agronomy

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RZWQM2 Simulated Irrigation Strategies to Mitigate Climate Change Impacts on Cotton Production in Hyper–Arid Areas

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Abstract: Improving cotton (*Gossypium hirsutum* L.) yield and water use efficiency (WUE) under future climate scenarios by optimizing irrigation regimes is crucial in hyper-arid areas. Assuming a current baseline atmospheric carbon dioxide concentration ($[CO_2]_{atm}$) of 380 ppm (baseline, $BL_{0/380}$), the Root Zone Water Quality Model (RZWQM2) was used to evaluate the effects of four climate change scenarios—$S_{1.5/380}$ ($\Delta T^{\circ}_{air} = 1.5\ ^{\circ}C, \Delta[CO_2]_{atm} = 0$), $S_{2.0/380}$ ($\Delta T^{\circ}_{air} = 2.0\ ^{\circ}C, \Delta[CO_2]_{atm} = 0$), $S_{1.5/490}$ ($\Delta T^{\circ}_{air} = 1.5\ ^{\circ}C, \Delta[CO_2]_{atm} = +110$ ppm) and $S_{2.0/650}$ ($\Delta T^{\circ}_{air} = 2.0\ ^{\circ}C, \Delta[CO_2]_{atm} = +270$ ppm) on soil water content (θ), soil temperature (T°_{soil}), aboveground biomass, cotton yield and WUE under full irrigation. Cotton yield and irrigation water use efficiency (IWUE) under 10 different irrigation management strategies were analysed for economic benefits. Under the $S_{1.5/380}$ and $S_{2.0/380}$ scenarios, the average simulated aboveground biomass of cotton (vs. $BL_{0/380}$) declined by 11% and 16%, whereas under $S_{1.5/490}$ and $S_{2.0/650}$ scenarios it increased by 12% and 30%, respectively. The simulated average seed cotton yield (vs. $BL_{0/380}$) increased by 9.0% and 20.3% under the $S_{1.5/490}$ and $S_{2.0/650}$ scenarios, but decreased by 10.5% and 15.3% under the $S_{1.5/380}$ and $S_{2.0/380}$ scenarios, respectively. Owing to greater cotton yield and lesser transpiration, a 9.0% and 24.2% increase (vs. $BL_{0/380}$) in cotton WUE occurred under the $S_{1.5/490}$ and $S_{2.0/650}$ scenarios, respectively. The highest net income (\$3741 ha^{-1}) and net water yield (\$1.14 m^{-3}) of cotton under climate change occurred when irrigated at 650 mm and 500 mm per growing season, respectively. These results suggested that deficit irrigation can be adopted in irrigated cotton fields to address the agricultural water crisis expected under climate change.

Keywords: global warming; deficit irrigation; cotton yield; water use; RZWQM2

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Citation: Chen, X.; Dong, H.; Feng, S.; Gui, D.; Ma, L.; Thorp, K.R.; Wu, H.; Liu, B.; Qi, Z. RZWQM2 Simulated Irrigation Strategies to Mitigate Climate Change Impacts on Cotton Production in Hyper–Arid Areas. *Agronomy* **2023**, *13*, 2529. https://doi.org/10.3390/agronomy13102529

Academic Editor: Iván F. García Tejero

Received: 10 August 2023
Revised: 15 September 2023
Accepted: 28 September 2023
Published: 29 September 2023

1. Introduction

Severe water shortages brought on by climate change will lead to more unstable crop production in the arid regions of northwest China. Climate change, characterized by global warming, threatens the stability of cotton (*Gossypium hirsutum* L.) production in Xinjiang, China [1]. To mitigate the risks and impacts of climate change, the 2015 Paris Agreement stated that one must "hold the increase in the global average temperature to well below 2.0 °C above pre–industrial levels" and "pursue efforts to limit the temperature increase to 1.5 °C above pre–industrial levels" [2]. As one of the most important cash and fiber crops in China, Xinjiang cotton accounts for 89% and 83% of the nation's cotton production and acreage, respectively (National Bureau of Statistic of China 2021). Water for cotton irrigation in Xinjiang consumes 23.5×10^9 m^3 y^{-1}, accounting for approximately 6% of agricultural water use in the region. The amelioration of saline–alkaline soil has led to an increase in irrigation water usage. In addition, 48.6% of irrigation water for cotton comes from mountain snows and glacial meltwater and contributes to 55.9% of the total cotton production in southern Xinjiang. Moreover, cotton acreage and irrigation water consumption in Xinjiang is predicted to increase in the future [3]. However, future climate change and water scarcity seriously threaten sustainable cotton production in this arid region [4–6]. Therefore, governments at several levels, scientists, and producers are concerned about the effects of climate warming on cotton yield and how to improve water use efficiency (WUE) and the economic benefits of crop production in arid regions.

Global warming of 1.5 °C and 2.0 °C has already resulted in more negative than positive impacts on global crop yields. In China's arid region, T°_{air} has increased by 1.5 °C over the past 50 years and regional warming is expected to continue in the future [7]. Based on 1.5 °C and 2.0 °C warming scenarios, He et al. [8] predicted that the area suitable for planting summer maize (*Zea mays* L.) would decline by 40% to 55%, and that the negative effects of a 2.0 °C warming scenario on maize yield would exceed those under a 1.5 °C warming scenario. Liu et al. [9] predicted that the risk of extremely low wheat (*Triticum aestivum* L.) yields may increase in the hot–dry regions under 1.5 °C and 2.0 °C global warming scenarios. Similarly, Ye et al. [10] and Liu et al. [11] showed that crop yields under the 2.0 °C warming scenario would be much lower than under the 1.5 °C warming scenario. Many studies reported that global warming would increase crop evapotranspiration (ET), accelerate the fertility process and shorten the crop growth period [12–14], ultimately leading to yield reduction [15,16]. Irrigation water is essential to maintain crop yields in an arid region [17]. Therefore, irrigation practices need to be optimized to mitigate the adverse effects of water scarcity on crop production under climate change.

