

Assessment of Future Cotton Production in the Tarim River Basin under Climate Model Projections and Water Management

Shengru Yue^{1,2}, Lunche Wang^{*1}, Qian Cao¹, Jia Sun¹

1. School of Geography and Information Engineering, China University of Geosciences (Wuhan), Wuhan 430078, China

2. College of Hydraulic and Architectural Engineering, Tarim University, Alaer 843300, China

ABSTRACT: Climate change is significantly impacting cotton production in the Tarim River Basin. The study investigated the climate change characteristics from 2021 to 2100 using climate change datasets simulated per the coupled model inter-comparison project phase six (CMIP6) climatic patterns under the shared socioeconomic pathways SSP2-4.5 and SSP5-8.5. The DSSAT-CROPGRO-Cotton model, along with stepwise multiple regression analyses, was used to simulate changes in the potential yield of seed cotton due to climate change. The results show that while future temperatures in the Tarim River Basin will rise significantly, changes in precipitation and radiation during the cotton-growing season are minimal. Seed cotton yields are more sensitive to low temperatures than to precipitation and radiation. The potential yield of seed cotton under the SSP2-4.5 scenario would increase by 14.8%, 23.7%, 29.0%, and 29.4% in the 2030S, 2050S, 2070S, and 2090S, respectively. In contrast, under the SSP5-8.5 scenario, the potential yield of seed cotton would see increases of 17.5%, 27.1%, 30.1%, and 22.6%, respectively. Except for the 2090s under the SSP5-8.5 scenario, future seed cotton production can withstand a 10% to 20% deficit in irrigation. These findings will help develop climate change adaptation strategies for cotton cultivation.

KEY WORDS: climate change, Tarim River Basin, potential yield of seed cotton, DSSAT, CMIP6, future cotton production.

0 INTRODUCTION

As a versatile crop, cotton is one of the most important natural textile fibers and the raw materials for yielding cottonseed oil for cooking and providing livestock with proteins (Khan et al., 2020). Climate, CO₂ concentration, irrigation level, fertilization, crop varieties, and soil types are the primary factors influencing cotton growth (Lin et al., 2024; Xu et al., 2022; Li, 2021; Li et al., 2018). The global average surface temperature rise is projected to reach or exceed 1.5 °C within the next 20 years, according to the sixth assessment report of the intergovernmental panel on climate change (IPCC). The average precipitation would also increase, though it might vary depending on the season and region (Zhou et al., 2021). Liang et al. (2020) projected that the optimal observation-constrained warming ranges during 2081–2100 would be approximately 0.52 to 1.66 and 2.72 to 4.77 K for the SSP1-2.6 and SSP5-8.5 scenarios, respectively. Chen et al. (2023) predicted that rising emissions would cause

the arid Northwest China region to transform from a “warm-wet” to a “warm-dry” state by the end of this century (2070–2100).

China ranks among the top cotton producers globally, with the Tarim River Basin in Xinjiang as its foremost cotton-producing region (Lin et al., 2024; Li, 2021). More than 70% of the arable land in this basin is used for cotton cultivation (Wu et al., 2022). The Tarim River Basin is a typical irrigated agricultural area where climate change raises significant demand for future atmospheric evaporation. A meteorological drought here would threaten cotton growth, consequently impacting production (Tian et al., 2023; Xu et al., 2022). Furthermore, climate change may disrupt the existing balance of water resources in the Tarim River Basin by altering the proportion of snowfall and the timing of snowmelt. Research has indicated that in the event of a 4 °C increase in global temperatures, alternative water sources would need to satisfy up to 40% of the Tarim River Basin’s irrigation needs. This would significantly impact irrigated agriculture that depends on snowmelt runoff (Wu et al., 2022; Qin et al., 2020). One of the primary factors affecting cotton development is a rise in CO₂ content, which can improve photosynthesis and cotton output (Xu et al., 2022; Li, 2021). Nevertheless, the effect of CO₂ varies by region and may be weakened by future changes in temperature and precipitation

*Corresponding author: wang@cug.edu.cn

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(Xu et al., 2022; Osanai et al., 2017; Adhikari et al., 2016). Numerous researchers have undertaken extensive research on this effect. Li et al. (2020) established the optimal equation between seed cotton production and climatic variables in Xinjiang using Pearson correlation, multiple linear regression, and multiple nonlinear regression techniques. They concluded that sunshine duration, average temperature, maximum temperature, and minimum temperature are the primary variables affecting seed cotton production. Xu et al. (2022) utilized the APSIM-Cotton model to simulate changes in cotton production under several future scenarios. Consequently, they discovered that while rising CO₂ concentration may boost cotton production in Central Asia, climate change would likely decrease it. Using grey relational analysis, Lin et al. (2024) determined the optimal water and fertilizer requirements for different Xinjiang regions, emphasizing the significance of climatic factors. Zhao (2019) developed a large-scale water-nitrogen coupling model based on integrated field experimental data. The model estimates the potential cotton yield under mulched drip irrigation in Xinjiang and predicts the region's cotton production in 2020 with limited water resources. Li et al. (2023) employed the MaxEnt model to explore locations suitable for cotton cultivation in Xinjiang. They discovered that temperature factors accounted for 71% of the suitability while terrain and soil factors contributed just 22%. However, regarding cotton production in the Tarim River Basin, previous studies have mainly used mathematical statistics and crop models to explore the response of cotton to changes in climate and CO₂ concentration, as well as the optimal water and fertilizer requirements. The main issues include a small number of selected stations, insufficient consideration of the heterogeneity of the agricultural ecological regions in the basin, and still inadequate discussion on the risks of water resource shortage under climate change to cotton cultivation. Crop models are a valuable tool for evaluating the effects of climate change on growth and yield and developing effective irrigation strategies (Adhikari et al., 2016). The DSSAT-CROPGRO-Cotton model, which is distributed with the decision support system for agrotechnology transfer (DSSAT), can simulate cotton growth and yield responses to weather conditions, soil characteristics, and management practices, making it widely applicable (Wang et al., 2022; Li, 2020; Adhikari et al., 2016). Based on the observed climate data from 37 stations in the Tarim River Basin for the period of 2001–2020, as well as the climate dataset simulated under the CMIP6 scenarios for the period of 2021–2100, the DSSAT-CROPGRO-Cotton model was used to simulate the impact of future climate change on the potential yield of seed cotton in the Tarim River Basin, and to identify the contribution of changes in CO₂ concentration to this impact. In addition, we addressed the characteristics of cotton's response to different water resource supply schemes. We evaluated the risk to the Tarim River Basin's cotton output under changes in the climate to provide scientific evidence for developing adaptation strate-

gies to sustain cotton production in the future.

1 MATERIALS AND METHODS

1.1 Survey Area

The Tarim River Basin (73° 10'E–94° 05'E and 34° 55'N–43° 08'N) is located in the southern Xinjiang Uygur Autonomous Region. It is surrounded by high mountains such as the Tianshan Mountains, eastern Pamirs, Kunlun Mountains, and Karakoram Mountains. It spans an area of approximately 1.02×10^6 km² (Figure 1). It has a typical temperate arid and semi-arid climate, with little precipitation and high evaporation rates. High-altitude glacier melting and the precipitation in mountainous areas are the primary water sources here. According to statistical bulletins on the national and regional economic and social development of the People's Republic of China in 2022, this basin is a central agricultural region in China, with the cotton cultivation area accounting for approximately 44.8% of the national total and the cotton yield representing about 62.3% of the national total. Climate change has significantly affected vegetation growth and productivity in the Tarim River Basin (Yue et al., 2025; Yue S R et al., 2024).

