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# Impact of Climate Warming on Cotton Growth and Yields in China and Pakistan: A Regional Perspective

Adnan Arshad [1], Muhammad Ali Raza [2], Yue Zhang [1], Lizhen Zhang [1,*], Xuejiao Wang [3], Mukhtar Ahmed [4,5] and Muhammad Habib-ur-Rehman [6,7,8]

1 College of Resources and Environmental Sciences, China Agricultural University, Yuanmingyuan West Rd. No.2, Haidian District, Beijing 100193, China; ad@cau.edu.cn (A.A.); zhangyue93@cau.edu.cn (Y.Z.)
2 College of Agronomy, Sichuan Agricultural University, Chengdu 625014, China; L201601001@stu.sicau.edu.cn
3 Xinjiang Agro-meteorological Observatory, Urumqi 830002, China; Xue.Jiao.WANG@outlook.com
4 Department of Agricultural Research for Northern Sweden, Swedish University of Agricultural Sciences, P.O. Box 7070, SE-750 07 Uppsala, Sweden; mukhtar.ahmed@slu.se
5 Department of Agronomy, Pir Mehr Ali Shah, Arid Agriculture University, Rawalpindi 46000, Pakistan
6 Institute of Crop Science and Resource Conservation (INRES) University Bonn, 53115 Bonn, Germany; mhabibur@uni-bonn.de
7 Department of Agronomy, Muhammad Nawaz Shareef Agriculture University, Multan 60800, Pakistan
8 AgWeatherNet Program, Washington State University, Prosser, Washington, DC 99350, USA
* Correspondence: zhanglizhen@cau.edu.cn

**Abstract:** Year to year change in weather poses serious threats to agriculture globally, especially in developing countries. Global climate models simulate an increase in global temperature between 2.9 to 5.5 °C till 2060, and crop production is highly vulnerable to climate warming trends. Extreme temperature causes a significant reduction in crop yields by negatively regulating the crop phenology. Therefore, to evaluate warming impact on cotton (*Gossypium hirsutum* L.) production and management practices, we quantified agrometeorological data of 30 years by applying multiple crop modelling tools to compute the expected rise in temperature, impact of crop phenology, yield loss, provision of agrometeorology-services, agronomic technologies, and adaptation to climate-smart agriculture. Model projections of 15 agrometeorology stations showed that the growing duration of the sowing-boll opening and sowing-harvesting stages was reduced by 2.30 to 5.66 days decade$^{-1}$ and 4.23 days decade$^{-1}$, respectively, in Pakistan. Temperature rise in China also advanced the planting dates, sowing emergence, 3–5 leaves, budding anthesis, full-bloom, cleft-boll, boll-opening, and boll-opening filling by 24.4, 26.2, 24.8, 23.3, 22.6, 15.8, 14.6, 5.4, 2.9, and 8.0 days. Furthermore, present findings exhibited that the warming effect of sowing-harvest time was observed 2.16 days premature, and delayed for 8.2, 2.4, and 5.3 days in the 1970s, 1980s, and 1990s in China. APSIM-cotton quantification revealed that the sowing, emergence, flowering, and maturity stages were negatively correlated with temperature −2.03, −1.93, −1.09, and −0.42 days °C$^{-1}$ on average, respectively. This study also provided insight into the adaptation of smart and better cotton by improving agrotechnological services.

**Keywords:** agrometeorology; temperature increase; cotton phenology; climate-smart management; APSIM-cotton crop modelling



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## 1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) special report (SR) on stay below 1.5 °C mentioned that there is exceptionally high confidence in biological reactions to present climatic change, particularly rising temperature, based on further evidence from a wider series of species [1]. Crop production is extremely contingent on the regional climate and ecological environment. Consequently, the variations in the global environment could have critical effects on crop growth, development, phenology, and yields [2,3]. The increases in temperature and shift in the rainfall cycle affect cotton growth development [4] and threaten the permanence of cotton production and quality in Pakistan and China (Pak-China). Wide-reaching climate heating makes cotton vulnerable due to a rise in temperature, prolonged drought stresses, and erratic patterns of rainfall [5,6].

Extreme weather events (EWEs) are causing 50% of yield reductions in agronomic crops globally [7]. China's average air temperature from 1951–2001 has increased by 1.1 °C, respectively [8]. Thus, research of the spatiotemporal alteration in crop phenology, and the interaction between climate change and phenology, are essential to understand the mechanisms and managements underlying crop behavior and adaptation to meteorological warming and ongoing stressors. Ref. [9] reported that the average surface temperature has increased at the rate of 0.25 °C decade$^{-1}$ over the region's previous 50 years. In Pakistan, the decade of the 2000s was the warmest period as measured up with previous decades, and 2014 to 2016 were the hottest years compared with earlier periods. Similarly, in Punjab province, a warming trend has been signified during the past three decades, but predominantly in 2000–2016 [10]. Research findings indicated that the production of major crops in Pakistan could be significantly impacted due to a rise in temperature in the country by 0.5–0.9 °C transversely in the past thirty years [11,12]. The future climatic model projections indicate that evident variations in the frequency and intensity of the mean increase in heat will be higher than 1.4–3.7 °C, the expected global average [13].

In the statistics issued by the World Cotton Production (WCP) of 2017–2018, India is the top country with 6.21 million metric tons, followed by China (5.99 million metric tons), and Pakistan is ranked at 5th with 1.79 million metric tons production [4,14]. Cotton is one of the most important profitable crops for Pakistan and China. The total cotton production acreage in China amounts to around 3.2 million hectares, and 2.8 million hectares have been reported in Pakistan [15,16]. The textile industry is the major economic sector, involving more than 10 million workers in China [17]. Globally, a 9% cotton production decline has been documented [18]; cotton producing countries such as China, the U.S.A., and Pakistan have faced 17%, 19%, and 5% of the decline in production during the past years since 2015, respectively. Over this outlook, better cotton production is indispensable to gather increasing future demands.

Cotton is the second major crop in terms of area-cover after wheat [3,15], contributing 6.5% to agricultural value. Agriculture in Pakistan is the second largest sector, contributing 19.5% to gross domestic product (GDP). The agricultural sector in Pakistan is highly susceptible to climate change and highly vulnerable to escalating weather unpredictability in the cotton-growing belts [19]. Pakistani rivers and storage dams face severe water shortages [3], which may cause delays in land preparation and late cotton sowing, which decreases the number of bolls plant$^{-1}$, fiber quality, dry matter [20,21], cottonseed yield and the physiological maturity of plants. Future climate projections have suggested that the production of the major crops in Pakistan could be drastically affected due to erratic rainfalls, a rise in temperature by 0.5 degrees across the country during the past three decades, and considerable deviation in frequency and intensity of floods, heatwaves, and droughts over the episodes of 1995 to 2017 [22,23]. Changing climate has affected the cotton production in Pakistan [24,25] and unproductive cotton production management techniques [4,26]. Due to the indeterminate growth pattern, cotton crop stands with a composite set of fruits, which are considered extremely vulnerable to extreme weather shifts and a differential response with management techniques [27,28]. Depending upon the developmental stages and severity, the cotton plant responds differently.

The Xinjiang (XUAR) is in the northwest of China and famous for its high-quality cotton. The area has short and hot summers, a cold desert winter, arid conditions, and low night temperatures in spring and autumn, and [21] characterized shallow rainfall average ranges of 37.1 mm year$^{-1}$ in the last thirty years. Due to the short-term growing season and frost's occurrence at night, the province is highly appropriate for early and mid-early maturity varieties. All cotton in Xinjiang province is irrigated [29,30], and Xinjiang is one of the essential producing vicinities of upland and sea-island cotton in the world. Along with ideal cultivation technology and management systems, including "dwarf, dense, early", core technology includes supporting practices such as a range of appropriate cultivars, film mulching, and the drip irrigation method. Furthermore, intercropping of crops improves the utilization of available resources, such as land, sunlight, water, and nutrients [31–33]. Consequently, it confirms the sustainable cultivation goals of high quality and constant yield of cotton in China.

Numerous studies found that the regional climate is also changing and accumulating climate disaster risks to agrometeorology in this cotton region [5]. Cotton production has already declined in Pakistan and is expected to decline in countries such as China, India, and Uzbekistan [5,17,23]. According to the numbers published by the Pakistan Cotton Ginners Association (PCGA), cotton output lessened to only 5.951 million bales in Punjab from 10.7 million bales harvested in 2017, which counts as a 33.9% overall decline in cotton production. Xinjiang produced 74.4% of China's cotton in 2017 [23], and both regions have similarities in sowing windows, agronomic management practices, surface irrigation, and plant and sowing density [20,30]. Meanwhile, in Xinjiang, the plantation is smart and highly mechanized. The escalating temperature in cotton areas increases evapotranspiration rates, sometimes causing severe water stress [21,29] and fruit abscission, thus reducing plant growth and yield. The influence of elevated variations in the rain from mean values negatively resulted in the productivity of cotton.

Extreme temperature during plant flowering and boll development stages in Xinjiang and Punjab is causing severe boll abortion in recent years [24,34]. Both regions' higher temperatures also made the crop plants more vulnerable to pest attacks and viral diseases. The high temperature limited the natural response of self-defense, causing loss of vegetative and fruiting parts [35]. Xinjiang and Punjab are also famous worldwide for their good quality long preference fiber and are well-known for cotton textile products [4,20]. The cotton fruit quality in both regions is specifically dependent on experience to local weather conditions during development stages.

Further, the fiber quality anticipates the relationship between the plant's fruit positioning architecture, air temperature, and agronomic practices, respectively [9,36,37]. This study aimed to (1) quantify spatiotemporal changes in cotton phenology to climate change conditions in Xinjiang cotton zone, (2) observe the relations between climate change and the lengths of different cotton-growing periods and impact of crop yield, (3) identify significances in phenological differences and their implications for cotton production and adaptation to climate change in cotton zones. This research could provide the best climate-smart practices to cope with warming.