Cotton growth and yield in arid regions are directly influenced by climate change and irrigation practices. Global warming will lead to lesser soil water levels and greater drought conditions in arid regions, while increased evaporative demand under rising temperatures will lead to increased evaporative losses from the surface and greater soil water deficits [18]. Soil water and temperature conditions are important environmental factors required for crop growth and development and the formation of crop yield [19]. Soil water plays a key role in the physiological–ecological processes of cotton production, and deficiencies or excesses could adversely affect cotton production [1]. Trends in soil moisture in both drying and wetting zones are mainly influenced by climate change [20]. Insufficient soil water will, in turn, increase near–surface atmospheric temperatures [21,22], thereby decreasing cotton yields due to soil water and high temperature stress. Stefanon et al. [23] and Pablos et al. [24] noted that soil temperature (T°_{soil}) controls ET and indirectly affects soil water. High T°_{soil} due to soil water deficits exacerbate the effects of meteorological drought on agricultural systems [25]. The frequency and intensity of high temperature extremes would increase in arid regions under future climate change [26]. However, soil moisture is the main limiting factor affecting crop yields in the arid regions of Northwest China [27]. Meanwhile, the interaction between soil water and heat will be influenced by an elevated atmospheric CO_2 concentration ($[CO_2]_{atm}$). In agroecosystems, an elevated $[CO_2]_{atm}$ not only has a fertilization effect on increased cotton yields, but also decreases leaf stomatal conductance, ET and crop water loss, with the consequence of mitigating the problem of insufficient soil water availability [28,29]. Noteworthy, cotton is a drought-tolerant crop and adapts well to deficit irrigation (DI) practices. Li et al. [30] concluded that DI helped to maximize the yield per unit of water for a given crop under water scarcity and drought conditions. However, owing to high cost (difficult to control climate factors) in field experiments, studies on the effects of future climate change on cotton yield under DI are rare.

Optimizing irrigation scheduling is critical to improving crop yields and IWUE in response to global warming, especially in hyper–arid areas. Elliott et al. [17] reported that climate change affects the availability of water for irrigation and therefore has the potential to have a significant impact on agricultural production as well. Deficit irrigation is a common water–saving agricultural practice that optimizes the allocation of the amount of crop irrigation under water deficit conditions [31]. Oweis et al. [32] suggested that DI was a viable option for cotton production under water–scarce conditions without significantly reducing cotton yield. Thind et al. [33] and Ünlü et al. [34] suggested that 75% of full irrigation (FI) was optimal for achieving high cotton yields in arid and semi–arid regions. Crop growth and development are closely related to weather conditions, soil moisture and temperature, $[CO_2]_{atm}$, and agricultural management practices. However, it is difficult to control all factors in an actual field experiment when evaluating climate change effects on crop yields. Offering the benefit of combining crop growth and climatic conditions, crop models are widely used to simulate the effects of climate change on crop production under deficit irrigation. Employing the Decision Support System for Agrotechnology Transfer (DSSAT) model, Kothari et al. [35] found that, with a minor sorghum yield reduction of <11% in the Texas High Plains (THP) region, 20% deficit irrigation provided more WUE than full irrigation for current and future conditions. Using the DSSAT model, Winter et al. [36] proposed that DI could mitigate the impact of water scarcity on agricultural production under climate change. Crop models play an important role in evaluating the growth and environmental impacts of crop production under different management practices and weather conditions [37,38].

The Root Zone Water Quality Model (RZWQM2), as a coupling of the detailed soil water and management modules of RZWQM with the detailed plant growth modules of DSSAT 4.0, has the advantages of simulating changes in potential transpiration (ETp), actual transpiration (ETa), and crop water stress caused by the effects of heightened atmospheric CO_2 levels and different irrigation management practices on crop yields [30,39,40]. Based on RZWQM2, Chen et al. [6] predicted the impact of climate change on cotton yield and water requirements in northwest China in the near term (2041–2060) and for the long term (2061–2080). Zhang et al. [41] simulated the effects of deficit irrigation and climate change on sunflower (*Helianthus annuus* L.) yield in semi-arid Colorado under four RCP representative concentration emission pathways. However, studies investigating how to optimize deficit irrigation practices to address negative impacts of global warming on cotton yield in hyper-arid areas are rare. Therefore, using a previously calibrated and validated RZWQM2 model [42], the present study was designed to address the following objectives: (i) predict changes in soil water and temperature, aboveground biomass, yield and WUE of cotton in hyper–arid areas under $\Delta T^{\circ}_{air} = 1.5$ °C and $\Delta T^{\circ}_{air} = 2.0$ °C global warming scenarios and (ii) optimize irrigation scheduling under the climate change scenarios using an economic analysis approach.

2. Materials and Methods

2.1. Study Region

The Cele Oasis (36°54′ N–37°09′ N, 80°37′ E–80°59′ E; Figure 1), located on the southern edge of the Taklamakan Desert, Xinjiang, Northwest China, is subject to a hyper-arid climate region, with average annual rainfall of 50.9 mm. The average annual temperature (1960–2019) is 15.2 °C, with maxima and minima of 41.4 °C and −21 °C, respectively. Glacial meltwater and groundwater are the main sources of irrigation water for cotton in this region. The region's soils are dominated by a sandy soil.