1.2 Crop Model and Parameter Settings

The DSSAT-CROPGRO-Cotton model can be used to estimate the impact of climate change on cotton yield, and we used DSSAT version 4.6 in this research. This model requires soil parameters, crop management, cultivated varieties, climate data, CO₂ concentration, and the like to predict cotton yield. It can estimate crop growth phases from planting to harvesting using light and thermal accumulation, as well as simulate temporal changes in soil water, carbon, and nitrogen levels (Du et al., 2021; Adhikari et al., 2016; Wang, 2015). The parameters of the DSSAT-CROPGRO-Cotton model used in this study refer to relevant research findings (Wang et al., 2022). The model calibration against the actual data from 2017 revealed that the average absolute relative errors for simulated versus measured values of biomass and seed cotton yield were 10.97% and 9.02%, respectively. Validation with data from 2018 demonstrated that the model effectively simulated seed cotton yield when the irrigation quota was at least 30mm, although there was a significant deviation in the biomass simulation. The validation outcomes are detailed in Table 1. April 15th was chosen as the sowing date, while soil parameters, sowing depth, density, and cultivated varieties were referenced from relevant studies (Wang et al., 2022). There was no disease or pest damage, weeds, or nutrient limitations. The initial soil moisture content was the field capacity, and the irrigation method was automatic drip irrigation, which automatically irrigates water to the field capacity when the soil moisture level falls below the wilting coefficient. Daily maximum temperature, minimum temperature, precipitation, and radiation were input as climate variables. CO₂ concentrations from 2001 to 2020 were sourced from the National Cryosphere Desert Data Center (<http://www.>

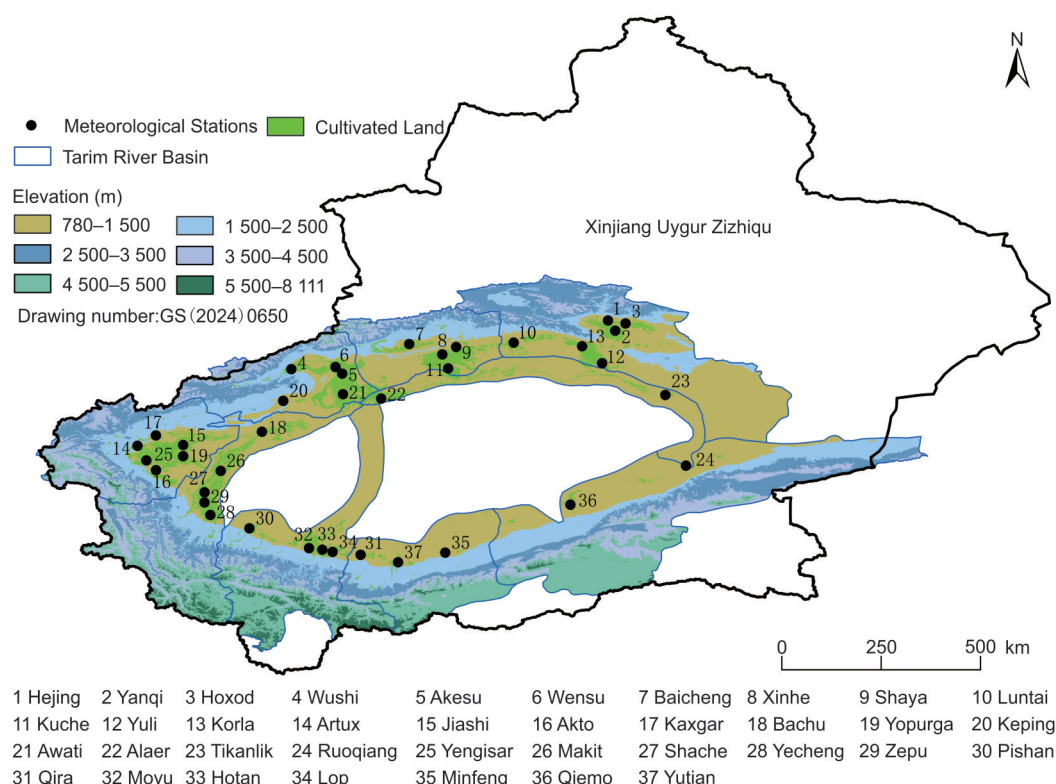


Figure 1. Overview of the study area and distribution of meteorological stations.

Table 1 Calibration and validation results of the DSSAT-CROPGRO-Cotton model

Year	Irrigation quota (mm)	Biomass (kg·hm ⁻²)			Seed cotton yield (kg·hm ⁻²)		
		Simulated value	Observed value	Relative error (%)	Simulated value	Observed value	Relative error (%)
2017 (model calibration)	24	12 866	12 528	2.7	4 770	5 645	15.5
	30	13 266	16 371	18.97	6 462	6 637	2.64
	36	14 025	15 803	11.25	6 564	6 026	8.93
				10.97			9.02
2018 (model validation)	24	10 028	15 878	36.84	3 448	4 690	26.48
	30	12 415	17 122	27.49	5 374	5 124	4.88
	36	13 471	18 876	28.63	6 067	5 655	7.29
				30.99			12.88

ncdc.ac.cn/portal/), while those for future scenarios were obtained from the China Science and Technology Resource Sharing Service Network (<https://escience.org.cn/>). Although there are significant differences in cotton field management and other aspects in different places in actual practice, since our goal is to analyze the impact of climate change, rather than to identify the effects of these factors on yield, we have chosen fixed conditions in various places of the Tarim River Basin.

Nine gradient irrigation schemes were established using the crop model's automatic irrigation evapotranspiration characteristics and pertinent irrigation scheme design research as a reference (Du et al., 2021) (Table 2). This allowed for a more thorough assessment of the characteristics of cotton's response to various scenarios for future water resources supply.