## 2. Materials and Methods

### 2.1. Study Area

The study is carried out in two cotton-producing provinces of China (Xinjiang) and Pakistan (Punjab), as presented in Figure 1. The Xinjiang cotton production area is located at latitude 36°0′–46°2′, belonging to mid-latitude regions, dry climate and infrequent rainfall, followed by the inland arid irrigation system. The yearly and average rains throughout the growing season of cotton crop are almost 34.5 mm and 30.7 mm, respectively. Huge fluctuations in temperature occur between day and night temperatures. The zone is also categorized by hot winters and cold summers, enough sunshine hours, drought, and ample heat and light availability. These environmental conditions are predominantly beneficial to cotton growth. The cotton belt in Punjab is completely irrigated and extends from latitude 31.1704° N to 72.7097° E longitude, and it has extreme weather conditions with foggy winters and erratic precipitation. The study area practices important daytime fluctuations, where mean daily air temperature ranges from 25 °C to 46.5 °C in summer and 4.5 °C to 24 °C during the winter spells, respectively. Maximum precipitation befalls during July–August (Monsoon season). Still, it is extremely variable. Long-term daily climate data of $T_{min}$ (minimum), $T_{max}$ (maximum) and mean air temperatures, rainfall, humidity, wind speed and solar radiation were attained from field stations of the Pakistan Meteorological

Department (PMD). After downscaling for future climate scenarios, the data of global climate models (GCMs) were further used in grouping with global and regional climate modelling (RCPs). The details related to the cotton varieties sown in both regions (Table 1) were requested from the Chinese Academy of Agricultural Sciences, Beijing, China, and the Pakistan Agriculture Research Center, Islamabad, Pakistan. Cotton sowing starts from April in Punjab because of the temporary water shortage at one of Pakistan's key reservoirs, which delays crop sowing [38].

### 2.2. Climate and Phenology Data

The historical climate data (1980–2018), soil profile, and crop phenology stages data were collected from Shihezi-51358 agrometeorological stations in Xinjiang and agrometeorological stations operated by the China Meteorology Administration (http://data.cma.cn/). The historical data of climate (1961–2015) and cotton phenology stages of fifteen agrometeorological sites in Punjab were collected from local meteorology departments and the Pakistan Meteorology Department. The study has also quantified the secondary dataset as a regional modelling comparison to formulate future decision support tools with the help of the RCP and GCM models.

**Table 1.** Comparison list of progressive, heat-tolerant, medium to short-duration, film mulching, local and international, cotton varieties of China (South and North Xinjiang), and Pakistan (Central and South Punjab) in cotton planting region.

| Country | Location | Genotype Origin | Varieties |
|---|---|---|---|
| Pakistan | South Punjab (cotton planting region) | a | MNH-786a, CIM-448a |
| | | b | FDH-170b, FH-628b, FDH-170b |
| | | c | CIM-496c, Neelam-121c, CIM-465c |
| | | d | CRSM-38d, NIBGE-2d |
| | | e | NIBGE-1e, NIAB-846e |
| | | g | IR-1524, VH-305, NIAB-78, B-821, NIAB-26, FH-113, AGC 999, CIM 109, TS-103, CYTO-177, FH-87, FH-657, MNH-516, IR 3701, B 820, BH 118, AA 703, AC 134, MM 58, B 803, FVH 49, 149-F, S 12, FH 629, MVH 518, VS-13, Tarzan-1, FH-113, TSR-2375, NIAB 846, FH Lalazar, CIM 240, CIM 1100, |
| | Central Punjab | a | CIM-506a, CIM-499a, BH-100a, CIM-482a, MNH-786a |
| | | b | FDH-228b, Sitara-008, NIBGE-901 |
| | | c | CIM-534c, NIAB-111c |
| | | d | NIAB-846d, NIAB-777d, CIM-473d |
| | | e | NIAB-2008e, FH-901e, CIM-446e, CIM-554e, BH-160e |
| | | g | AGC 777, NIBGE 6, FS 631, CIM 240, MG-6, CIM 707, Sitara 12, S 12, MNH 554, FVH 57, CYTO 124, BH 3297, B 803, MNH 552, IR 1524, MS 240, IR 1274, MNH 998, FH 901, CIM 110, CIM 435, CIM 602, CIM 600, FH 142, TCD 3, MNH 93, VH 259, CIM 109, Sitara 005, SLH 8, FH 685, NS 141 |
| China | Southern Xinjiang | f | Xinhai-21, Xinluzhong-36, Xinluzhong-37, Xinluzhong-42, Xinluzhong-47 and Xinluzhong-54, |
| | | b | Xinhai-24, Xinhai-35 and Xinhai-36 |
| | | f | Xinluzao-36, Xinluzao-37, Xinluzao-41, Xinluzao-48, |
| | Northern Xinjiang | b | Xinluzao-50 and Xinluzao-57 |
| | | f | Xinluzao-37 |

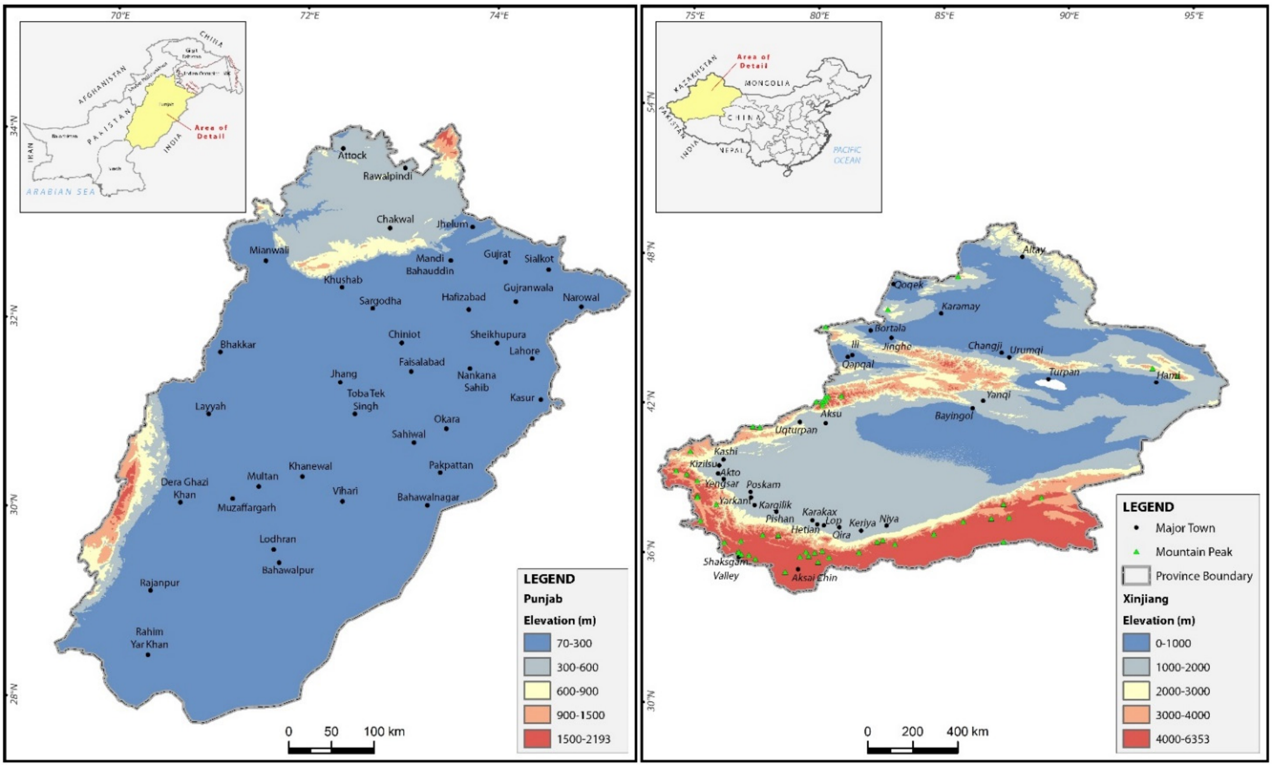



**Figure 1.** Location map of the study areas of Xinjiang province in China, and Punjab province in Pakistan on the basis of topographic elevation.

### *2.3. Model Selection for Cotton Growth-Yield*

Variations in inter-annual crop growth are primarily determined by ecological factors, such as location and climate, and non-environmental factors, i.e., pesticides, varieties, fertilizers, field management practices, etc. Furthermore, values of correlation coefficient directed which environmental variables were substantial for cotton growth at a certain level of significance. The finest regression function between climate variables ($P_{re}$—precipitation, $S_{un}$—sunshine hour, $H_{um}$—average air relative humidity, $T_{max}$—maximum temperature, $T_{min}$—minimum temperature, and $T_{ave}$—average temperature) and cotton growth indicators ($P_h$—plant height at flowering stage, $S_{cy}$—seed cotton yield, $C_{sw}$—cotton stalk weight, and $L_p$—lint percentage) was then selected through the process. The predictive ability and stability of the models were evaluated. The models' projecting performance was assessed by the root mean square error (RMSE); the lesser the RMSE, the better the model simulation performance.

### *2.4. Modelling Simulations and Future Scenarios*

The performance of multiple crop models was examined to quantify the gaps between extreme weather uncertainties and climate-smart farming. Process-based crop simulation models such as CSM-CROPGRO, DSSAT, APSIM, and FSPM were evaluated under the projected regional climatic condition and future production scenarios. APSIM (The Agricultural Production Systems sIMulator) was calibrated and validated with observational field data of historical cotton yield in Pakistan and China. The APSIM model application simulated that fruit growth of cotton occurs after the fractional cover of green leaves has reached up to 60% of full leaf cover. The phenology scaler (phen = 0.6) follows the description of the canopy and fruit development of cotton plants.

$$C_{fruit} = {}_{max}(0, NPP) \varkappa \text{ H R}$$

where HR is the harvest percentage (%) and NPP is the diurnal net primary productivity (kg yield$^{-1}$) of the cotton plant. On days with negative net primary productivity, fruit growth is stopped, but the accumulated yield is not declined because it is reflecting that boll development dominates plant growth at this stage of reproductive growth. The projection was analyzed to estimate the change in cotton cultivated area and shift in yield to observe the impact of future climatic warming on the cotton production dataset of USDA and GCMs.

### *2.5. APSIM-Cotton Simulations, Calibration and Validation*

Climate data (1980–2018) were quantified with the support of the APSIM-cotton model to analyze the effects of changing climatic conditions on the growth and yield of the cotton. Additionally, to differentiate the effect of rainfall and temperature, we applied the model tool for two types of environment scenarios: (a) Tem_Run, (b) Pre_Run, for experimental temperature data (1980–2018) and a fixed temperature and rainfall (1980) for observed temperature and rainfall (1980–2018). The 1980 year was just selected as a situation reference because it had favourable temperature and precipitation, and it was the earliest year of available data series. APSIM-cotton was further run with yield and climate observatories' observational field data, and then for five different sowing dates (2018–2019) to quantify the decline in total yield. The APSIM-cotton model was calibrated using the observed field data from the experiments (No. # 1 and 2) during the years 2018 and 2019 under contrasting weather conditions. Root mean square error (RMSE) was calculated from simulated (Si) and observed (Oi) values. Observed and simulated phenological stages were further evaluated by applying three statistical indicators.