2.2. RZWQM2 Model Description

RZWQM2 is an integrated physical, biological, and chemical process model that simulates movement of soil water and plant growth under a wide spectrum of management practices and scenarios [43]. The ability of the model to simulate soil water content (θ) and temperature, yield and biomass of cotton in response to temperature and $[CO_2]_{atm}$ has been documented on several occasions [5,6,44–46]. The detailed analysis of the crop photosynthetic response to variations in $[CO_2]_{atm}$ can be found in Islam et al. [47]. The parameters for soil hydraulic properties and cotton growth used in the RZWQM2 model were from Chen et al. [42], who calibrated and verified the model against data from a 4–year field experiment under FI and DI treatments. All parameters and agricultural management practices for simulating θ and T°_{soil} under future climate scenarios were consistent with the baseline period (1960–2019). Sowing and harvest dates were set as April 11 of each year (local multi-year average) and the date of maturity, respectively. Row spacing and planting depth were 0.30 m and 0.04 m, respectively. Irrigation water applied per growing season was 650 mm. Fertilizer application rates were 84 kg ha^{-1} NO_3^--N and 84 kg ha^{-1} NH_4^+-N before planting.

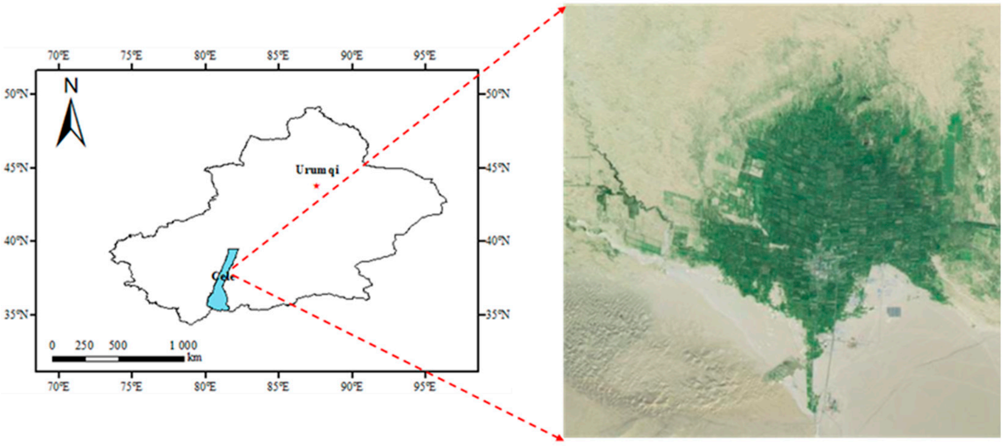

Figure 1. Location of the Cele Oasis in Xinjiang China.

2.3. Meteorological Data and Climate Scenarios

Historical weather data (daily maximum and minimum T°_{air}, shortwave radiation, wind speed, relative humidity, and rainfall) from 1960 to 2019 were downloaded from the China Meteorological Data Sharing Services System (CMDSSS, http://data.cma.cn/, accessed on 1 January 2020). Along with a baseline scenario, four future climate scenarios were generated for the RZWQM2 model to simulate θ and T°_{soil}, aboveground biomass and yield of cotton under 1.5 °C or 2.0 °C warming (ΔT°_{air} = +1.5 °C or ΔT°_{air} = +2.0 °C), with or without increases in $[CO_2]_{atm}$. The five scenarios are shown in Table 1.

Table 1. Description of five future climate scenarios.

Climate Scenario	Description
$BL_{0/380}$	ΔT°_{air} from present = 0 °C, $[CO_2]_{atm}$ = 380 ppm
$S_{1.5/380}$	ΔT°_{air} = 1.5 °C, $\Delta[CO_2]_{atm}$ = 0
$S_{2.0/380}$	ΔT°_{air} = 2.0 °C, $\Delta[CO_2]_{atm}$ = 0
$S_{1.5/490}$	ΔT°_{air} = 1.5 °C, $\Delta[CO_2]_{atm}$ = +110 ppm
$S_{2.0/650}$	ΔT°_{air} = 2.0 °C, $\Delta[CO_2]_{atm}$ = +270 ppm

The future $[CO_2]_{atm}$ in scenarios where $\Delta[CO_2]_{atm} \neq 0$ were 490 ppm and 650 ppm, based on the results of Moss et al. [48], IPCC [49], and Mohanty et al. [50].

2.4. Irrigation Practices and Economic Analysis

The RZWQM2 model was used to simulate cotton yield and irrigation WUE under deficit irrigation for a 60–year period (1960–2019). Considering that increased irrigation may increase cotton yields under future climate scenarios, 10 growing season drip irrigation treatments were set: Irr_{850} (850 mm), Irr_{750} (750 mm), Irr_{700} (700 mm), Irr_{650} (650 mm), Irr_{600} (600 mm), Irr_{550} (550 mm), Irr_{500} (500 mm), Irr_{450} (450 mm), Irr_{400} (400 mm) and Irr_{350} (350 mm). The depth of irrigation for the Irr_{650} treatment was based on the local multi–year average, defaulted to full irrigation (FI). The response of crop cotton to different excess or deficit irrigation levels was evaluated during the cotton growing season in future climate scenarios ($S_{1.5/380}$, $S_{2.0/380}$, $S_{1.5/490}$, $S_{2.0/650}$). Six irrigation events were scheduled for each growing season: April 7 (150 mm preplant), and the remainder in equal amounts on 14 June, 3 July, 15 July, 13 August, and 4 September (Table 2). Fixed irrigation dates were set based on local multi–year experience, due to the fact that there is very little rainfall during the growing season. The irrigation water use efficiency (IWUE) was calculated as the ratio of seed cotton yield to irrigation amount.