1.3 Climate Data Processing

The latest CMIP6 data has been used extensively to simulate future agricultural yield and adds to the consistently growing simulation accuracy of future climate (Zhu et al., 2023; Xu et al., 2022; Li, 2021). However, the global climate models (GCMs) remain at a low resolution. Therefore, using the rlplf1 experimental mode, this study adopted the daily maximum temperature, minimum temperature, precipitation, and radiation in the 13 GCMs with high original resolutions (Table 3). These GCMs have been widely used in relevant studies and have achieved good results, and their high temporal resolution is an important reason for selecting these GCMs (Li et al., 2024; Xu et al., 2022; Li, 2021). The future period was divided into four intervals: namely, 2030S (2021–2040), 2050S (2041–2060), 2070S (2061–2080), and

2090S (2081–2100). According to the experimental settings of CMIP6, two shared socioeconomic pathways (SSPs) were selected for analysis. SSP2-4.5 corresponds to a moderate radiative forcing scenario (medium scenario), and SSP5-8.5 refers to a high radiative forcing scenario (high scenario). The SSP2-4.5 and SSP5-8.5 scenarios are widely selected mainly because they represent two distinctly different pathways of future climate change (Li et al., 2024; Mai and Liu, 2023), thereby providing a sharply contrasting analytical framework for research. Choosing the SSP2-4.5 and SSP5-8.5 scenarios not only helps to gain a deeper understanding of the impact of climate change on cotton production in the Tarim River Basin under different emission reduction paths but also provides a scientific basis for formulating targeted

agricultural adaptation and mitigation strategies. Bilinear interpolation was used to resample the data to a resolution of $0.05^\circ \times 0.05^\circ$, then downscaled to station data spatially. Furthermore, baseline observation data were used to calibrate the model system's deviation, and a multi-model ensemble averaging approach was adopted to mitigate the uncertain influence of single models (Xu et al., 2022; Chen et al., 2020). The China Meteorological Administration provided climatic data for 37 stations in the Tarim River Basin during the baseline period (2001–2020). The daily sunshine hours were converted to solar radiation (Tong et al., 2005).

1.4 Stepwise Multiple Regression Analysis

To assess the impact of climate change on seed cot-

Table 2 Gradient irrigation schemes (mm)

Irrigation data	60% θ	70% θ	80% θ	90% θ	100% θ	110% θ	120% θ	130% θ	140% θ
5.20	18	21	24	27	30	33	36	39	41
6.06	18	21	24	27	30	33	36	39	41
6.19	18	21	24	27	30	33	36	39	41
6.28	18	21	24	27	30	33	36	39	41
7.04	18	21	24	27	30	33	36	39	41
7.10	18	21	24	27	30	33	36	39	41
7.15	18	21	24	27	30	33	36	39	41
7.19	18	21	24	27	30	33	36	39	41
7.23	18	21	24	27	30	33	36	39	41
7.28	18	21	24	27	30	33	36	39	41
8.02	18	21	24	27	30	33	36	39	41
8.07	18	21	24	27	30	33	36	39	41
8.12	18	21	24	27	30	33	36	39	41
8.15	18	21	24	27	30	33	36	39	41
8.20	18	21	24	27	30	33	36	39	41
8.25	18	21	24	27	30	33	36	39	41
8.29	18	21	24	27	30	33	36	39	41
9.04	18	21	24	27	30	33	36	39	41
9.11	18	21	24	27	30	33	36	39	41

Table 3 13 GCMs in the coupled model inter-comparison project phase six (CMIP6)

S/N	Name	Country	Year of publication	Grid resolution (longitude/latitude)
1	ACCESS-ESM1-5	Australia	2019	192 × 145
2	BCC-CSM2-MR	China	2017	320 × 160
3	CMCC-ESM2	Italy	2017	288 × 192
4	ESM2-0	China	2022	192 × 96
5	INM-CM4-8	Russia	2016	180 × 120
6	INM-CM5-0	Russia	2016	180 × 120
7	IPSL-CM6A-LR	France	2017	144 × 143
8	MPI-ESM1-2-HR	Germany	2017	384 × 192
9	MPI-ESM1-2-LR	Germany	2017	192 × 96
10	MRI-ESM2-0	Japan	2017	320 × 160
11	NESM3	China	2016	192 × 96
12	NorESM2-MM	Norway	2017	144 × 72
13	TaiESM1	China	2018	288 × 192

ton yield, the stepwise regression method was sampled to increase the number of climate variables in the function from 1 to n . The stability and predictive ability of the model was assessed. Model stability was assessed by adjusting the coefficient of determination, R^2_{adj} . The larger the value of R^2_{adj} at the significance level, the more stable the model (Zhang and Li, 2016). The predictive ability of the model was assessed by the root mean square error ($RMSE$), and the smaller the $RMSE$, the better the predictive ability of the model (Liu et al., 2013).

$$R^2_{adj} = 1 - \frac{\sum_{i=1}^n (\Delta Y_{obs} - \Delta Y_{pre})^2 / (n - k - 1)}{\sum_{i=1}^n (\Delta Y_{obs} - \bar{\Delta Y}_{obs})^2 / (n - 1)} \quad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (\Delta Y_{obs} - \Delta Y_{pre})^2}{n}} \quad (2)$$

Where ΔY_{obs} and ΔY_{pre} are the respective observed and estimated values of the first difference of the independent variable, n is the total number of samples; k is the number of explanatory variables.

2 RESULTS

2.1 Future Climate Change

Figure 2 exhibits the climate change characteristics under the SSP2-4.5 scenario during the cotton-growing season at 37 stations in the Tarim River Basin from 2021 to 2100 compared to the baseline period (2001–2020). The mean maximum and minimum temperatures for each station would increase by 2.2 and 2.1 °C to the 2090S during the growing season, while the cumulative precipitation would vary by -54.9 to 40.9 mm, with an average decrease of 3.2 mm. There is no discernible variation in the average radiation, which ranges from -3.0 to 1.1 MJ/(m²·d) and has an average attenuation of 0.7 MJ/(m²·d). According to projections, the Tarim River Basin's CO₂ concentration will rise from 393.0 ppm during 2001–2020 to 604.8 ppm in the 2090S. Figure 2 shows the climate change characteristics in the SSP5-8.5 scenario. The mean maximum and minimum temperatures for each station during the growing season would rise by 4.8 and 4.7 °C, respectively, to the 2090S. The cumulative precipitation would vary slightly, from -28.0 to 33.6 mm, with an average decrease of 4.4 mm. The average radiation shows no remarkable change, from -3.0 to 0.7 MJ/(m²·d), with an average increase of 0.8 MJ/(m²·d). The CO₂ concentration was projected to increase to 1 018.7 ppm in the 2090S.

2.2 Assessment of Future Risks in Seed Cotton Yield

2.2.1 Simulation of the potential yield and irrigation amount of seed cotton in the baseline period

The cotton production and irrigation amounts at 37 stations in the Tarim River Basin were simulated (Figure 3) using observed climatic data from 2001 to 2020, optimizing for the effects of water, fertilizer, pests and diseases, weeds, and soil salinization. The potential yield of

seed cotton was 6 389 kg/ha, with significant variations between stations. Cotton yields at the Hoxod, Wushi, and Baicheng stations were only 4 098 kg/ha, which was lower than the average potential yield, while the Kaxgar station had the highest yield potential (7 243 kg/ha). The average irrigation demand for the 37 stations was 490 mm. Wushi station had the lowest average irrigation demand (388 mm), while Ruoqiang station had the highest (550 mm). Other researchers have also investigated the potential yield of cotton in this basin.