### *2.6. Statistical Analysis*

The dataset of cotton phenology trends means temperature, duration of growing season length, and rainfall were calculated using MS Office 2016 (Redmond, WA, USA) software. Statistical trends significance was analyzed by applying ANOVA and *t*-test, followed by the Duncan's Multiple Range test (DMRT) post hoc test ($p < 0.05$; I.B.M., SPSS Statistics). The visual distribution of climate and crop phenology data was generated with the help of R–3.6. The results of the spatial distribution of the simulated and projected trends in cotton growth and yield and climate variables were plotted site-specifically using ArcMap 10.2 and Sigma Plot (version 14) software.

## 3. Results

### *3.1. Temporal Variations and Cotton Growth-Yield*

The temporal variations in the climate variables ($P_{re}$—precipitation, $S_{un}$—sunshine hour, $H_{um}$—average air relative humidity, $T_{max}$—maximum temperature, $T_{min}$—minimum temperature, and $T_{ave}$—average temperature) during the cotton growing seasons at the sites in Xinjiang, China are demonstrated as box plots in Figures 2 and 3 $P_{re}$—precipitation, $S_{un}$—sunshine hour, $H_{um}$—average air relative humidity, $T_{max}$—maximum temperature, $T_{min}$—minimum temperature, and $T_{ave}$—average temperature fluctuated within ranges of 2–315 mm, 1212–2371 h, 27–66%, 23.5–34.5 °C, 11–22 °C, 18–27 °C and 16–28 °C, respectively. $P_{re}$, $S_{un}$ and $H_{um}$ varied across the different sites of Xinjiang and in different years. The differences and ranges in the climatic variables reflected the general climate conditions in Xinjiang. There was inter-annual variation in crop growth indices at all the sites from Xinjiang during 1980–2018. The figure specifies the variability in cotton phenology (sowing-time, sowing-emergence, flowering, boll-opening and harvest-time) status in Xinjiang during the 38 years (Figures 4 and 5). The variability in cotton growth and phenology indicates the significant impact of climate warming in recent decades. Additionally, $P_h$, $S_{cy}$, and $L_p$ retorted considerably to fluctuations in $P_{re}$, but presented uncertainties in response to the shift in $S_{un}$ and $H_{um}$ at different locations.

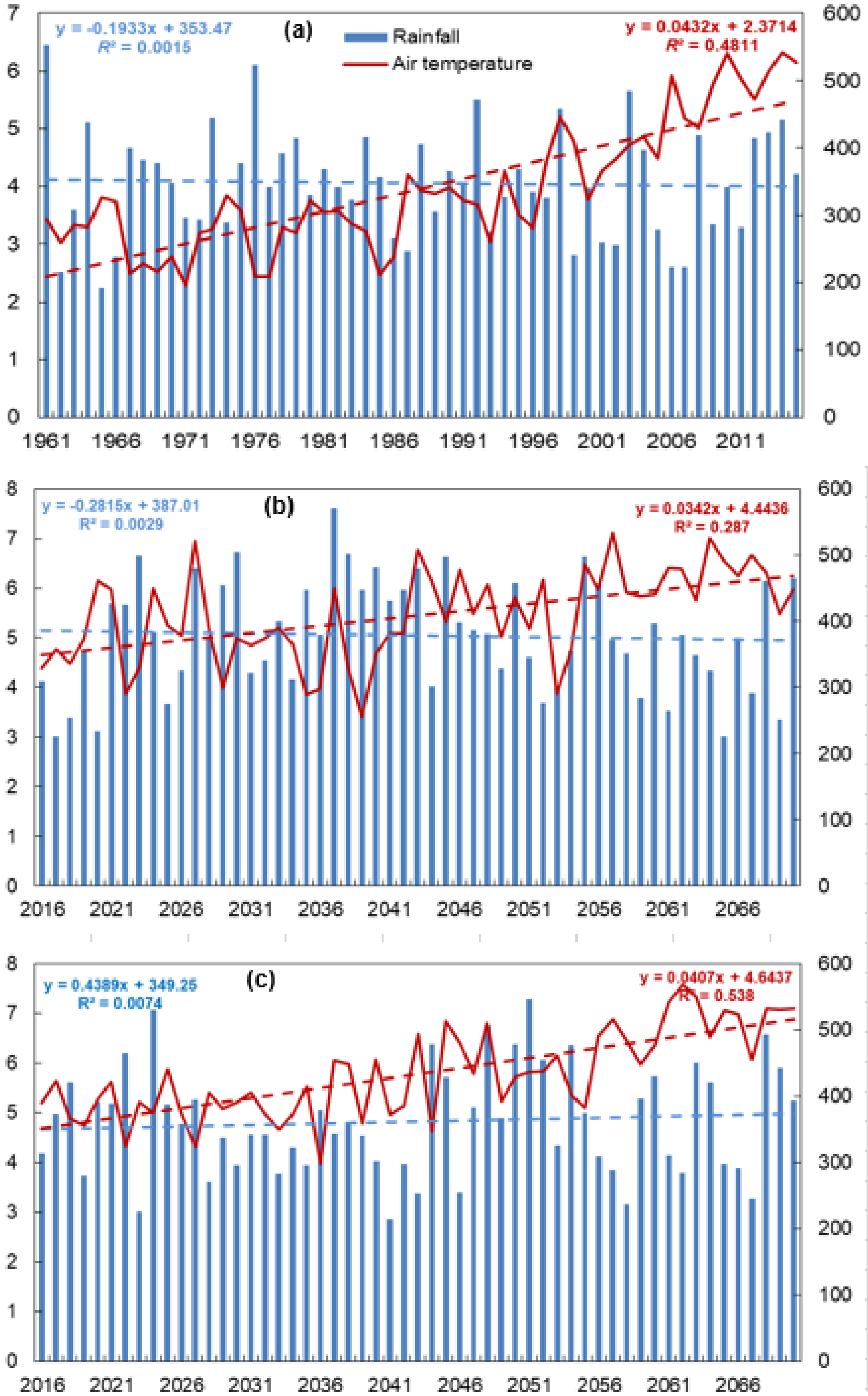



**Figure 2.** Quantification of climate warming trends (**a**) during the observed years, and two future scenarios: (**b**) RCP4.5, and (**c**) RCP8.5 for annual mean daily air temperature and annual rainfall in Punjab, values of $R^2$ in red indicate significance at $p < 0.01$. Intercepts represent the value during the first year of the time series, i.e., in figure (**a**) x = 1961 and in (**b**) x = 2016, and (**c**) x = 2016. The yearly variation is represented in the slopes (where $p = 0.43$).

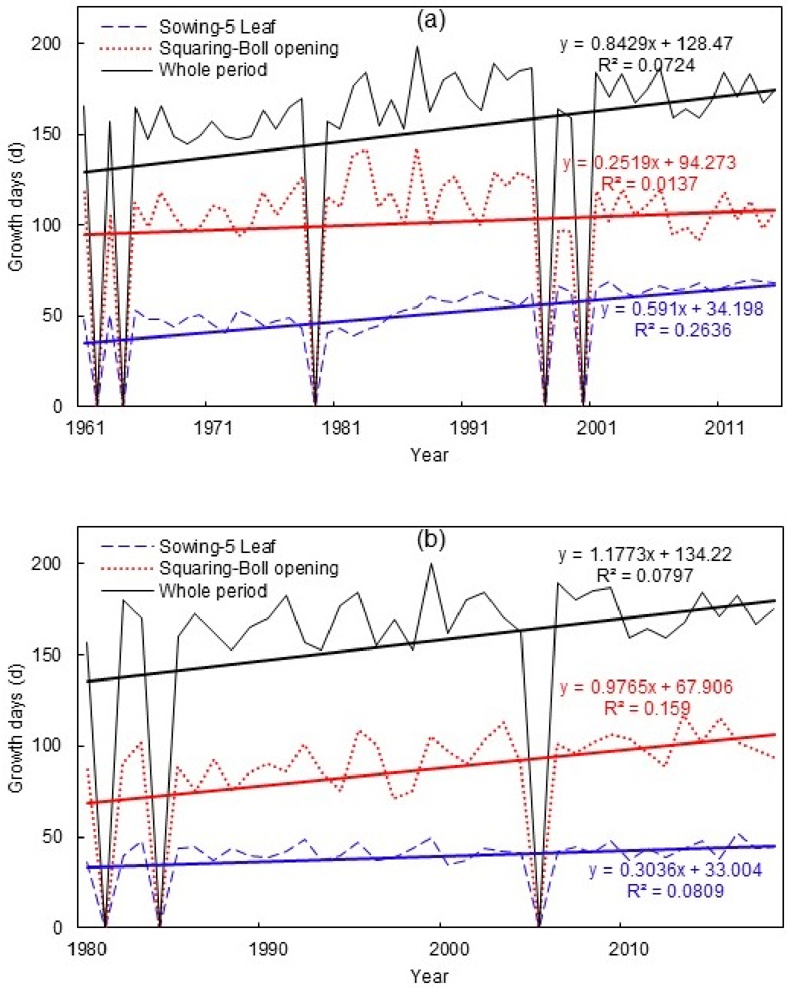



**Figure 3.** Simulated rends of (**a**) three simulated phenological growth stages of cotton from 1961–2015 in Punjab. Intercept values mentioned in the figure apply to the time of (growth days) sowing-five leaf stage, squaring to boll opening, and stop maturity in the starting year 1961. The variable x in the regression equations is calculated as x = year − 1961 (where $p$ = 0.52); (**b**) three simulated phenological growth stages of cotton from 1980–2018 in Xinjiang. Intercept values mentioned in the figure apply to the time of (growth days) sowing-five leaf stage, squaring to boll opening, and stop maturity in the starting year 1981. The variable x in the regression equations is calculated as x = year − 1981 (where $p$ = 0.18).

Temporal variation of the climatic variables across the different sites of Punjab, Pakistan during the cotton growing season (1961–2015) (Figure 3), $P_{re}$—precipitation, $S_{un}$—sunshine hour, $H_{um}$—average air relative humidity, $T_{max}$—maximum temperature, $T_{min}$—minimum temperature, and $T_{ave}$—average temperature, fluctuated within ranges of 35 to 439 mm, 1649–3013 h, 31–75%, 26.3–36.5 °C, 28–38 °C, 18–28 °C and 20–30 °C, respectively. The temperature increases in Punjab, Pakistan during the month of May–July (2015) was reported beyond 40 °C, and caused severe damage to cotton crops in the year 2014–2015 (1763 kg $ha^{-1}$), as compared to the previous years (2013 (2410 kg $ha^{-1}$), 2012 (2337 kg $ha^{-1}$)). Analysis of historical data of agrometeorological stations showed very clearly that, throughout the dynamic growth period of 186 days (May–October), 109 days were reported as the maximum number of (days) that remained hot. However, compared to the temperature conditions in 2012, the number of hot days was 66, in 2013 (64) and 2014 (56). Though optimal temperature fluctuated between 32 and 38 °C through all the previous five years, that may not be considered in linking with the decrease in cotton yield.