Table 2. The irrigation amount and dates for different irrigation treatments.

Irrigation Level	Irrigation Date and Amount (mm)					
	7 April	14 June	3 July	15 July	3 August	4 September
Irr_{850}	150	140	140	140	140	140
Irr_{750}	150	120	120	120	120	120
Irr_{700}	150	110	110	110	110	110
Irr_{650}	150	100	100	100	100	100
Irr_{600}	150	90	90	90	90	90
Irr_{550}	150	80	80	80	80	80
Irr_{500}	150	70	70	70	70	70
Irr_{450}	150	60	60	60	60	60
Irr_{400}	150	50	50	50	50	50
Irr_{350}	150	40	40	40	40	40

The economic analysis was based on 60 years (1960–2019) of simulated average cotton yield and irrigation volume. The economic indicators included water cost (\$ ha^{-1}), gross and net income (\$ ha^{-1}), and net water production (Nwp, \$ m^{-3}). Gross income was the product of seed cotton yield and unit price. Net income was the difference between gross income and costs. The costs include water costs and basic costs. Water costs were calculated based on the irrigation amount and the price of irrigation water. The basic cost was estimated at \$2000 ha^{-1} for each treatment, which mainly included labor cost, fertilizer, seeds, weeding, seeding and harvesting [43]. The Nwp was the ratio of net income to irrigation water applied. Water (\$0.04 m^{-3}) and cotton prices (\$1.3 kg^{-1}) were averaged from local government pricing and local market pricing, respectively [4]. The Nwp is calculated as follows:

$$\text{Nwp} = \frac{Ni}{Irr} \quad (1)$$

where Ni is the net income, and Irr is the irrigation amount.

3. Results

3.1. Responses of Soil Water and Temperature to Future Climate Scenarios

The soil water content and temperature under different climate scenarios at depths of 0–0.15 m, 0.15–0.25 m, 0.25–0.40 m, 0.40–0.65 m, and 0.65–1.00 m were simulated from planting to harvest. The simulated θ under different climate scenarios (Figure 2) showed a decreasing trend for all global warming scenarios, except for the $S_{2.0/650}$ scenario. The simulated baseline average θ was 0.127 cm^3 cm^{-3} during the growing season (April to October), whereas under the $S_{1.5/380}$, $S_{2.0/380}$, and $S_{1.5/490}$ scenarios, the simulated average θ in the soil's surface layer (0–0.15 m) decreased by 0.44%, 0.67% and 0.03%, respectively. In contrast, a 0.45% increase in average θ occurred under the $S_{2.0/650}$ scenario, with a maximum increase of 0.92% in the surface layer (0–0.15 m). The simulated monthly θ varied slightly for each scenario, with a maximum value in September for the $S_{2.0/650}$ scenario and a minimum value in August under $BL_{0/380}$.