2.2.2 The effect of climate change on seed cotton yield potential and irrigation amount

We used the SSP2-4.5 and SSP5-8.5 scenarios to evaluate how seed cotton yield potential and irrigation amount would react to climate change during 2021–2100. To distinguish between the effects of climate variability and CO₂ concentration changes on the potential yield of seed cotton, we kept the CO₂ concentration constant at 400 ppm, corresponding to a similar level as in 2020. Under future climate change scenarios, seed cotton would experience a rise in potential yield followed by a drop and an increase in irrigation demand, with significant variations between stations (Figure 4). At the basin scale, the potential yield of seed cotton under the SSP2-4.5 scenario was projected to increase by 7.0%, 7.6%, 6.8%, and 4.3% in the 2030S, 2050S, 2070S, and 2090S compared to the baseline period, exhibiting a trend of an initial increase followed by a drop. In contrast, the potential yield under the SSP5-8.5 scenario in the 2030S, 2050S, 2070S, and 2090S remained consistent with the baseline period but with greater magnitudes of 8.2%, 4.9%, -4.1%, and -18.6%, respectively. Some stations were projected to have a significantly increased potential seed cotton yield. Under the SSP2-4.5 scenario, the potential yield of seed cotton at Hoxod, Wushi, and Baicheng stations would increase by 3% to 68.5% (51.4% on average) compared to the baseline period. Meanwhile, under the SSP5-8.5 scenario, that potential yield would grow by 3% to 71.5%, with an average gain of 47.2%. Under the SSP2-4.5 scenario, the irrigation demand was projected to increase by 2.3%, 4.0%, 6.0%, and 7.5% in the 2030S, 2050S, 2070S, and 2090S, respectively, compared to the baseline period, showing a progressively increasing trend. In comparison, under the SSP5-8.5 scenario, the trend of irrigation demand changes in the 2030S, 2050S, 2070S, and 2090S remained unchanged from the baseline period but with an increase of 2.2%, 5.6%, 11.7%, and 20.1%, respectively.

Stepwise multiple regression analysis was used to objectively assess the relationship between the potential yield of seed cotton and climatic factors. The regression equations for the potential yield of seed cotton at each station were described by the maximum temperature (T_{max}), minimum temperature (T_{min}), cumulative precipitation (P), and average radiation (RA) during the growing season, involving 12 variables: T_{max}^1 , T_{max}^2 , T_{max}^3 , T_{min}^1 , T_{min}^2 , T_{min}^3 , P , P^2 , P^3 , RA , RA^2 , and RA^3 . After adjusting for variable collinear-

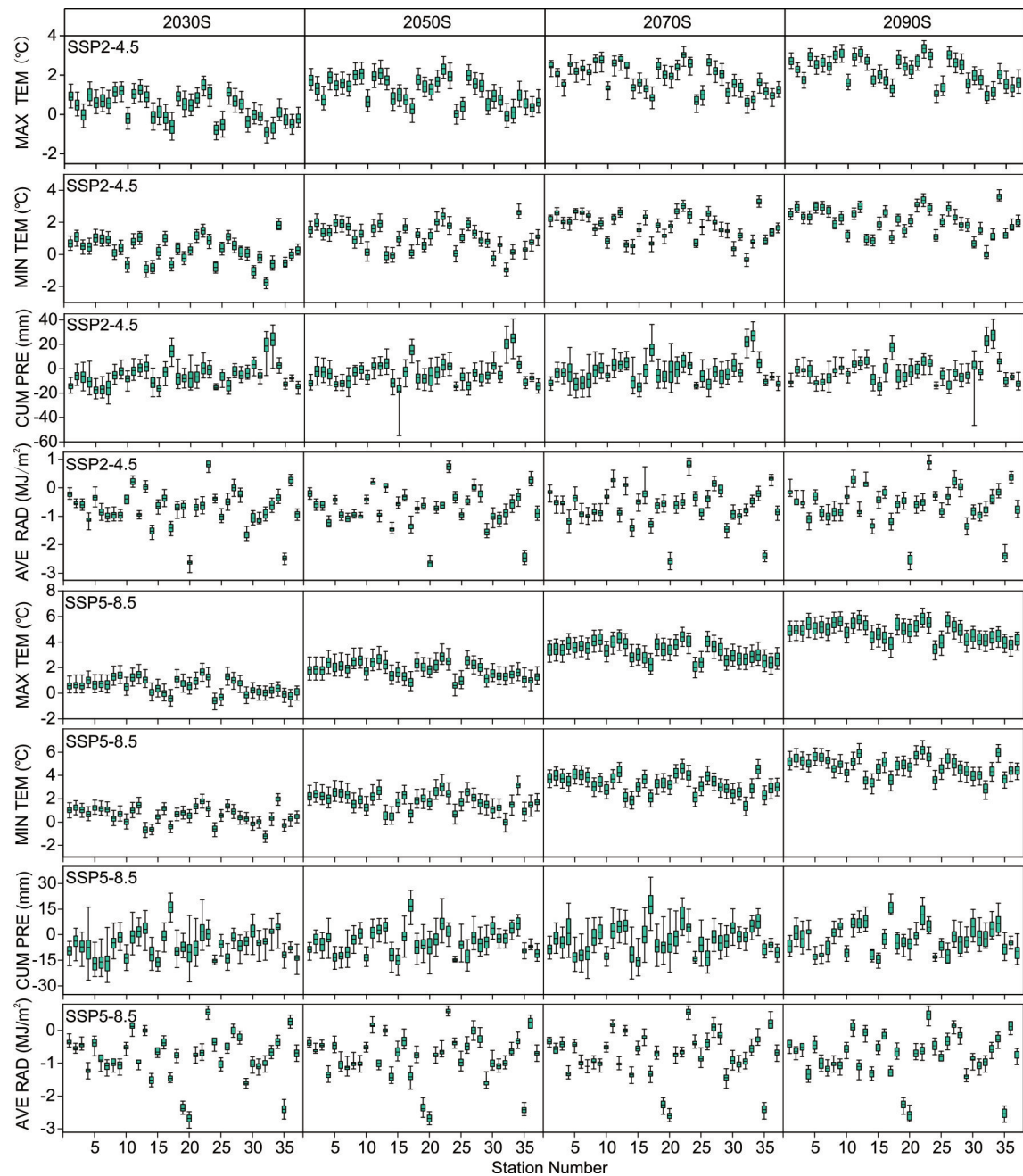


Figure 2. Changes in maximum temperature (MAX TEM), minimum temperature (MIN TEM), cumulative precipitation (CUM PRE), and average radiation (AVE RAD) in future scenarios for 37 stations in the Tarim River Basin compared to the base period. The box boundaries indicate the 25th and 75th percentiles, the black line inside the box indicates the mean, and the whiskers below and above the box indicate the minimum and maximum values, respectively.

ity, the equation with the highest determination coefficient (R^2) and the smallest root mean square error ($RMSE$) was selected as the optimal regression equation.