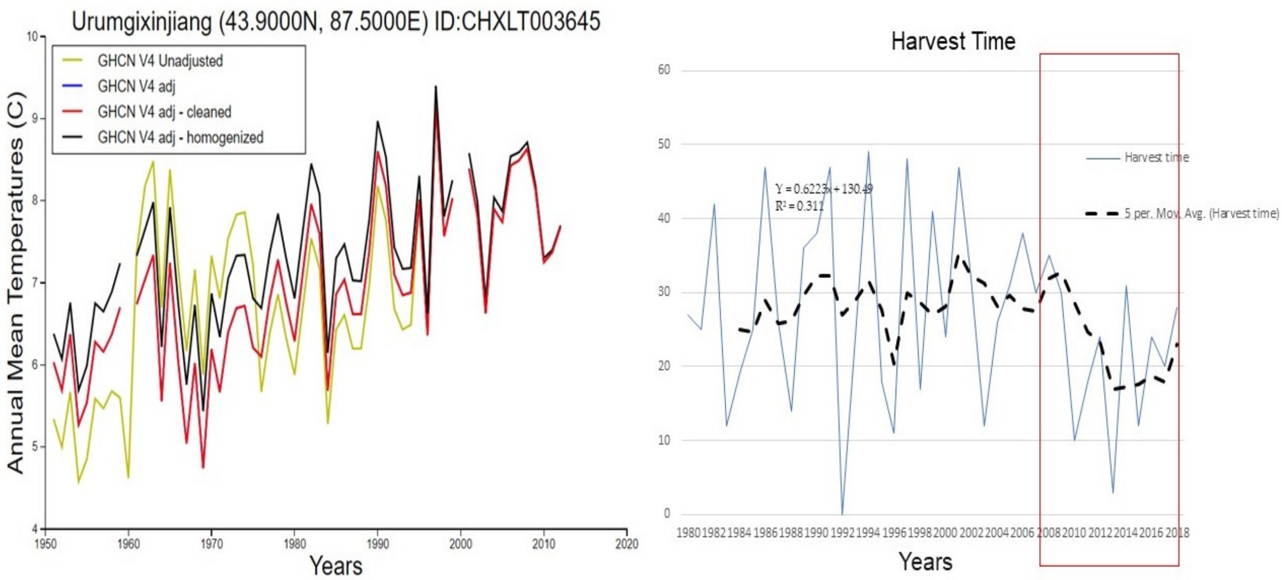



**Figure 4.** CHCN simulation of observed data of annual mean temperature (°C) effect on variation in the length of cotton harvesting time in Xinjiang during 1980–2018 ($p$ = 0.39).

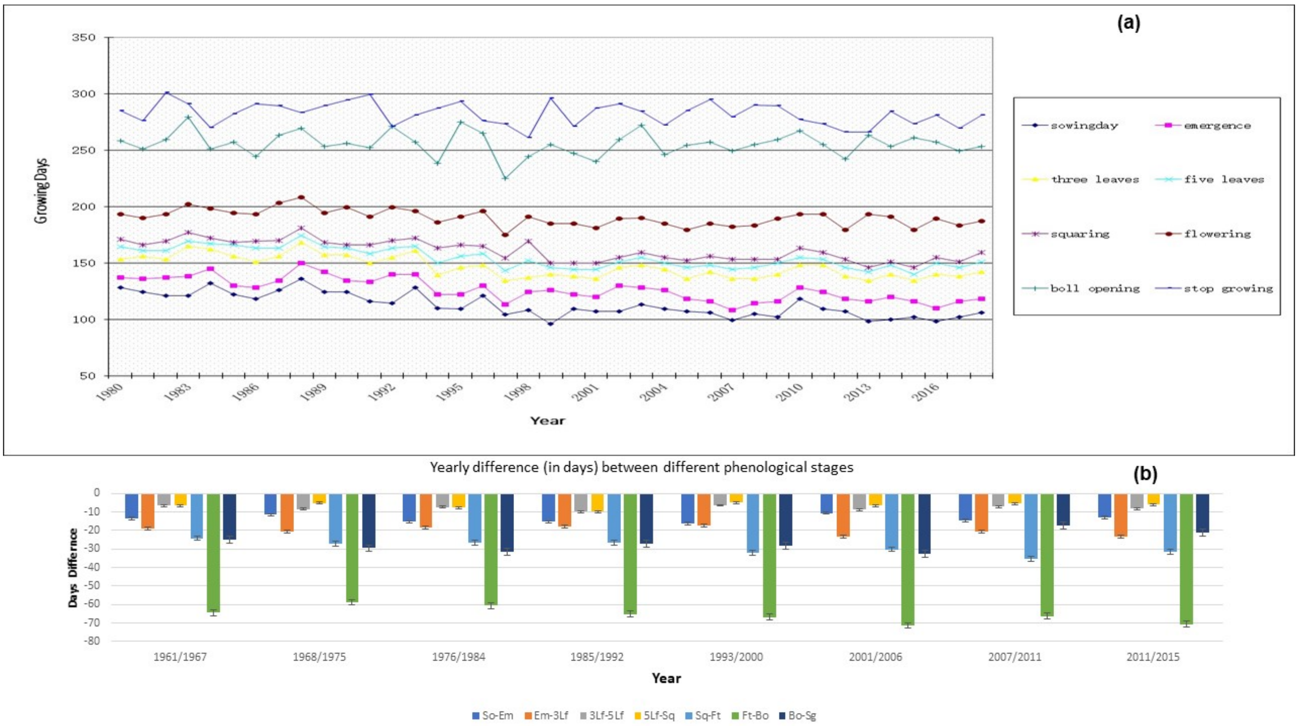



**Figure 5.** Trends observed in experimental changes in phenological stages of cotton sown (**a**) in Xinjiang during 1980–2018, and (**b**) in Punjab during 1961–2015 time period ($p$ = 0.05).

### *3.2. Limiting Meteorological Factors for Cotton Growth, Development and Yields*

Phenological growth events of emergence, 3–5 leaves, flowering, boll opening and maturity simulated by APSIM-cotton showed good results, with the observations both in calibrations and validations (Figure 3). The warming trend since 1981 shortened the simulated duration of vegetative growth by 1.7 ± 2.1 days decade$^{-1}$. The growing season was reduced by 2.8 ± 3.9 days decade$^{-1}$ (Figure 3), whereas reduction in the crop duration was observed at 81.2%, 82.4%, and 84.1% at the studied stations, resulting in 3.2, 6.0- and 3.5-days decade$^{-1}$ on average from the years 1980 to 2018. The FSPM model results revealed (Figure 5) that climate warming conditions during the period of 1980–2018 had advanced the planting times, sowing to emergence, three-leaf stages, five leaves, budding, anthesis, full blooming, cleft-boll, boll opening, boll opening to boll filling and physical maturity earlier by 24.43, 26.18, 24.76, 23.29, 22.62, 15.65, 14.68, 5.47, 2.95, 8.14, and 2.26 days.

Air temperature projection of Punjab from 1961–2015 showed rising tendency ranging from 0.52 to 0.86 °C, 0.72 to 1.05 °C and 0.56 to 0.99 °C decade$^{-1}$ through the phenological stages, which included sowing-anthesis, sowing to maturity and anthesis to maturity (Figure 3). The agrometeorological data projections of (1961–2015) from the experimental station showed (Figure 4) that the cotton duration after sowing to physiological maturity was shirked up to 2.30 to 5.66 days decade$^{-1}$ because of early sowing and then physiological maturity, and average phenological stages were compacted by 4.23 days decade$^{-1}$ between sowing-maturity. While in the Punjab region, the decrease in duration of the growing season from 1961 to 2015 meant that cotton harvest reduced by 363.1 ± 428.6 kg ha$^{-1}$ per decade (Figure 3). The yield decline in response to past climate change was quantified up to 18.2% decade$^{-1}$. Consequently, the declining yield result is due to mutual fluctuations in the pattern of rain and temperature, but the increasing temperature is much bigger than the effect of shift and precipitation pattern. Although running the model for the temperature rise simulation was amounted in 1997–2015, the rise in air temperature consequently decreased cotton yields by 473.5 ± 518.2 kg ha$^{-1}$.

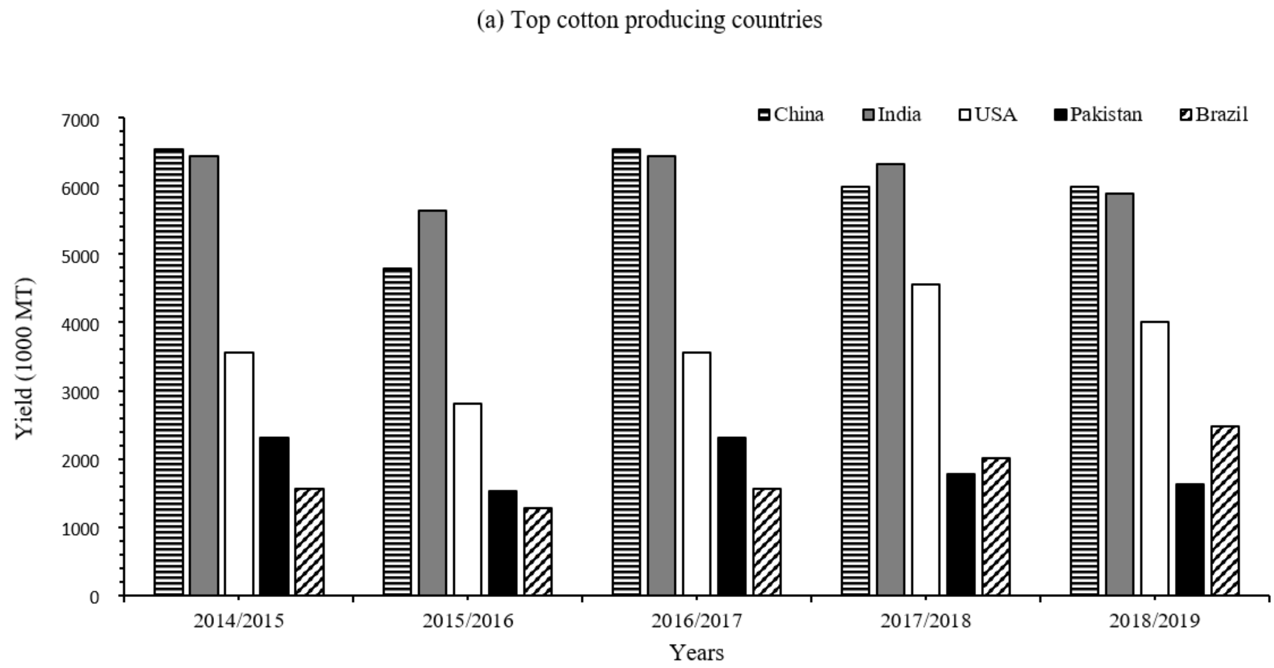
### *3.3. Changes in the Length of Cotton Phenophases*

Furthermore, due to increasing temperature, cotton growth has advanced phenology stages and has shortened the cotton crop duration in China. However, crop maturity dates were significantly delayed up to 61.5% at eight stations. Furthermore, the time length between flowering to boll opening stage and boll opening to harvest maturity duration has risen up to 77.01% at ten locations. Simulations of long-term weather data showed a decadal rise in China's mean temperature overland from the average simulation of future climate scenarios. The regression coefficient of cotton yield in other parts of China and Xinjiang reported (Table 2) significant production change (%). The current production change was observed as −1.1–1.5, while the $\Delta T_{avg}$ was 4.4–14.4%. The analysis of Δthe DTR (diurnal temperature range) impact on phenology events due to China's changing climate showed a significant yield loss (Figure 3).