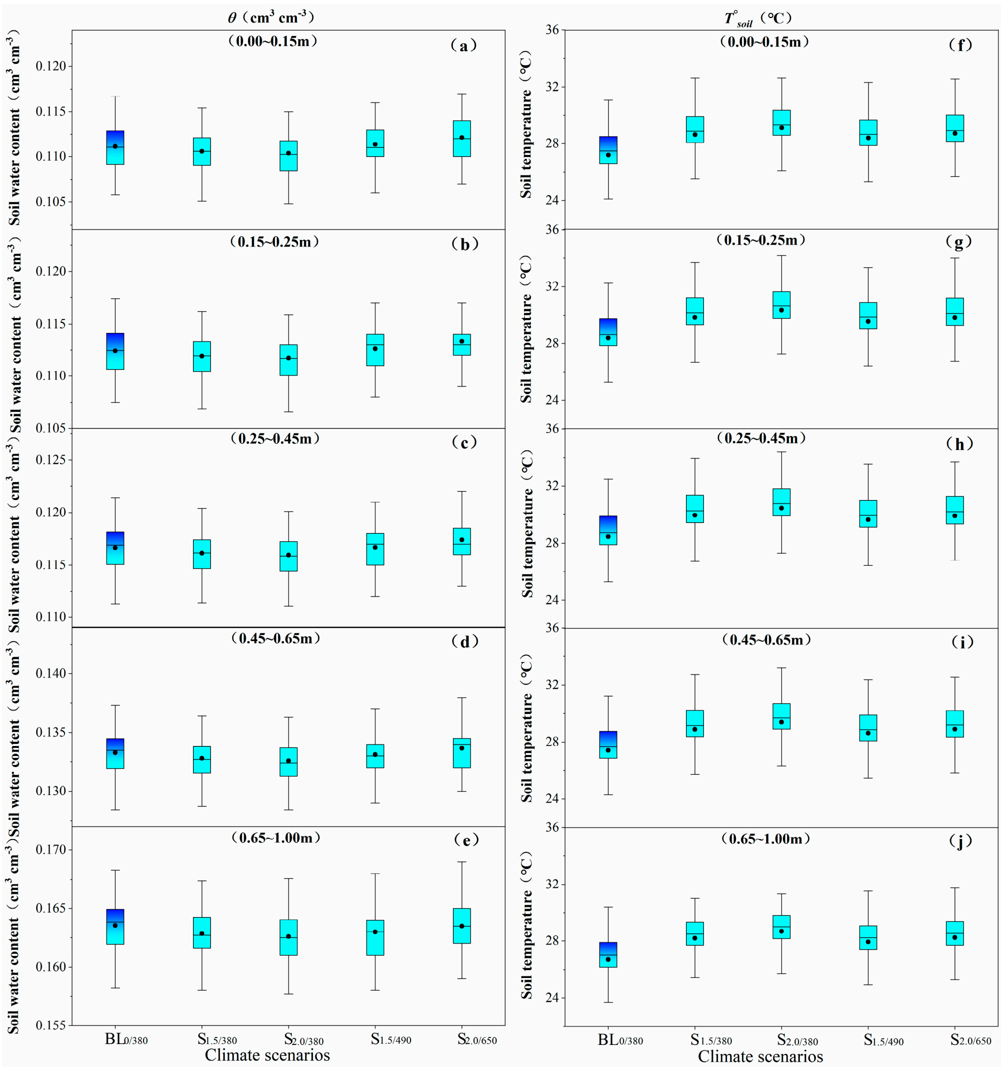

Figure 2. Simulated soil water content (**a**–**e**) and soil temperature (**f**–**j**) under four future climate scenarios, as well as baseline conditions. $BL_{0/380}$, ΔT°_{air} from present = 0 °C, $[CO_2]_{atm}$ = 380 ppm; $S_{1.5/380}$, ΔT°_{air} = 1.5 °C, $\Delta[CO_2]_{atm}$ = 0; $S_{2.0/380}$, ΔT°_{air} = 2.0 °C, $\Delta[CO_2]_{atm}$ = 0; $S_{1.5/490}$, ΔT°_{air} = 1.5 °C, $\Delta[CO_2]_{atm}$ = +110 ppm; $S_{2.0/650}$, ΔT°_{air} = 2.0 °C, $\Delta[CO_2]_{atm}$ = +270 ppm.

Different climate scenarios led to increases in T°_{soil} for each soil layer (Figure 2). The simulated average T°_{soil} for the $S_{1.5/380}$, $S_{2.0/380}$, $S_{1.5/490}$ and $S_{2.0/650}$ scenarios increased by 1.48 °C (5.35%), 1.97 °C (7.14%), 1.21 °C (4.36%), and 1.49 °C (5.4%), respectively, compared to the T°_{soil} under $BL_{0/380}$ (27.63 °C). The highest T°_{soil} occurred in 0.25–0.45 m soil layer under the $S_{2.0/380}$ scenario, while the lowest T°_{soil} occurred in the 0.65–1.00 m soil layer under $BL_{0/380}$.

3.2. *Impacts of Future Climate Scenarios on Aboveground Biomass and Yield under Full Irrigation*

Figure 3 shows the simulated aboveground biomass of cotton from flowering to harvest under different climate scenarios. Simulations predicted that, compared to the $BL_{0/380}$ scenario, aboveground biomass of cotton would decrease under scenarios of current $[CO_2]_{atm}$ but increase under scenarios of elevated $[CO_2]_{atm}$ over the whole growth period. The simulated average aboveground biomasses of cotton under $BL_{0/380}$ were 0.93 Mg ha^{-1}, 3.63 Mg ha^{-1}, 8.85 Mg ha^{-1} and 10.51 Mg ha^{-1} at the flowering, first seed, cracked B1 and harvest stages, respectively. Compared with BL, the simulated average aboveground biomass of cotton under the $S_{1.5/380}$ and $S_{2.0/380}$ decreased by 11% and 16%, respectively. In contrast, under the $S_{1.5/490}$ and $S_{2.0/650}$ scenarios the average aboveground biomass of cotton increased by 12% and 30%, respectively, compared to $BL_{0/380}$. The simulated average seed cotton yield for the baseline period (1960–2019) was 3.77 Mg ha^{-1} (Figure 4). Seed cotton yield decreases of 0.39 Mg ha^{-1} (10.46%) and 0.58 Mg ha^{-1} (15.32%) occurred under the $S_{1.5/380}$ and $S_{2.0/380}$ scenarios, respectively. In contrast, simulated seed cotton yield under scenarios $S_{1.5/490}$ and $S_{2.0/650}$ increased by 0.34 Mg ha^{-1} (9.01%) and 0.77 Mg ha^{-1} (20.30%), respectively, compared to $BL_{0/380}$.