According to the stepwise regression analysis, climatic factors under the SSP2-4.5 scenario in the basin can account for 36.7% to 96.6% of the variation in the potential yield of seed cotton ($p \leq 0.01$). In contrast, climatic factors under the SSP5-8.5 scenario can explain the 87.0% to 98.7% variation in seed cotton potential yield ($p \leq 0.01$). The stepwise multiple regression analysis approach is an excellent way to portray the impact of climat-

ic factors on the potential yield of seed cotton. Climatic factors at 89.2% of stations could account for the projected potential yield of seed cotton in the SSP5-8.5 scenario more effectively than they did under the SSP2-4.5 scenario. Temperature was the most important climatic factor influencing prospective seed cotton output, and it varied by station. The potential yield of seed cotton was projected to increase, or increase first and then decrease, or decrease in response to an increase in temperature across the 37 stations. Under the SSP2-4.5 scenario, the proportions of stations exhibiting these three patterns of change

were approximately 16.2%, 56.8%, and 27.0%, respectively. Under the SSP5-8.5 scenario, the proportions of stations exhibiting these three patterns of change were around 0.0%, 51.4%, and 48.6%, respectively. The regression equations for 86.5% of stations in the Tarim River Basin revealed that the minimum temperature had a more significant impact on seed cotton production potential than the maximum temperature. The established optimal regression equation includes fewer stations with precipitation and radiation indices. This could be because the Tarim River Basin is an irrigated agricultural area, making it impossible to determine the impact of precipitation on the potential yield of seed cotton. In addition, radi-

ation has a minimal effect on the prospective production of seed cotton, and this mechanism is to be further studied.

2.2.3 Effect of CO₂ concentration on seed cotton yield potential and irrigation amount

With a change in CO₂ concentration, the response laws of seed cotton yield potential to future climatic change would be altered, resulting in a considerable increase in prospective yield but a limited impact on irrigation demand (Figure 5). Taking CO₂ concentration changes into consideration, the potential yield of seed cotton under the SSP2-4.5 scenario was projected to increase

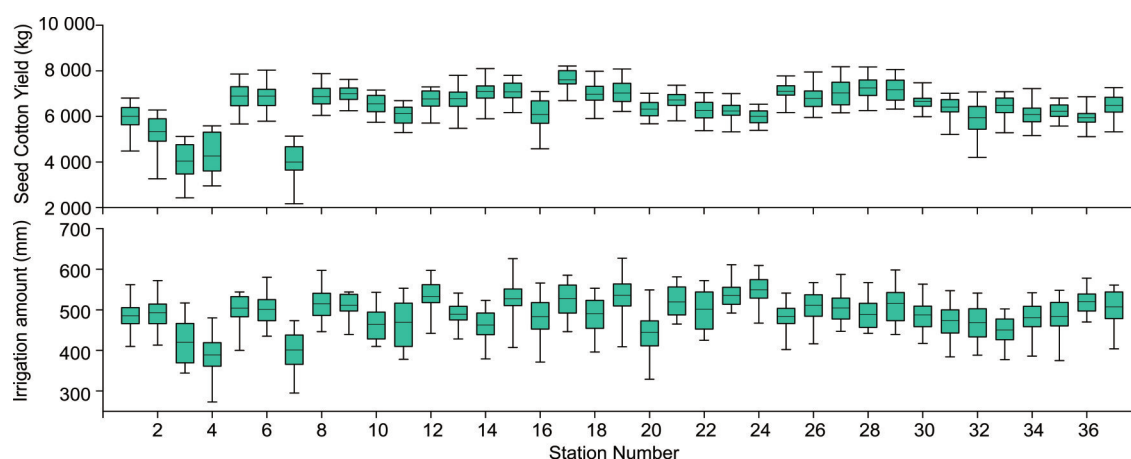


Figure 3. The estimated potential yield and irrigation amount of seed cotton in the baseline period based on observed data. The box boundaries indicate the 25th and 75th percentiles, the black line inside the box indicates the mean, and the whiskers below and above the box indicate the minimum and maximum values, respectively.

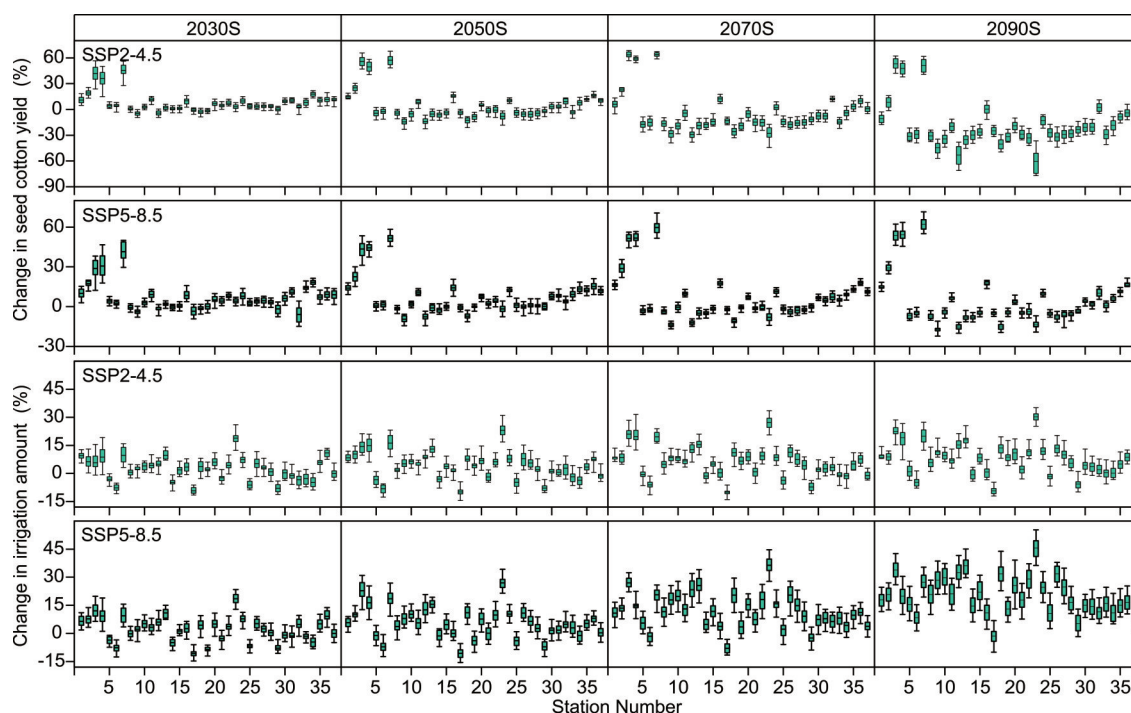


Figure 4. Changes in the potential yield and irrigation amount of seed cotton under future scenarios, regardless of CO₂ levels. The box boundaries indicate the 25th and 75th percentiles, the black line inside the box indicates the mean, and the whiskers below and above the box indicate the minimum and maximum values, respectively.