**Table 2.** Average (%) regression coefficients of average cotton production change and climate variables generated by a past accumulated change in climatic variables in the cotton-producing regions of China from 1980–2018 (Where $\Delta T_{avg}$ average change in temperature, ΔDTR change in diurnal temperature range and $\Delta P_{rcp}$ average shift in precipitation)

| Climate Variables | China Cotton Region | | Xinjiang Cotton Region | |
|---|---|---|---|---|
| | **Present Regression Coefficient** | **Production Change (%)** | **Present Regression Coefficient** | **Production Change (%)** |
| $\Delta T_{avg}$ | −0.1% °C$^{-1}$ | −0.1 | 10.0% °C$^{-1}$ | 12.7 |
| ΔDTR | 10.4% °C$^{-1}$ | −5.5 | 4.8% °C$^{-1}$ | −4.2 |
| $\Delta P_{rcp}$ | 4.4% (100 mm)$^{-1}$ | −1.1 | 14.4% (100 mm)$^{-1}$ | 1.5 |

Data analysis of temperature revealed that climate warming trends are decreasing cotton yield by accelerating plant growth and development rate while reducing the accumulation of economic yield. Most likely because of rising temperature extremes and heat stress, yield reduced by approximately 2.01–6.4%. The DTR (diurnal temperature range) declined, but few locations observed advantageous effects of this DTR decrease. The change in DTR evolved in an average drop off in cotton production by approximately 5.5–8% across mainland China (Figure 6). There was a significant variation in the quantification of the warming effect on phenological events (1961–2015) in Punjab. Results generated with the Global Historical Climatology Network (CHCN) V4-model amounted that the sowing dates, emergence, flowering, and harvesting stages were negatively correlated with temperature (per °C) by an average of −2.04, −1.92, −1.08 and −0.41 days (Figure 3).



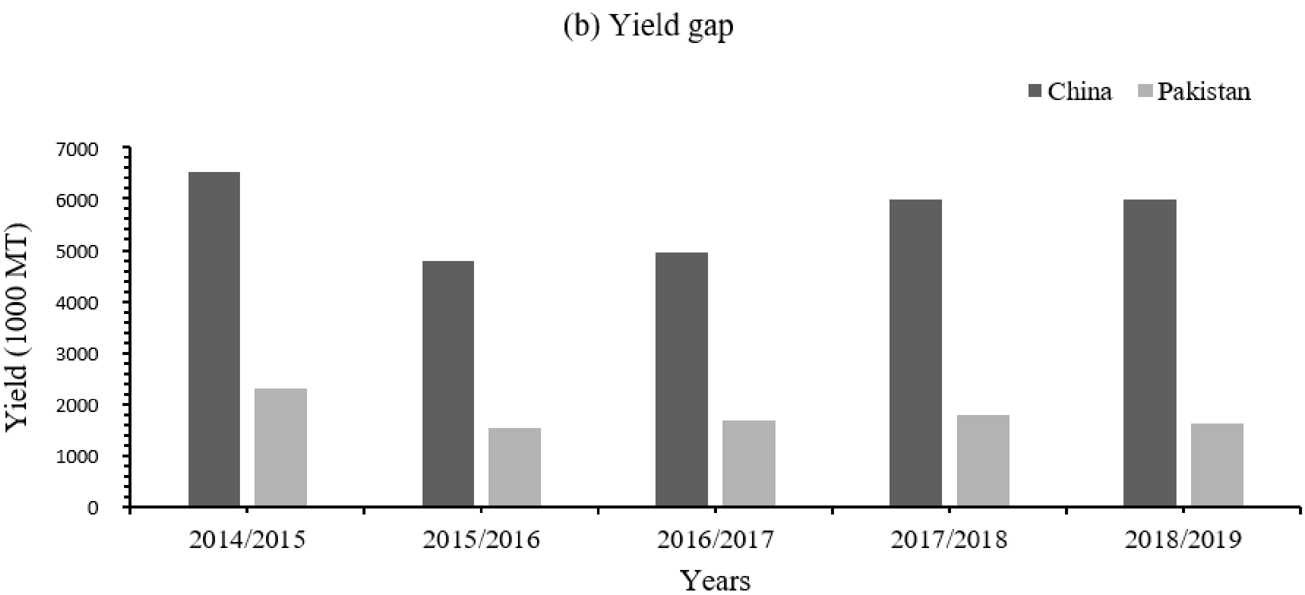




**Figure 6.** Cotton production statistics (**a**) yield comparison of the world's top five cotton-producing countries; (**b**) yield comparison of Pak-China cotton production during 2014–2019 (1000 MT), where the model predicts 2018/19 yield.

Meanwhile, the observed planting to anthesis stages, anthesis to maturity, and planting to full maturity stages were also negatively correlated with temperature (per °C) by an average of −0.93, −0.68, and −1.62 days, respectively. During the vegetative stages of the cotton crop, the increase in AT (accumulated temperature) led to reduced cottonseed yield, but rising at some stage in reproductive periods enhanced seed yield. Moreover, an increase in every one-degree mean temperature caused advanced phonologies by 2.28 to 4.04, 2.17 to 4.16, and 2.41 to 4.76 days, respectively. Moreover, every 1°C increase in AT (≥10 and ≥0 °C) led to a dropped-off cottonseed yield (Figure 3).

Field experiments at both sites observed that higher temperature disrupts the photosynthesis and respiration mechanism. Higher soil temperature reasons stem scorches (stem girdle) at the ground level, i.e., cotton (Figure 6). The cotton harvested area of China in 2017/2018 was estimated at 3.4 million hectares, 500,000 above the year 2016/2017, while yield has increased to 1761 kg/hectare, up 3.1%, respectively. In Pakistan, approximately 1.5 million small landholding farmers rely on cotton for their livelihood. According to economic model simulations, due to the annual loss in cotton production, the yield will be USD 16 billion by the end of this century. China is the top (Figure 6) leading cotton-producing country worldwide with 6532 thousand metric tons. Pakistan ranked fourth with 2308 thousand metric tons and grew cotton over three million hectares of land, covering 15% of its total cultivated area, respectively. As per observed data analysis, cotton return reduced to as far as 5.951 million bales only in Punjab from 10.7 million bales collected in 2017. This counts as a 33.9% overall decline in cotton production (Figures 6 and 7).