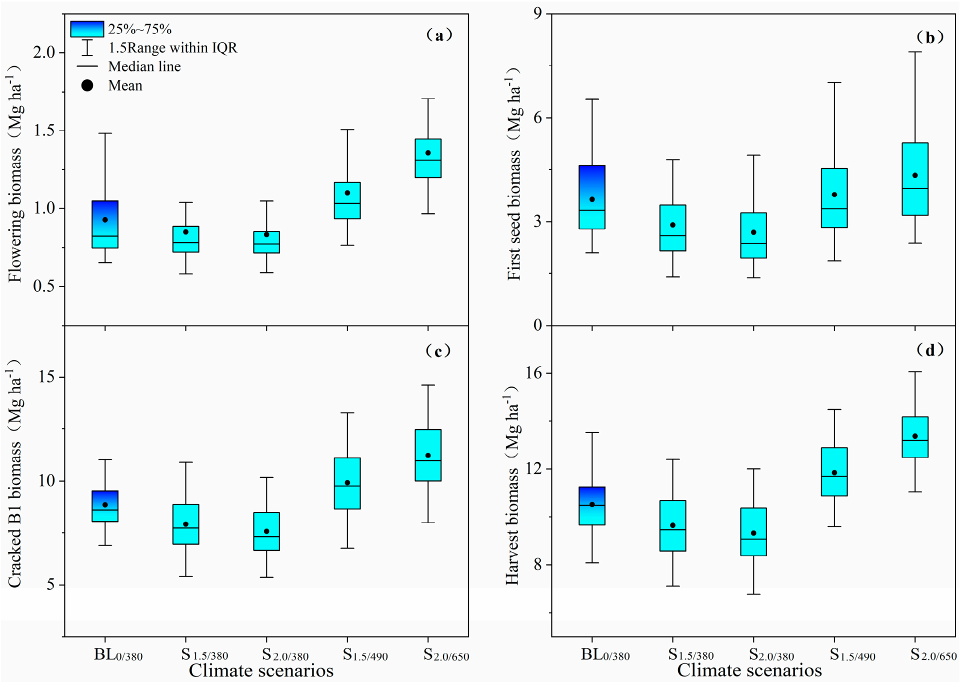

Figure 3. Simulated aboveground biomass of cotton at the flowering (**a**), first seed (**b**), cracked B1 (**c**), and harvest (**d**) stages in response to four future climate scenarios, as well as baseline conditions. $BL_{0/380}$, ΔT°_{air} from present $= 0$ °C, $[CO_2]_{atm} = 380$ ppm; $S_{1.5/380}$, $\Delta T^{\circ}_{air} = 1.5$ °C, $\Delta[CO_2]_{atm} = 0$; $S_{2.0/380}$, $\Delta T^{\circ}_{air} = 2.0$ °C, $\Delta[CO_2]_{atm} = 0$; $S_{1.5/490}$, $\Delta T^{\circ}_{air} = 1.5$°C, $\Delta[CO_2]_{atm} = +110$ ppm; $S_{2.0/650}$, $\Delta T^{\circ}_{air} = 2.0$ °C, $\Delta[CO_2]_{atm} = +270$ ppm.

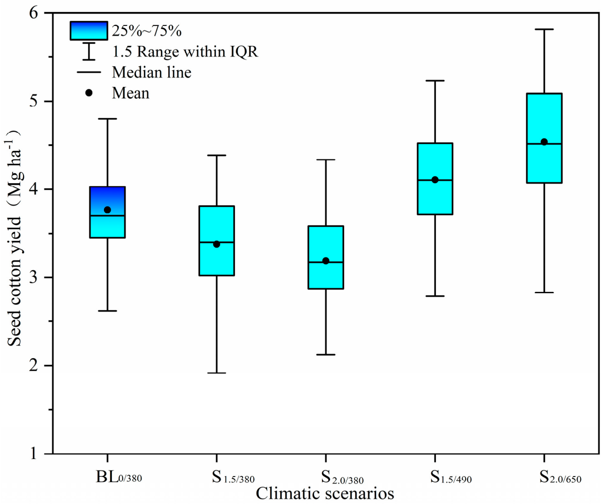

Figure 4. Simulated seed cotton yield under four future climate scenarios, as well as baseline conditions. $BL_{0/380}$, ΔT°_{air} from present $= 0$ °C, $[CO_2]_{atm} = 380$ ppm; $S_{1.5/380}$, $\Delta T^{\circ}_{air} = 1.5$ °C, $\Delta[CO_2]_{atm} = 0$; $S_{2.0/380}$, $\Delta T^{\circ}_{air} = 2.0$ °C, $\Delta[CO_2]_{atm} = 0$; $S_{1.5/490}$, $\Delta T^{\circ}_{air} = 1.5$ °C, $\Delta[CO_2]_{atm} = +110$ ppm; $S_{2.0/650}$, $\Delta T^{\circ}_{air} = 2.0$ °C, $\Delta[CO_2]_{atm} = +270$ ppm.

3.3. Response of ET_p and WUE to Future Climate Scenarios under Full Irrigation

The simulated growing season potential evapotranspiration (ET_p) increased under the $S_{1.5/380}$ and $S_{2.0/380}$ scenarios, but there was no change under $S_{1.5/490}$ and ET_p decreased under the $S_{2.0/650}$ scenario. However, the simulated evapotranspiration (ETc) was unchanged under $S_{1.5/380}$ and $S_{2.0/380}$ scenarios, but slightly decreased under $S_{1.5/490}$ scenario and increased under $S_{2.0/650}$ scenario (Table 3). The simulated potential evaporation (E_p) and transpiration (T_p) under $BL_{0/380}$ were 289 mm and 326 mm, respectively. The simulated average E_p for $S_{1.5/380}$ and $S_{2.0/380}$ were, respectively, 24 mm (8.3%) and 32 mm (11.1%) greater than for $BL_{0/380}$. A 2.9% to 7.5% increase in the simulated average E_c under future climate scenarios was found compared to the BL. A slight reduction in T_p was found under the different climate scenarios, except for the $S_{2.0/650}$ scenario. The simulated average T_c under future climate scenarios decreased by 2% to 4.8%, compared with BL. Compared to that under $BL_{0/380,}$ the simulated cotton WUE decreased by 0.83 kg ha^{-1} mm^{-1} (13.54%) and 1.18 kg ha^{-1} mm^{-1} (19.25%) under the $S_{1.5/380}$ and $S_{2.0/380}$ scenarios, respectively, but increased by 0.55 kg ha^{-1} mm^{-1} (9.02%) and 1.48 kg ha^{-1} mm^{-1} (24.16%) under the $S_{1.5/490}$ and $S_{2.0/650}$ scenarios, respectively.

Table 3. Simulated cotton actual and potential evapotranspiration and WUE of cotton from sowing to maturity under four future climate scenarios, as well as baseline conditions.