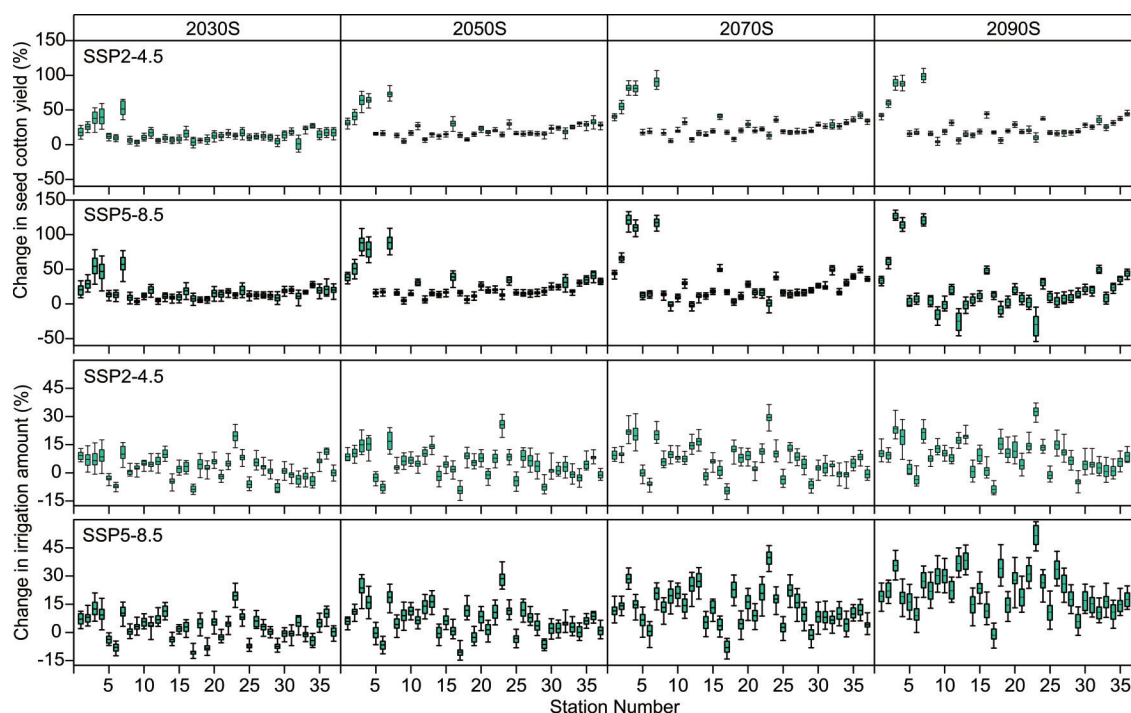


Figure 5. Changes in seed cotton yield potential and irrigation amount under future scenarios taking CO_2 concentration change into consideration. The box boundaries indicate the 25th and 75th percentiles, the black line inside the box indicates the mean, and the whiskers below and above the box indicate the minimum and maximum values, respectively.

by 14.8%, 23.7%, 29.0%, and 29.4% in the 2030S, 2050S, 2070S, and 2090S, respectively, in comparison to the baseline period. In the four periods mentioned above, the potential yield under the SSP5-8.5 scenario would grow initially before declining, with even more significant variations of 17.5%, 27.1%, 30.1%, and 22.6%, respectively, from the yield in the baseline period. Some stations would witness a remarkable rise in potential yield: for instance, the potential yield of seed cotton in Hoxod station would increase by 127.5% in the 2090S. As CO_2 concentrations vary, irrigation demand under the SSP2-4.5 scenario would increase progressively by 2.7%, 4.9%, 6.8%, and 8.6% in the 2030S, 2050S, 2070S, and 2090S, respectively, over the baseline period. The SSP5-8.5 scenario anticipated a similar shift trend in irrigation demand in these four periods, but the magnitude of the increase was as high as 2.6%, 6.4%, 12.8%, and 21.2%, respectively. Regardless of the decrease in CO_2 content, the irrigation amount increased marginally, on average, by less than 1% compared with that projected (Figure 4). Thus, there would be minimal effect on irrigation demand from a change in CO_2 concentration.

2.2.4 The response of seed cotton yield potential to limited water resources

The simulated effects of various irrigation schemes (Table 2) on the seed cotton yield potential under future scenarios that consider changes in climate and CO_2 concentration are shown in Figures 6 and 7. Before full irrigation, the potential yield of seed cotton would increase, al-

beit to varying degrees among stations. Under future scenarios, the coupling effects of climate change, CO_2 concentration, and moisture might mitigate the impact of water scarcity on seed cotton yield potential. The irrigation plan of 90% θ closely resembles the simulated irrigation level during the baseline period (Figure 3). Hence, the baseline irrigation level was considered to be 90% θ . The yield potential of seed cotton under the SSP2-4.5 scenario would vary from the baseline period by 6.8%, 10.8%, 12.0%, and 8.6% in the 2030S, 2050S, 2070S, and 2090S, respectively, assuming that the irrigation level in this basin stays at 90% θ under future scenarios. In contrast, the yield potential under the SSP5-8.5 scenario would change by 9.0%, 10.0%, 0.8%, and -19.8% in these four periods, respectively.

Given future changes in climate, CO_2 concentration, and irrigation demand, the resistance to water deficit would differ depending on the scenario and period. For example, under the SSP2-4.5 scenario, seed cotton yield potential in the 2090S would increase by 8.6%, compared to the baseline period, despite an 8.6% water deficit. Similarly, the SSP5-8.5 scenario would ensure a 0.8% increase in yield potential in the 2070S over the baseline period despite a 12.8% water deficit. We assumed that the potential yield of seed cotton stayed at the average level of the baseline period. In that case, future climate and CO_2 concentration changes might withstand a water deficiency of approximately 10% to 20% under the SSP2-4.5 scenario. Changes under the SSP5-8.5 scenario might result in a 10% to 15% water deficit in the 2030S, 2050S, and 2070S. In the 2090S, there would

be little resistance to water deficit, and a severe shortage would cause the potential yield of seed cotton to fall abruptly. The irrigation scheme in this basin was set at 60% θ since it may experience significant water scarcity in the future. With this setting, the seed cotton yield potential under the SSP2-4.5 scenario would decline from the baseline period by 28.4%, 28.7%, 29.9%, and 33.5% in the 2030S, 2050S, 2070S, and 2090S, respectively. The declines in the same periods in the SSP5-8.5 scenario would be 27.9%, 31.8%, 42.1%, and 59.8%.

At the station level, there would be significant variations in the water resource pressure required to maintain a particular seed cotton yield potential under future scenarios. Future scenarios may require some stations (such as Hoxod, Wushi, and Baicheng) to maintain or raise the seed cotton yield potential by retaining a low irrigation level. However, other stations (such as Shaya, Yu-

li, and Tikanlik) may require constant irrigation enhancement to maintain the current level of seed cotton yield. Under the SSP2-4.5 scenario, the water resource pressure at some stations, like Pishan, Qira, Moyu, Hotan, Lop, Minfeng, Qiemo, and Yutian, might not change much; however, under the SSP5-8.5 scenario, some of these stations may encounter increased water resource pressure.