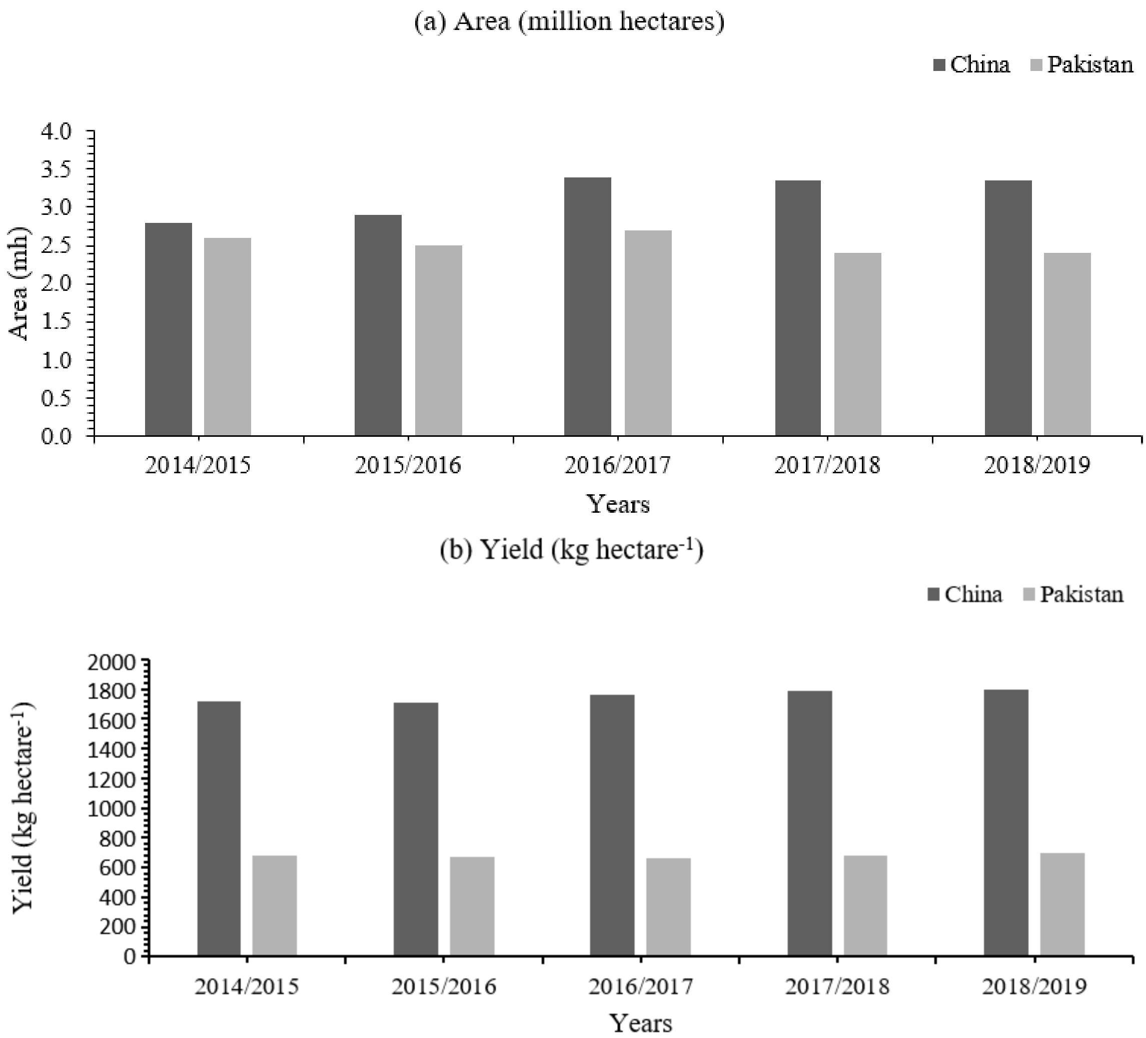



**Figure 7.** *Cont.*

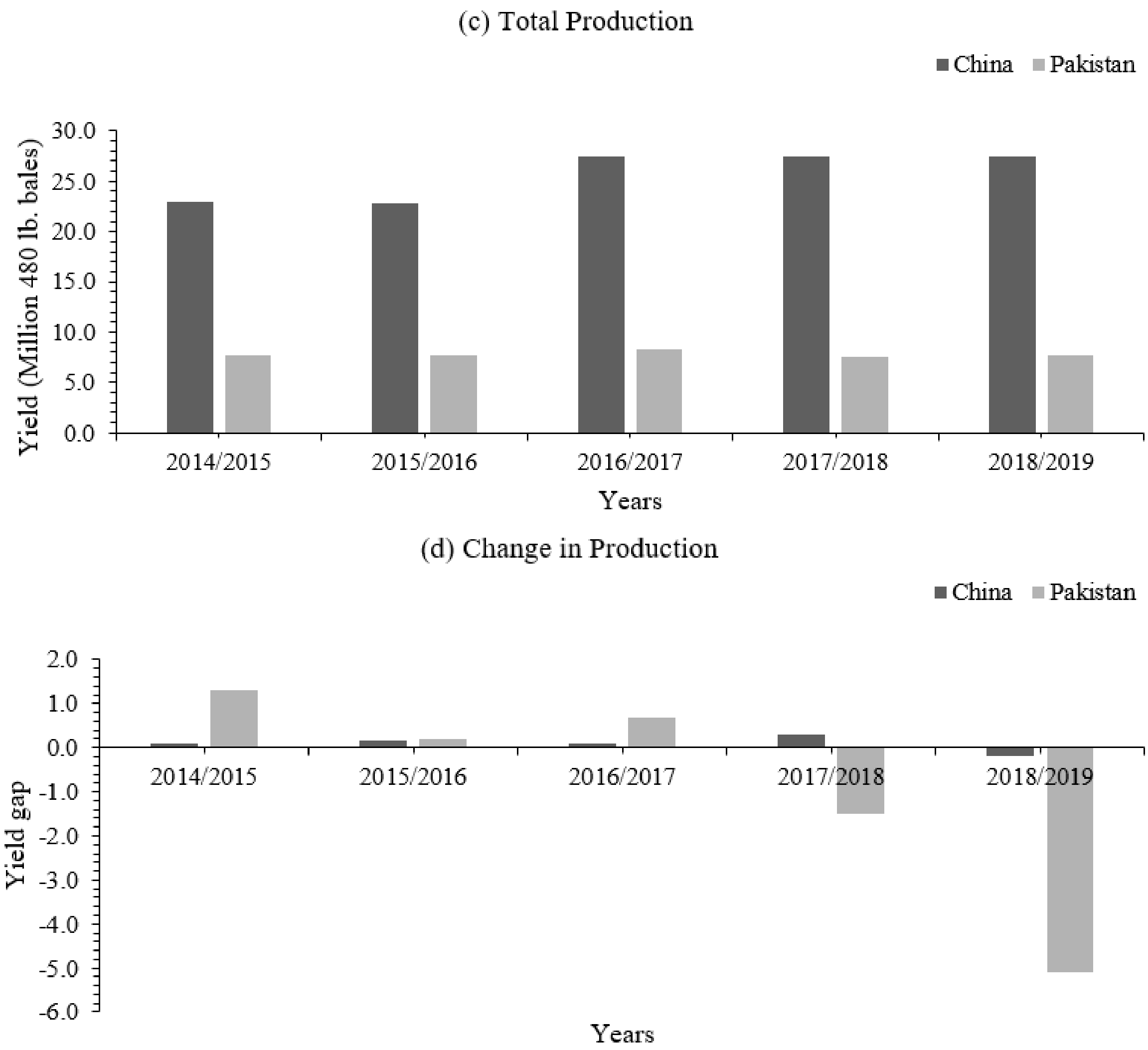



**Figure 7.** Yearly assessment of Pakistan and China (**a**) cotton production area (million hectares); (**b**) production (million bales); (**c**) yield (kg/hectare); (**d**) trends of change in production during growing seasons of 2015–2019, where 2018/2019 are predicted values on the basis of the previous data analysis.

### *3.4. Climate Risk and Yield-Gap Response*

Sowing cotton 10–14 days earlier than average (i.e., 4 March–18 March) in 2018 and 2019 resulted in maximum yield (Table S1) output and simulated the potential yields over the last 30 years in Punjab. However, the high temperature at the end of April and early start of May (>40 degrees) was observed in shortening the growing period of sowing-emergence (1.65 days decade$^{-1}$) and emergence-squaring (1.89 days decade$^{-1}$). Under delay practices, the squaring-flowering developmental stage, followed by elevated temperature (>40 degrees) with less soil moisture (<4–11 mm), leads to an increase in the shedding of flowering buds, affecting the boll retention and also producing an altered size of boll and maturation phase. The phenology phases between planting to flowering, full maturity to full maturity (Figure 5), and planting to complete maturity were reduced by an average of 2.45, 1.86- and 4.13-days decade$^{-1}$, while temperature increase in China also advanced the planting-dates, sowing-emergence, 3–5 leaves, budding-anthesis, full-bloom, cleft-boll, boll-opening, and boll-opening filling by 24.42, 26.19, 24.75, 23.28, 22.62, 15.75, 14.58, 5.37, 2.85, and 8.04 days.

According to the comparative analysis of yield worldwide in recent years, cotton production in China reduced from 6532 (1000 MT) to 4790 MT in 2015/2016–2016/2017 and 2017/2018, and produced 5987 MT. In the meantime, cotton production in Pakistan declined from 2308 MT to 1676 MT, and yield significantly decreased up to 1633 MT during 2018/2019 in Xinjiang. Worldwide cotton outlook analysis (Figure 6) reported that the cotton production areas in Pakistan and China are equally increasing, but a significant yield decline was reported in Pakistan. The per hectare yield gap between China and Pakistan is around 1000 kg hectare$^{-1}$. The future prediction of change in production in Pakistan and China might be −7.13 in Pakistan compared to China during 2019/2020. Likewise, the rising temperature also appeared to affect fiber length and quality as well.

### *3.5. APSIM-Cotton Model Calibration and Validation*

The present study also evaluated the performance of the APSIM-cotton model to quantify the long-term cotton-growth yield under different sowing windows. Long-term yield (kg/ha$^{-1}$) quantification and model optimization of Xinjiang (1980–2018) and Punjab (1961–2015) cotton zones showed good agreement with observational data, both in calibration and validation (Figure 8). The NRMSE results of calibration for emergence, flowering, and maturity were 26.2%, 4.5% and 1.7%, respectively. The values of NRMSE validation were 21.3%, 7.2% and 5.8%, respectively. The APSIM-cotton model calibration and validation of cotton yield (kg/ha$^{-1}$) under different sowing-dates presented a good performance with observed yields (NRMSE, 17.4%). For the years calibration of Punjab, the model projected yield also obtained a good result with an RMSE of 0.81 t ha$^{-1}$ and an NRMSE of 14.9%. The findings of model calibration and validation of cotton total dry matter (kg/ha$^{-1}$) under different sowing dates also showed variation among change in sowing time, influenced by climatic warming. APSIM-cotton quantification revealed that the sowing, emergence, flowering, and maturity stages were negatively correlated with temperature −2.03, −1.93, −1.09, and −0.42 days °C$^{-1}$ on average, respectively. The comparison of the APSIM-cotton modelling results showed that climatic warming in Xinjiang, China also advanced the dates of seed drilling, drilling to seed emergence, three-leaf stage, five-leaf stage, budding, anthesis, full bloom, cleft-boll, boll-opening, and boll-opening filling, and further growth was stopped earlier than normal.

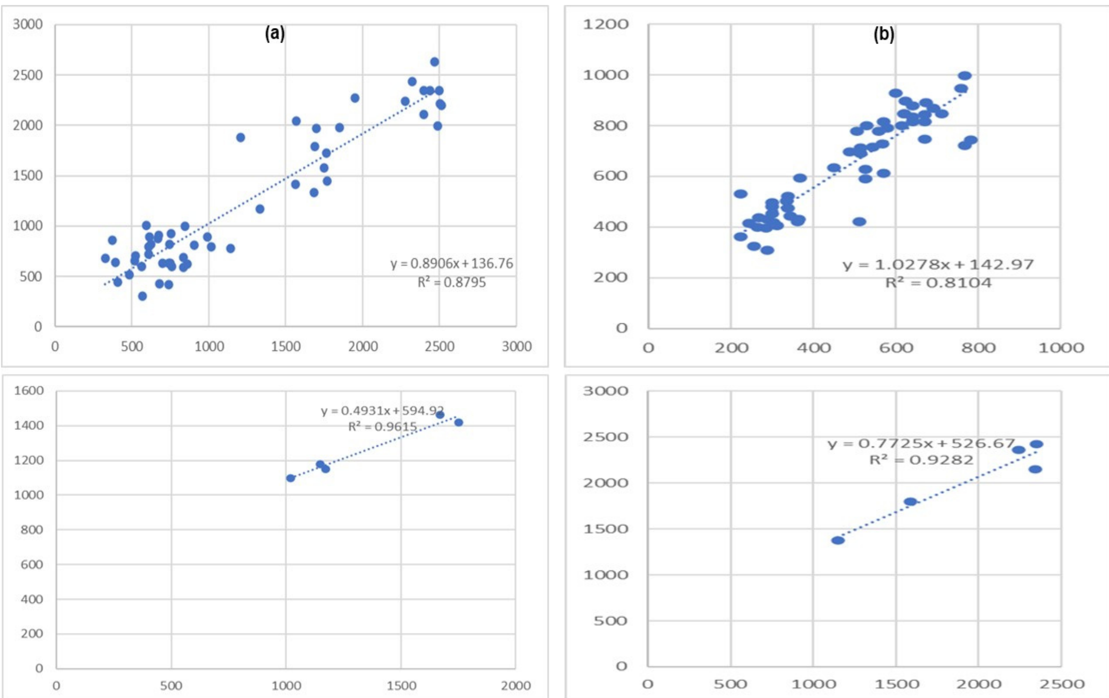



**Figure 8.** Calibration and validation of the APSIM-cotton model to compare the simulated and observational yield (kg/ha$^{-1}$) data with different sowing dates (**a**) simulated and recorded yield in Xinjiang (1980–2018); (**b**) simulated and recorded yield in Punjab (1961–2015), where for long-term yield $p$ = 0.31 and observational yield $p$ = 0.93.