Climate Scenario	Cotton Crop and Water Balance Parameters: Mean and (% Difference from Baseline)							
	Yield (Mg ha^{-1})	**E_p (mm)**	**E_c (mm)**	**T_p (mm)**	**T_c (mm)**	**ET_p (mm)**	**ET_c (mm)**	**WUE (kg ha^{-1} mm^{-1})**
$BL_{0/380}$	3.77 c	289 b	141 c	326 a	294 a	615 b	435 a	6.13 c
$S_{1.5/380}$	3.38 d	313 a	149 ab	324 a	286 a	637 a	435 a	5.30 d
$S_{2.0/380}$	3.19 d	321 a	152 a	324 a	283 a	645 a	435 a	4.95 d
$S_{1.5/490}$	4.11 b	295 b	145 bc	320 ab	288 a	615 b	433 a	6.68 b
$S_{2.0/650}$	4.54 a	289 b	146 b	307 b	280 a	596 b	426 a	7.61 a

Note: E_p, potential evaporation; T_p, potential transpiration; ET_p, potential evapotranspiration (ET_p is the sum of E_p and T_p); E_c, actual evaporation; T_c, actual transpiration; ET_c, actual evapotranspiration; WUE = Yield/ET_p, water use efficiency. $BL_{0/380}$, ΔT°_{air} from present = 0°C, $[CO_2]_{atm}$ = 380ppm; $S_{1.5/380}$, ΔT°_{air} = 1.5 °C, $\Delta[CO_2]_{atm}$ = 0; $S_{2.0/380}$, ΔT°_{air} = 2.0 °C, $\Delta[CO_2]_{atm}$ = 0; $S_{1.5/490}$, ΔT°_{air} = 1.5 °C, $\Delta[CO_2]_{atm}$ = +110 ppm; $S_{2.0/650}$, ΔT°_{air} = 2.0 °C, $\Delta[CO_2]_{atm}$ = +270 ppm. Within columns and for the same factor, means within a column followed by the same letter are not significantly different at $p < 0.05$.

3.4. Yield and IWUE Response to Different Irrigation Treatments under Future Climate Scenarios

Figure 5 shows the simulated seed cotton yield and IWUE for different irrigation treatments. Simulated seed cotton yield and IWUE under the $BL_{0/380}$ scenario were 3.77 Mg ha^{-1} and 5.80 kg ha^{-1} mm^{-1}. Under the $S_{1.5/380}$ and $S_{2.0/380}$ scenarios, the simulated maximum seed cotton yield occurred under the Irr_{700} and Irr_{750} treatments, but decreased by 10.1% and 14.5%, respectively, compared to $BL_{0/380}$ scenario. Under the $S_{1.5/490}$ and $S_{2.0/650}$, the Irr_{700} and Irr_{650} scenarios provided the maximum simulated seed cotton yield, showing respective increases of 9.2% and 20.3% compared to the $BL_{0/380}$ scenario. The Irr_{400} treatment under the $S_{1.5/380}$ scenario, Irr_{500} treatment under the $S_{1.5/490}$ scenario and Irr_{450} treatment under the $S_{2.0/650}$ provided the highest IWUE: 0.99 kg ha^{-1} mm^{-1}, 1.75 kg ha^{-1} mm^{-1}, and 2.85 kg ha^{-1} mm^{-1}, respectively. These IWUE values were 17%, 30% and 49% greater than those under BL, respectively. However, under the $S_{2.0/380}$ scenario, the simulated average IWUE for each irrigation rate was lower than that under $BL_{0/380}$.