3 DISCUSSION

3.1 Adaptation of Crop Models

The potential yield of cotton under mulched drip irrigation in southern Xinjiang was 6 773 kg/ha, with an optimal irrigation amount of 604 mm (Zhao, 2019). The average optimal potential yield of seed cotton at the Korla, Akesu, and Alaer stations was 5 957 kg/ha, with an average optimal irrigation amount of 578 mm (Lin et al.,

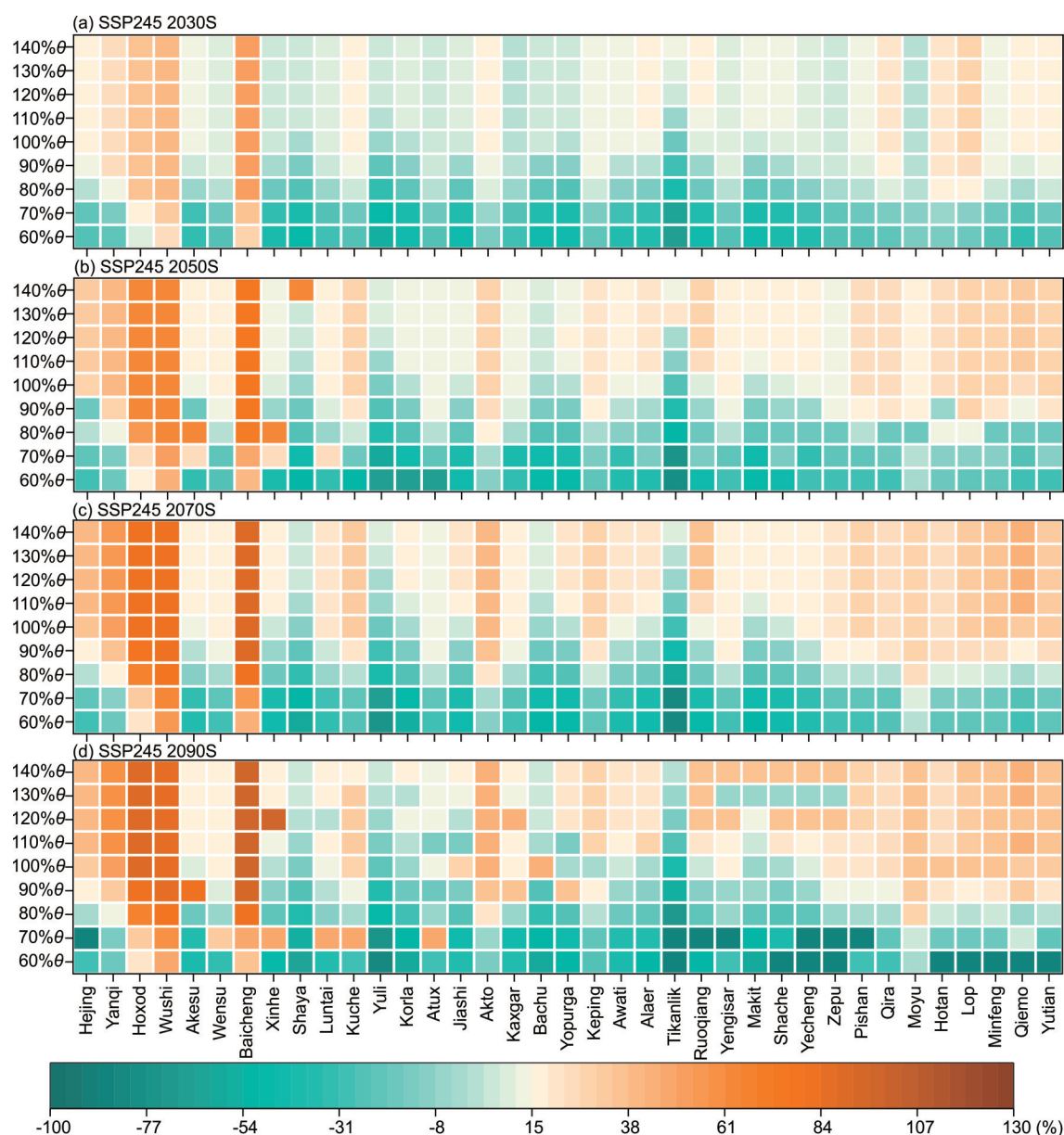


Figure 6. Responses of seed cotton yield potential to different irrigation schemes under the SSP2-4.5 scenario.

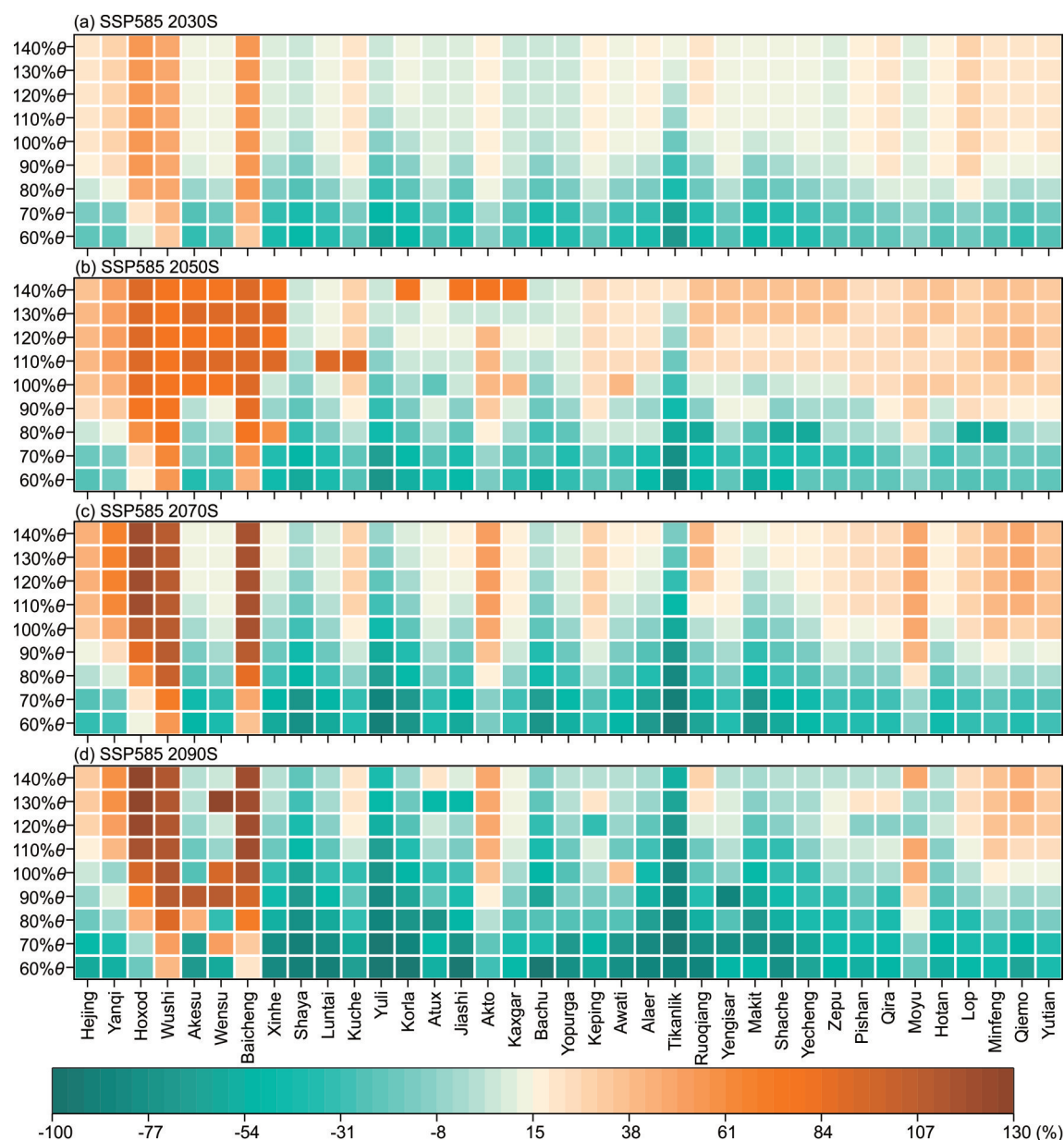


Figure 7. Responses of seed cotton yield potential to different irrigation schemes under the SSP5-8.5 scenario.