## 4. Discussion

Yield dropping was induced by delaying every single day among each phonological stage. The relationship between environmental variables, cotton growth and yield indices were location and region-specific. For plant growth and development, the temperature is also critical, and the optimum microclimate is required to obtain maximum dry-matter accumulation. At high-rise temperatures, water becomes a crucial priority, particularly in the flowering and boll formation stages. An infestation of diseases and pests/insects will pose additional threats as higher temperatures provide a favorable environment where both flourishes. Insects could adjust more easily with rising temperatures than plants, and their metabolism could improve by speeding up the rate of reproduction.

### 4.1. Plant Functioning under Extreme Temperature

The estimated optimal temperature to biomass accumulation is between 20 to 30 °C, and 23.5–32 °C is the most favorable heat for the ultimate functioning of the metabolism and associated enzymes in cotton. Higher temperature (>32 °C) experience resulted in limited plant growth and development. In common maximum phenology, stages are vulnerable to excessive temperature, but the reproductive period is highly critical and sensitive. Climate warming is tending to root-causes of rising in average temperatures, which may affect crops in the form of longer growing seasons, vulnerability to unpredictable rainfalls, and thus undersized growing phases [39,40]. Previously, scientists [39] investigated that the heat stress in terms of both high and low temperature induces different physiological responses and metabolic action in cotton, and causes variation in plant photosynthetic processes, stomatal closure, oxidative balance, membrane injury, normal protein synthesis, lipid peroxidation and the development of carbohydrate performance. The results illustrated that the suboptimal temperature restricted boll retention and yield significantly. Moreover, an increase of even 1 °C temperature at field conditions from optimal-ambient temperatures dropped lint yield up to 110 kg $ha^{-1}$. This devaluation of lint yield is principally affected by insignificant boll biomass and reduced number of seeds $plant^{-1}$ developed in a boll by heat-induced pollen injury, which leads to reduced efficiency of fertility and fertilization. Planting density and the sowing date of cotton are still crucial for future management decisions because dates of drilling and planting population significantly impact cotton thickening and development. Mainly, during flower initiation and development [3], they are occurring in crop maturity delay. These findings suggested that maximum plant density and belated drill dates could delay crop maturity. Such shifts in plant density and the reallocation of sowing date management might help high-temperature areas such as Punjab, Pakistan and some parts of China. In the North China Plain (NCP) cotton belt, it was also discovered that the planting dates, seed emergence, squaring, flowering, and boll opening days were earlier by 0.25, 1.39, 0.92, 2.81, and 0.83 $decade^{-1}$ [20,21].

### 4.2. Adaptation to Climate-Smart Management

Adaptation to smart and sustainable cotton production practices is the only solution to combat future climate warming and vulnerabilities. At the end of this century, in Punjab, Pakistan, the rise in average temperature simulated by RCP scenarios will be above 2 to 3 °C (Figure 2). Fruits initiated 60 to 70 schedule days before final harvesting do not supply to yield [28]. Hence, suitable timing of topping to avoid fruits' inadequate formation is vital for high-quality and maximum yield. The topping of branches should be performed at the same time or not later than 14 to 24 days after central shoot topping to boost yields by improving fiber quality [3]. For optimizing the topping time of main stem and fruit branches, in China, farmers generally apply the count number of fruit branches as an indicator. Different regions have diverse environmental conditions and distinct degrees of dependency on a flawed cropping production system.

Currently, 2.7 million hectares are spread by plastic mulch film every year in arid and semi-arid regions of China, particularly in Xinjiang [41]. Fortunately, this provides good conditions to increase the soil's temperature, increase moisture conservation, discourage weeds, and control salinity in the root-zone [42], respectively. Cotton varieties Xinluzao 57, Xinluzhong 36, Xinluzhong-37, Xinluzhong 42, Xinluza 50, Xinluzhong 47, Xinluzhong 54, Xinhai 21, Xinluzao 48, Xinhai 24, Xinhai 35, Xinluzao 41, Xinhai 36, Xinluzao 36 and Xinluzao-37 all are adaptive to higher planting density and mode to film mulch farming (Table 1). Adaptation to film mulching in drought-prone cultivated Punjab areas might be beneficial to enhance yield to obtain sustainable production. In Pakistan, film mulch with a 150, 160, 180, and 190 cm width will be more applicable. The results reported (Table 3) that exposure to conventional post-sowing with advanced mulching has increased up to 11.3% stand establishment, 8.0% reduction in leaf Na+ (mg/g) levels, and 7.1% of the decline in lint yield and 9.9% of biomass accumulation, respectively. Adaptation to early mulching practices showed 73% earliness compared with conventional and non-mulch strategies. Consequently, in the shift to increase sustainable cotton production, there should be options to choose systems that; (1) promote new cotton varieties; (2) establish an agricultural meteorology advisory system; (3) upgrading farmers' knowledge of climate-smart agriculture; (4) perform minimum tillage to reduce GHG emissions; and adapt to real and simulated yield (%) green road or sustainable cotton production.

**Table 3.** Effects of strategies approach to no, early and conventional mulching interactions effect of cultivation practices on plant $Na^+$ content, biomass (g/plant), lint yield, stand establishment, and earliness (%).

| Treatment | Biomass (g/plant) | $Na^+$ (mg/g) | Stand Establishment (%) | Lint Yield (kg ha$^{-1}$) | Earliness (%) |
|---|---|---|---|---|---|
| No-mulching | 1.57c | 11.3a | 47.7c | 900c | 64b |
| Conventional mulching | 1.71b | 10b | 59.5b | 1000b | 71.4a |
| Early mulching | 1.88a | 9.2c | 66.4a | 1071a | 73a |

Note: different letters represent statistical differences.

### *4.3. Managing Future Climate Risks*

This study also investigated that vegetative branch removal has decreased boll shedding by 9%, improved weight up to 7%, and enhanced cottonseed yield by 8.7%. Above management practice also raised several fruiting nods leaf$^{-1}$ areas (31.1%) along with 88.9% of the dry mass of fruiting parts leaf$^{-1}$ area. Cotton plant's vegetative branches do not bear fruits directly; therefore, they consume nutrients tremendously [14,20]. It is essential to recognize the best time for such management practices. This resulted in boll shedding, especially in a medium height plant. Suitable time for topping was suggested as mid or late July, while the number of fruit branches achieved 8 to 10 (m$^2$) of land area. Management practices could provide in-situ relief to the plants under heat and water stress to save water and nutrients and mightily boost the cotton yield, improve fiber quality, and reduce input cost, respectively. However, the production level of cotton has restricted capability to respond against heat stress and compensatory growth. Many experimented adaptation strategies include: (a) minimum or zero tillage; (b) maintaining soil cover; (c) appropriate plant diversity and density; (d) shift in sowing windows; (e) introducing resistant cotton varieties. Climate change is shifting the production economics and demanding that farming communities consider numerous livelihood approaches, including planting other crops and seeking alternative streams to non-farm income.

There might be other aspects, including site-specific factors such as carbon dioxide concentration, water availability, soil nutrients, plant density and sowing dates, extensive tillage, insect pest diseases, and so on. Rising temperature is not the only factor that can influence cottonseed yields. These components do not function solely but can act together and interact further, respectively. However, it is essential to take climate-smart adaptation approaches. Similarly, rotten and unopened bolls of cotton decrease crop productivity up to 40 to 60% on dependent factors, i.e., weather, disease or insect attack, and geographic position as well [37]. MC (mepiquat chloride) is a growth regulator and is commonly used in China's cotton belt and worldwide to improve fiber quality and seed yields [43]. MC application increases leaf thickness, reduces leaf area, shortens internodes and decreases plant height, resulting in an extra dense architecture of the plant. Multiple studies also discovered that MC improved lint yield under higher (7.5 plants per $m^2$) plant population densities. The cultivated area of cotton-efficient irrigation by the drip system in Xinjiang is above 1.2 million hectares [44,45].

### 4.4. Simulated Variations of Meteorological Factors

Temperature rising affects mineral nutrition to shoots, leaves boarding, and develops boll, resulting in low yields in the near future [25,29,46]. A future climate model projected that the annual mean temperature by 2050 in China could rise by 2.3 °C to 3.3 °C, and precipitation up to 5% to 7%. SimCLIM model predictions for the Punjab cotton scenario showed a significant decline in yield, and a fraction increases because of the rise in the concentration level of $CO_2$ between 2025 and 2050 in climatic projections [47]. Modelling also projected that higher phosphorous levels have an adverse impact due to climate prototypes simulated by an average of GCMs (Figure 9). There has been objection regarding substandard fiber quality and yield losses as a result of mechanically harvesting the crop [3,39]: (a) advancement of research and technology will take some time for the Xinjiang cotton zone to introduce smart technology; (b) including appropriate cotton varieties will make them adaptive to local conditions and agronomical practices; (c) overall up-scaling of the mechanized harvesting system will appropriately improve the productivity to ensure sustainable cotton; (d) cotton breeders are required to emphasize the selection of cultivar highly resistant to heat and drought stresses. A simulated rise in average cyclic temperature was up to 1.53 °C and 2.61 °C in the RCP 4.5 scenario (Figures 2 and 9). The projected expansion was observed as 1.56 °C and 3.47 °C in the RCP 8.5 scenario. Furthermore, the 4.5 and 8.5 scenarios contrasted with the seasonal baseline (31.48 °C) in the upcoming years 2010 to 2039 and long-term years 2040 to 2069, respectively (Figure 2). GCMs' upper consensus revealed an increase in temperature ranges of 1.2 to 1.8 °C and 2.2 to 3.1 °C in the RCP 4.5 framework, while a 1.4 to 2.2 °C and a 3.0 to 3.9 °C boost is expected under RCP 8.5 for the near and long-term time interlude, accordingly. Likewise, the precipitation pattern is anticipated to be −8 to 15% and −5 to 17% in the RCP 4.5 scenario. Meanwhile, the RCP 8.5 scenario rainfall simulation is −8 to 22% and −2 to 20%, and further variation would be estimated in the near and long-term production cycle.

