed management in Dong Nai Watershed-Vietnam. In: Synergistic approach to appropriate forestry technology for sustaining rainforest ecosystems: proceedings International Forestry Seminar. Universiti Putra, Malaysia

Luo Q, Bange M, Clancy L (2014) Cotton crop phenology in a new temperature regime. Ecol Model 285:22–29

Luo Q, Bange M, Braunack M, Johnston D (2016) Effectiveness of agronomic practices in dealing with climate change impacts in the Australian cotton industry–a simulation study. Agric Syst 147:1–9

Makhdum AH, Khan HN, Ahmad S (2011) Reducing cotton footprints through implementation of better management practices in cotton production; a step towards better cotton initiative. In: Proceedings of the fifth meeting of the Asian Cotton Research and Development Network, Lahore, Pakistan, 23–26 Feb 2011, pp 1–18. https://www.icac.org/tis/regional_networks/asian_network/meeting_5/. Accessed 4 Jan 2018

Manik SN, Pengilley G, Dean G, Field B, Shabala S, Zhou M (2019) Soil and crop management practices to minimize the impact of waterlogging on crop productivity. Front Plant Sci 10:140. https://doi.org/10.3389/fpls.2019.00140

Manpreet S, Gumber RK, Brar AS, Mukesh S (2007) Performance of drip irrigation systems in cotton in relation to lateral patterns and irrigation levels. In: World Cotton Research Conference-4, Lubbock, Texas, USA, 10–14 Sept 2007. International Cotton Advisory Committee (ICAC)

Mir SA, Quadri SMK (2009) Decision support systems: concepts, progress and issues–a review. In: Lichtfouse E (ed) Climate change, intercropping, pest control and beneficial microorganisms, Sustainable agricultural reviews, vol 2. Springer, Dordrecht, pp 373–399

Muthamilselvan M, Rangasamy K, Ananthakrishnan D, Manian R (2007) Mechanical picking of cotton: a review. Agric Rev 28:118–126

Nazli H, Orden D, Sarker R, Meilke K (2012) Bt cotton adoption and wellbeing of farmers in Pakistan. In: Proceedings of the International Association of Agricultural Economists (IAAE) Triennial Conference, Foz do Iguaçu, Brazil, 18–24 Aug 2012, pp 1–26. ageconsearch.umn.edu/bitstream/126172/

Pasha HA (2015) Growth of the provincial economies. Institute for Policy Reforms (IPR), Pakistan. http://ipr.org.pk/wp-content/uploads/2016/04/GROWTH-OF-PROVINCIAL-ECONOMICS-.pdf

Perumal NK, Hebba KB, Rao MRK, Singh P (2006) Physiological disorders in cotton. Central Institute for Cotton Research, Nagpur, pp 1–25

Pettigrew WT, Johnson JT (2005) Effects of different seeding rates and plant growth regulators on earlyplanted cotton. J Cotton Sci 9:189–198

Petzoldt C, Seaman A (2006) Climate change effects on insects and pathogens. Clim Change Agric: Promoting Practical Profitable Responses 3:6–16

Rahman H, Malik SA, Saleem M (2004) Heat tolerance of upland cotton during the fruiting stage evaluated using cellular membrane thermos stability. Field Crop Res 85:149–158

Rahman MH, Ahmad A, Wajid A, Hussain M, Akhtar J, Hoogenboom G (2016) Estimation of temporal variation resilience in cotton varieties using statistical models. Pak J Agric Sci 53:787–807

Rahman MH, Ahmad A, Wajid A, Hussain M, Rasul F, Ishaque W, Islam MA, Shelia V, Awais M, Ullah A, Wahid A, Sultana SR, Saud S, Khan S, Fahad S, Hussain M, Hussain S, Nasim W (2017) Application of CSMCROPGRO-Cotton model for cultivars and optimum planting dates: evaluation in changing semi-arid climate. Field Crop Res. https://doi.org/10.1016/j.fcr.2017.007

Rahman MH, Ahmad A, Wang X, Wajid A, Nasim W, Hussain M, Ahmad B, Ahmad I, Ali Z, Ishaque W, Awais M, Shelia V, Ahmad S, Fahad S, Alam M, Ullah H, Hoogenboom G (2018) Multi-model projections of future climate and climate change impacts uncertainty assessment for cotton production in Pakistan. Agric For Meteorol 253–254:94–113

Rane J, Nagarajan S (2004) High temperature index—for field evaluation of heat tolerance in wheat varieties. Agric Syst 79(2):243–255

Rasul G, Mahmood A, Sadiq A, Khan SI (2012) Vulnerability of the Indus Delta to climate change in Pakistan. Pak J Meteorol 8(16):89–107

Rasul F, Gull U, Rahman MH, Hussain Q, Chaudhary HJ, Matloob A, Shahzad S, Iqbal S, Shelia V, Masood S, Bajwa HM (2016) Biochar an emerging technology for climate change mitigation. J Environ Agric Sci 9:37–43

Raza A, Ahmad M (2015) Analysing the impact of climate change on cotton productivity in Punjab and Sindh, Pakistan. Pakistan Institute of Development Economics (PIDE), Islamabad, Pakistan, pp 1–32

Reddy KR, Zhao D (2005) Interactive effects of elevated CO_2 and potassium deficiency on photosynthesis, growth, and biomass partitioning of cotton. Field Crop Res 94:201–213

Reddy KR, Doma PR, Mearns LO, Boone MYL, Hodges HF, Richardson AG, Kakani VG (2002) Simulating the impacts of climate change on cotton production in the Mississippi delta. Clim Res 22:271–281