2024). The simulation effect was deemed adequate based on a comparison with measured data (Lin et al., 2024). Our study's simulation results deviated from the previously simulated potential yield of seed cotton by approximately 6%. The two simulation results are identical when considering the differences in simulation methods, stations, varieties, and soil parameters. Moreover, we simulated the irrigation amount based on the assumption that the initial soil moisture was the field capacity. Thus, using the DSSAT-CROPGRO-Cotton model to simulate seed cotton production and irrigation requirements in the Tarim River Basin is feasible.

3.2 Impact of Climate Change on Cotton Production

Climate change largely determines the growth and development, yield, and quality of cotton (Li, 2021; Li et

al., 2020; Wang, 2015). Future climate scenarios would initially increase the seed cotton yield potential in the Tarim River Basin, followed by a decrease, while constantly increasing the irrigation demand. This would result in a greater sensitivity of the potential yield to the minimum temperature, albeit varying amongst stations. This finding is consistent with the conclusion of Shikha et al. (2022). In addition, the responses of cotton yield to future climate change would also vary in different climatic regions. A slight temperature rise may be suitable for cotton production, while a high increase in temperature may go against cotton production.

Specific indices that affect the potential yield of seed cotton in Xinjiang include average air pressure, maximum temperature, sunshine hours, average temperature, and average relative humidity; however, precipitation and average minimum temperature had minimal effects (Lin

et al., 2024). According to other researchers, the duration of sunshine, average temperature, maximum temperature, and minimum temperature are the main climatic factors affecting the potential production of seed cotton in Xinjiang (Li et al., 2020). Similarly, this investigation revealed that seed cotton yield potential strongly responded to minimum temperature but not to cumulative precipitation or average radiation. The selected study area, spatial scale, and analytic techniques could all be responsible for this discrepancy.

The CO₂ concentration affects the seed cotton's net photosynthetic rate and radiation use efficiency (Xu et al., 2022). Consistent with prior research findings, this study demonstrated that an increase in CO₂ concentration can counteract the detrimental effects of climate change on cotton yield and substantially boost the potential yield of seed cotton (Xu et al., 2022). In the future, rising irrigation demand for cotton production in this basin may be linked to increased evapotranspiration caused by rising temperatures (Allen et al., 1998). Crop water use efficiency and cotton yield would both increase with an intensification of CO₂ concentration (Tian et al., 2023; Xu et al., 2022). However, the future temperature rises and precipitation changes may counteract or boost the effect of increased CO₂ concentration on cotton yield, indicating regional and station-specific variations (Nasim et al., 2016; Hatfield and Prueger, 2015). Water scarcity may limit the potential yield of seed cotton under the combined effect of future climate and CO₂ concentration, as indicated by relevant studies (Adhikari et al., 2015). Future irrigation demands will depend on climate change and crop response to CO₂ concentration to sustain cotton production in the Tarim River Basin (Tian et al., 2023). In addition, there will be station-specific differences in water resource pressure under future scenarios.

3.3 Limitations and Suggestions

This study has few limitations because of data uncertainty and the complexity of agricultural production. This study did not consider variables like the variety diversity, and variations in sowing dates and irrigation regimes within the basin while exploring the effects of climate factors, CO₂ concentration, and water resource supply on the potential yield of seed cotton. Differences in soil quality are also an important factor affecting vegetation growth, but this was not considered in this study (Yue Y M et al., 2024). The production course of seed cotton is impacted by climatic change, which in turn affects the cotton's yield potential and quality (Li, 2021; Wang, 2015); however, the phenology and quality of cotton are not covered in this work. The crop growth and development course employed in the model is simplified and may differ from the natural growth conditions. Furthermore, this study did not consider limiting factors inconsistent with the actual production conditions, such as pests, diseases, weeds, and nutrient stress. Soil salinization in the Tarim River Basin significantly affects the growth and water use efficiency of cotton (Ding et al., 2020; Yang et al.,

2016; Zhao et al., 2015), highlighting the need to study the impact of future scenarios on cotton production in the context of soil salinization. However, it's a fact that a study can only focus on limited variables at one time to give informative results. The uncertainty in climate change impact predictions is related to a variety of factors, including the selection of climate models and the uncertainties of crop models, among others (Li et al., 2024; ur Rahman et al., 2018). By comparing and analyzing the results of different climate models, a better understanding of the sources of uncertainty can be achieved. Incorporating predictions from multiple crop models can help avoid the limitations of a single crop model, thereby increasing the robustness of the simulation results.

The potential increase in temperature and water scarcity may increase the risks associated with cotton production in the Tarim River Basin, thus necessitating improvements in irrigation and water resource management methods. These improvements could include advanced irrigation technologies and water-saving methods. To adapt to the anticipated climatic conditions, it is important to select cotton varieties that can withstand high temperatures and drought, and maintain or improve photosynthetic efficiency under elevated CO₂ levels. Furthermore, adjusting the areas where cotton is planted in response to climate change is also worth considering. In summary, this paper discusses the future scenarios of seed cotton yield potential and risks in the Tarim River Basin from the perspectives of climate change, elevated CO₂ concentration, and limited water resources at both basin and station levels. The results can be a theoretical reference in formulating rational strategic policies to adjust cotton yield to climate change. The findings and methods of this study are not only applicable to the Tarim River Basin but can also be extended to other arid and semi-arid regions, providing references for agricultural adaptation to climate change in similar areas. The climate models and crop simulation models used, as well as irrigation management and variety selection strategies, are also instructive for other crops and agricultural systems, helping global agriculture cope with the challenges of climate change. In future research, incorporating more factors such as soil heterogeneity, cotton variety diversity, and field management, and further exploring the uncertainties brought about by the selection of climate and crop models, is a reliable measure to improve the accuracy of simulations.

4 CONCLUSIONS

This study utilized data from meteorological observations and a literature review to assess the simulated potential yield and irrigation requirements of seed cotton in the Tarim River Basin using the DSSAT-CROPGRO-Cotton model. The key findings are as follows.

(1) The Tarim River Basin is projected to experience a significant temperature increase in the future, with no significant changes in precipitation or radiation during the cotton growing season.

(2) The DSSAT-CROPGRO-Cotton model accurately simulates the potential yield and irrigation needs of seed cotton, which will initially increase and then decrease due to climate change.

(3) An increase in CO₂ levels will significantly enhance the potential yield of seed cotton, with a minimal impact on irrigation demand.

(4) At higher CO₂ concentrations, water scarcity will limit the potential yield of seed cotton, with varying impacts under different scenarios and time periods.

Specifically, under the SSP2-4.5 scenario, the potential yield of seed cotton is expected to increase by 4.3% to 29.4% from the 2030s to the 2090s compared to the baseline period. In contrast, under the SSP5-8.5 scenario, the yield potential may decrease by 18.6% or increase by up to 30.1%. Moreover, while current irrigation levels can be maintained under the SSP2-4.5 scenario, the resistance to irrigation water deficit in the 2090s under the SSP5-8.5 scenario will be considerably limited.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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