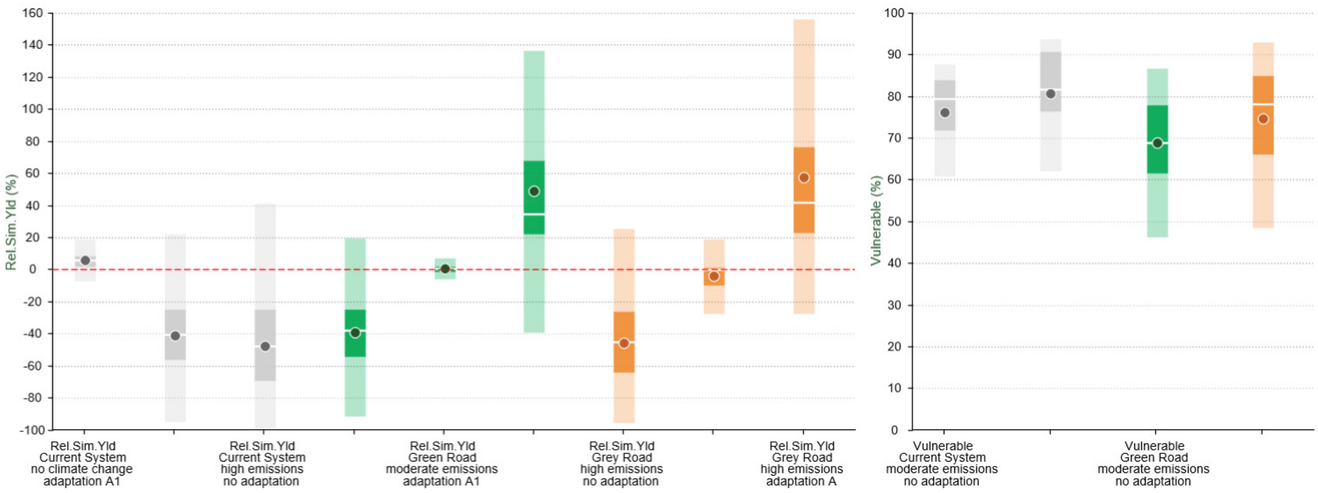



**Figure 9.** Pathways and modelling future scenarios to adopt climate-smart systems to minimize the vulnerability and promote environmentally friendly (green road) better cotton.

*4.5. Climate-Smart Cotton, a Future Perspective*

Environmental warming is primarily represented by expanding base temperature, falling range of DTR, and escalating minimum hotness that could protect the cotton from frosts and low-temperature damage. Furthermore, [29] reported that heat stress lengthened the entire growth period of cotton in Xinjiang. The research findings have documented exact cotton phenology changes across regions that anticipated climate warming. Nevertheless, many scientists have paid attention to main food crops, and few of them have studied time variation in cotton phenology in the climate warming context. Studies have shown that plant growth and development speed up under warming, significantly impacting the maximum growth stages of cotton. However, on average, weather warming lengthened the time phase between bolls opening and harvest by 5.58 days per degree temperature. Therefore, apart from the belated harvest dates, all other cotton phenological dates were in advance. As a result, growth was accelerated by a hit of climate warming, although the harvesting time was postponed because of the indeterminate growth habit of the cotton plant. However, a rise in base temperature at the time of seed germination upheld growth in spring. Maintaining minimum heat on biological growth in summer and the postponement of the growth dates in autumn mightily enhanced cotton yield. However, the sowing dates affected the time frame of all the following events of phenology. This negative impact might be mitigated by adaptation to cotton varieties requiring a higher growing degree day followed by advanced plantation. Adaptation to machine-driven methods and the removal of early fruit-branches (REFB) 60-days after plantation delay the senescence phase. Furthermore, it will also enhance nitrogen concentration, promote plant height, and improve nodes over damaged bolls. It is an environmentally friendly agronomic practice.

Functional, structural plant modelling (FSPM) is an appropriate tool for simulating the spatial and temporal heterogeneity of light interception and for incorporating growth concerns [37]. For example, crop model applications, such as CottonXL, estimate the progress of plant geometry influenced by cultural practices. This model has been functioning as a tool to investigate the relations among plant arrangement (Figure 10) and execution, and to validate agronomic practices related to the cotton plant's morphology. Additionally, FSPM could provide services such as a crop tool to comprehend yield as affected by external ecological conditions. The model's fiber quality (length, strength, and micronaire) could be calculated at the fruiting stage, as determined by hotness (daily average, maximum, minimum, and difference between the maximum and minimum temperatures). Entire plant maturity is also driven by temperature and further determined by the date of drilling, film mulching, and plant topping. The productivity of the FSPM incorporates the allocation of cotton bolls and canopy growth within the thermal time (Figure 10). The model could also calibrate and validate the fiber length and quality of all individual bolls. The present research intervention suggests an advanced tool to investigate the acquired agrometeorological impacts throughout the cultivation and adaptation of smart management practices. Under the current environmental conditions, adaptation to smart and sustainable management practices, i.e., sowing dates (S.D.) and planting density (P.D.), is the foremost driver of better cotton productivity [48]. China has improved productivity by minimizing input-cost through the adjustment of optimal sowing date (S.D.) and plant density (P.D.) in Yangtze River valley China, North China plain [21], and the Xinjiang cotton belt to some extent, but in Pakistan, particularly in Punjab, it is not decided yet. This study will help us examine the research gaps of agrometeorology and adaptation to Xinjiang's smart management practices.

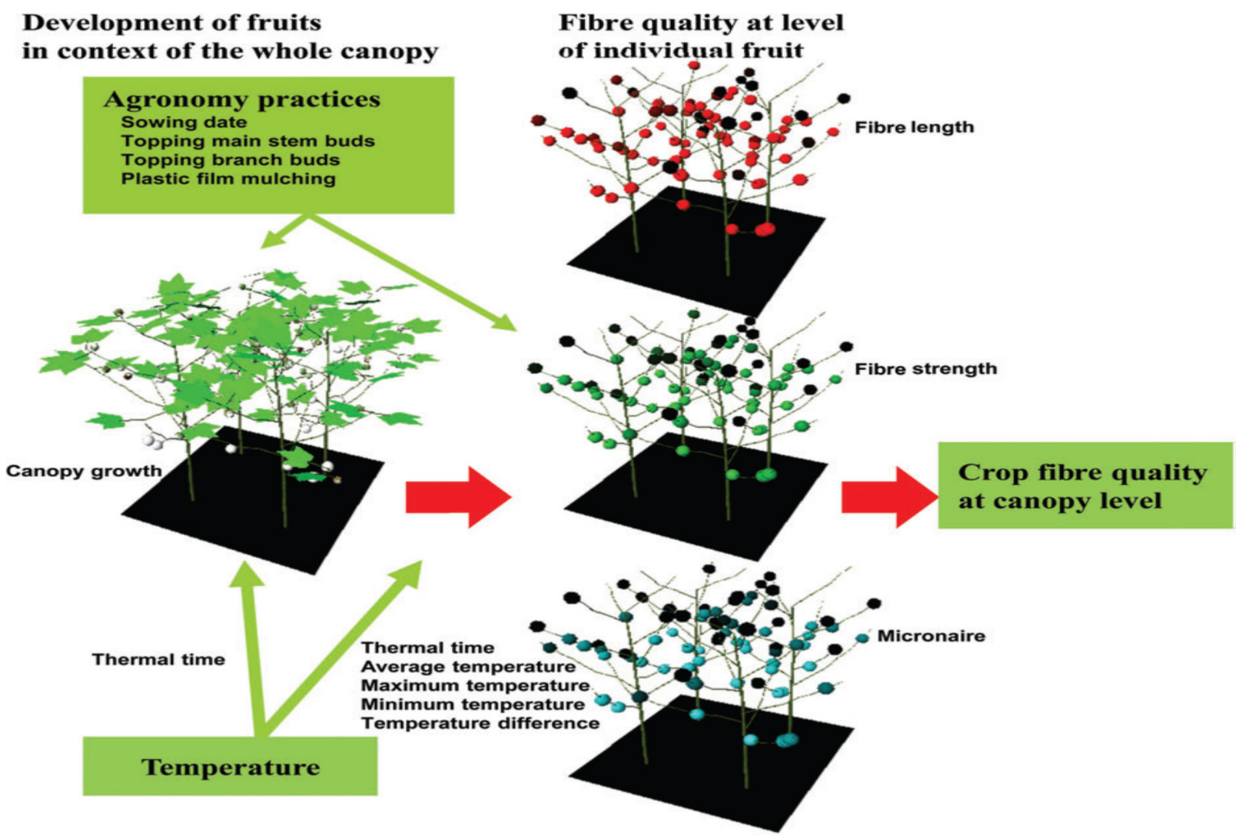



**Figure 10.** Flowchart of FSPM model to demonstrate temperature differences and growth functioning of the cotton plant.

## 5. Conclusions

Field experiments were conducted to calibrate and validate the APSIM-cotton model. The calibrated model was capable of simulating all the studied parameters of different locations at various dates. The study concluded that the outcome of planting dates on quality and yield looks upon the accessibility of heat resources. Warming trends advanced the phenological stages, which reduced the crop phenological phases. Several smart management approaches have been adapted to slow-down senescence to harmonize the accessibility of carbohydrates from plant leaves with bolls demand, such as maximum planting density, reduced plant spacing, the basal application of mepiquat chloride (MC), and the removal of early squares and fruiting branches, which can trigger regulation in senescence, bolls characteristics, and harvest index. Relay intercropping of wheat and cotton would be a better adaptation to high temperature to delay early-stage phenology; thus, the cotton in the intercropping schemes was delayed through 10–15 days, which corresponded to 4.8 physiological days or 116 degree-days. Therefore, adaptation to such integrated smart practices could improve crop yields in both regions. The present status of China's cotton-growing techniques might be better than climate-smart adaptation measures for sustainable cotton production in Pakistan. This research overviewed combining smart practices to combat extreme temperatures and expected drought stresses in the future.

**Supplementary Materials:** The following are available online at https://www.mdpi.com/2077-0472/11/2/97/s1. The supplementary dataset record, excel sheets, and developed tables will be provided on the demand and need bases. Table S1, Observational field data to calibrate and validate the APSIM-cotton model to quantify the effect of different sowing dates of growth and yield of the cotton crop during 2018 and 2019; Figure S1, Cumulative plot of the climate variables Radn (MJ/m2), Tmax (°C), Tmin (°C), Rh (%) rain (mm), Evpo (mm) and S-hour during cotton growth season in Xinjiang.

**Author Contributions:** Conceptualization, A.A., and L.Z.; methodology and investigation, A.A., L.Z., M.A.R., X.W.; data organization, Y.Z., A.A.; writing the initial draft preparation, A.A., L.Z.; writing, review, and editing, M.A.R., M.H.-u.-R., A.A., L.Z., M.A.; supervision by L.Z. All authors read and approved the final version of this manuscript for further development with no objections in research data, analysis, and funding to support this project.

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**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

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