Reddy KR, Koti S, Davidonis GH, Reddy VR (2004) Interactive effects of carbon dioxide and nitrogen nutrition on cotton growth, development, yield, and fiber quality. Agronomy 96:1148–1157

Reddy KC, Malik RK, Reddy SS, Nayakatawa EZ (2007) Cotton growth and yield response to nitrogen applied through fresh and composted poultry litter. J Cotton Sci 11:26–34

Rosenzweig C, Elliott J, Deryng D, Ruane AC, Müller C, Arneth A, Boote KJ, Folberth C, Glotter M, Khabarov N, Neumann K, Piontek F, Pugh TAM, Schmid E, Stehfest E, Yang H, Jones JW (2014) Assessing agricultural risks of climate change in the 21st century in a global gridded crop model inter comparison. Proc Natl Acad Sci U S A 111:3268–3273

Ruane AC, Cecil LD, Horton RM, Gordón R, McCollum R, Brown D, Killough B, Goldberg R, Greeley AP, Rosenzweig C (2013) Climate change impact uncertainties for maize in Panama: farm information, climate projections, and yield sensitivities. Agric For Meteorol 170:132–145

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

Ruane AC, Winter JM, McDermid SP, Hudson NI (2015b) AgMIP climate datasets and scenarios for integrated assessment. In: Rosenzweig C, Hillel D (eds) Handbook of climate change and agroecosystems: the agricultural model inter comparison and improvement project (AgMIP) integrated crop and economic assessments, Part 1, ICP series on climate change impacts, adaptation, and mitigation, vol 3. Imperial College Press, London, pp 45–78

Sala S (2009) Information and communication technologies for climate change adaptation, with a focus on the agricultural sector. In: Thinkpiece for CGIAR science forum workshop on "ICTs transforming agricultural science, research and technology generation" Wageningen, Netherlands, pp 16–17

Singh RP, Vara Prasad PV, Sunita K, Giri SN, Reddy KR (2007) Influence of high temperature and breeding for heat tolerance in cotton: a review. Adv Agron 93:313–385

Tariq M, Yasmeen A, Ahmad S, Hussain N, Afzal MN, Hasanuzzaman M (2017) Shedding of fruiting structures in cotton: factors, compensation and prevention. Trop Subtrop Agroecosyst 20(2):251–262

Tariq M, Afzal MN, Muhammad D, Ahmad S, Shahzad AN, Kiran A, Wakeel A (2018) Relationship of tissue potassium content with yield and fiber quality components of Bt cotton as influenced by potassium application methods. Field Crop Res 229:37–43

Turner NC (1979) Drought resistance and adaptation to water deficits in crop plants. In: Mussell H, Staples RC (eds) Stress physiology in crop plants. Wiley, New York, pp 343–372

USDA (United States Department of Agriculture) (2018) Pakistan sugar annual report. Global Agricultural Information Network. https://gain.fas.usda.gov

Usman M, Ahmad A, Ahmad S, Irshad M, Khaliq T, Wajid A, Hussain K, Nasim W, Chattha TM, Trethowan R, Hoogenboom G (2009) Development and application of crop water stress index for scheduling irrigation in cotton (*Gossypium hirsutum* L.) under semiarid environment. J Food Agric Environ 7(3&4):386–391

Van Vuuren DP, Edmonds J, Kainuma M et al (2011) The representative concentration pathways: an overview. Clim Chang 109:5. https://doi.org/10.1007/s10584-011-0148-z

Vara Prasad PV, Allen LH, Boote KJ (2005) Crop responses to elevated carbon dioxide and interactions with temperature. J Crop Improv 13:113–155

Wajid A, Ahmad A, Hussain M, Rahman MH, Khaliq T, Mubeen M, Rasul F, Bashir U, Awais M, Iqbal J, Sultana SR, Hoogenboom G (2014) Modeling growth, development and seed-cotton yield for varying nitrogen increments and planting dates using DSSAT. Pak J Agric Sci 51:639–647

Walker P, White DH (2001) INSIGHT: a framework for determining impacts of changes in land and water policies. Environ Int 27:127–132

Wang S, Li X, Lu J, Hong J, Chen G, Xue X, Li J, Wei Y, Zou J, Liu G (2013) Effects of controlled-release urea application on the growth, yield and nitrogen recovery efficiency of cotton. Agric Sci 4:33–38

Watto MA, Mugera AW (2015) Econometric estimation of groundwater irrigation efficiency of cotton cultivation farms in Pakistan. J Hydrol Reg Stud 4:193–211

Williams A, White N, Mushtaq S, Cockfield G, Power B, Kouadio L (2015) Quantifying the response of cotton production in Eastern Australia to climate change. Clim Chang 129:183–196

Woodfin CA, Rosenow DT, Clark LE, Johnson JW (1979) Differential response of sorghum cultivars to drought stress. Am Soc Agron Abstr, p 82

Wrather JA, Phipps BJ, Stevens WE, Phillips AS, Vories ED (2008) Cotton planting date and plant population effects on yield and fiber quality in the Mississippi Delta. J Cotton Sci 12:1–7

Zhu T, Ringler C, Iqbal MM, Sulser TB, Goheer MA (2013) Climate change impacts and adaptation options for water and food in Pakistan: scenario analysis using an integrated global water and food projections model. Water Int 38:651–669

Zulfiqar F, Datta A, Thapa GB (2017) Determinants and resource use efficiency of "better cotton": an innovative cleaner production alternative. J Clean Prod 166:1372–1380