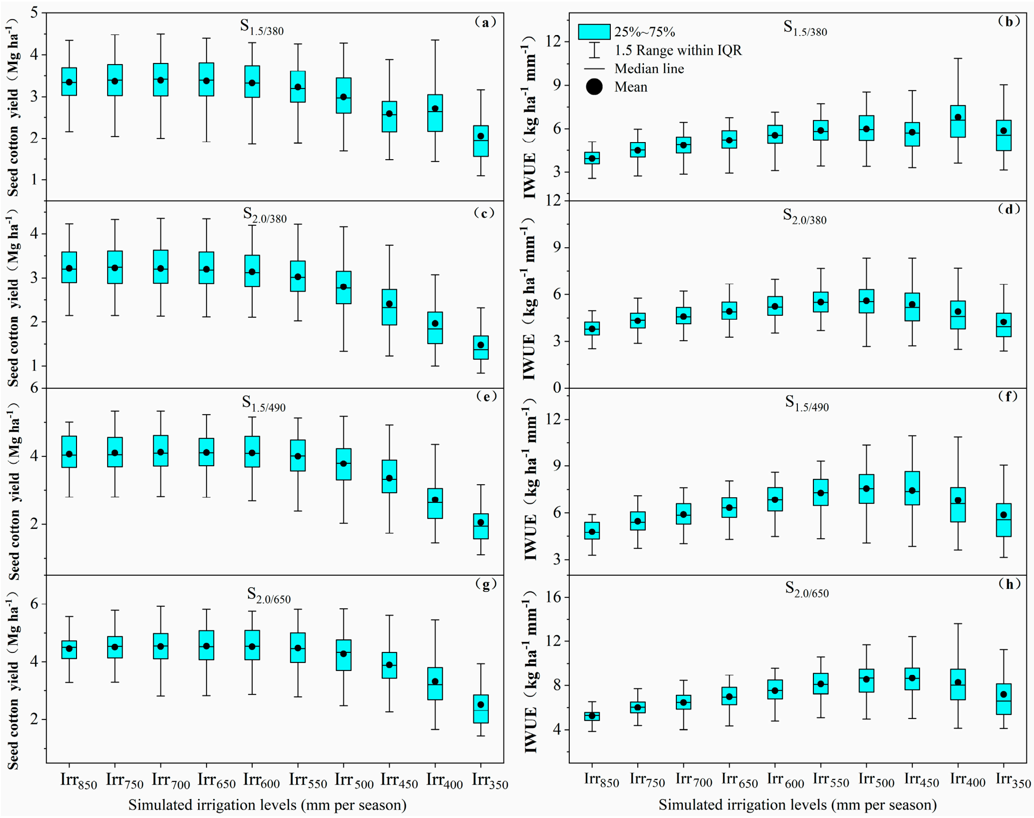

Figure 5. Simulated seed cotton yield and irrigation water use efficiency under different irrigation treatments (**a**–**h**) for four future climate scenarios. $S_{1.5/380}$, $\Delta T^{\circ}_{air} = 1.5$ °C, $\Delta[CO_2]_{atm} = 0$; $S_{2.0/380}$, $\Delta T^{\circ}_{air} = 2.0$ °C, $\Delta[CO_2]_{atm} = 0$; $S_{1.5/490}$, $\Delta T^{\circ}_{air} = 1.5$ °C, $\Delta[CO_2]_{atm} = +110$ ppm; $S_{2.0/650}$, $\Delta T^{\circ}_{air} = 2.0$ °C, $\Delta[CO_2]_{atm} = +270$ ppm. The 25-75% shading—the number from the 25th to the 75th percentile of all values in the data column, in descending order; 1.5 Range with IQR, maximum and minimum values in the non-abnormal range (upper and lower limits); IQR, Inter-Quartile Range. IWUE = Yield/Irrigation amount, Irrigation water use efficiency.

3.5. Economic Analysis of Irrigation Strategy under Future Climate Scenarios

Simulations indicated that more irrigation provided a greater gross and net income, but that deficit irrigation resulted in a greater Nwp under global warming of 1.5 °C and 2.0 °C (Table 4). Under the $S_{1.5/380}$ and $S_{1.5/490}$ scenarios, the Irr_{700} treatment generated the greatest gross (\$4408 ha^{-1} and \$5358 ha^{-1}) and net incomes (\$2240 ha^{-1} and \$3190 ha^{-1}), respectively. However, under the $S_{2.0/380}$ and $S_{2.0/650}$ scenarios, the Irr_{750} and Irr_{650} treatments provided the greatest gross (\$4192 ha^{-1} and \$5897 ha^{-1}) and net income (\$2012 ha^{-1} and \$3741 ha^{-1}), respectively. The maximum Nwp under the $S_{1.5/380}$ and $S_{2.0/380}$ scenarios was \$0.63 m^{-3} and \$0.55 m^{-3}, respectively, both obtained under the Irr_{550} treatment. The water cost for the Irr_{550} treatment was \$132 ha^{-1}, which was 55%, 36%, 27% and 18% lower than that for the Irr_{850}, Irr_{750}, Irr_{700} and Irr_{650} treatments, respectively. Under the $S_{1.5/490}$ and $S_{2.0/650}$ scenarios, the highest Nwp values (\$0.93 m^{-3} and \$1.14 m^{-3}, respectively) were attained under the Irr_{500} treatment. The water cost for the Irr_{500} treatment was \$120 ha^{-1}, which was 70%, 50%, 40%, and 30% lower than that for the Irr_{850}, Irr_{750}, Irr_{700} and Irr_{650} treatments, respectively.

Table 4. Economic benefits of different cotton irrigation regimes under four future climate scenarios.

Treatment	Irrigation (m^3 ha^{-1})	Water Cost ($ ha^{-1})	Gross Income ($ ha^{-1})				Net Income ($ ha^{-1})				Net Water Production ($ m^{-3})			
			$S_{1.5/380}$	$S_{2.0/380}$	$S_{1.5/490}$	$S_{2.0/650}$	$S_{1.5/380}$	$S_{2.0/380}$	$S_{1.5/490}$	$S_{2.0/650}$	$S_{1.5/380}$	$S_{2.0/380}$	$S_{1.5/490}$	$S_{2.0/650}$
Irr_{850}	5100	204	4344	4182	5282	5781	2140	1978	3078	3577	0.42	0.39	0.6	0.7
Irr_{750}	4500	180	4379	4192	5331	5852	2199	2012	3151	3672	0.49	0.45	0.7	0.82
Irr_{700}	4200	168	4408	4177	5358	5883	2240	2009	3190	3715	0.53	0.48	0.76	0.88
Irr_{650}	3900	156	4389	4150	5343	5897	2233	1994	3187	3741	0.57	0.51	0.82	0.96
Irr_{600}	3600	144	4324	4078	5331	5867	2180	1934	3187	3723	0.61	0.54	0.89	1.03
Irr_{550}	3300	132	4198	3933	5196	5806	2066	1801	3064	3674	0.63	0.55	0.93	1.11
Irr_{500}	3000	120	3893	3634	4906	5553	1773	1514	2786	3433	0.59	0.5	0.93	1.14
Irr_{450}	2700	108	3365	3135	4350	5061	1257	1027	2242	2953	0.47	0.38	0.83	1.09
Irr_{400}	2400	96	3531	2548	3531	4299	1435	452	1435	2203	0.6	0.19	0.6	0.92
Irr_{350}	2100	84	2669	1925	2669	3272	585	−159	585	1188	0.28	−0.08	0.28	0.57

4. Discussion

4.1. Changes in Soil Water and Temperature under Future Climate Scenarios

The simulations demonstrated that global warming of 1.5 °C or 2.0 °C with a rise in $[CO_2]_{atm}$ increased θ and T°_{soil} in the surface soil layer in hyper-arid areas. However, the simulated θ for all layers decreased with global warming of 1.5 °C or 2.0 °C was not associated with a rise in $[CO_2]_{atm}$. A greater $[CO_2]_{atm}$ improved leaf photosynthetic rate and crop radiation utilization [51] decreased the crop's stomatal conductance and leaf transpiration [9,52,53], thereby reducing the θ depletion in different soil layers [54]. Ghannoum [55] reported that a decrease in stomatal conductance owing to the effect of $[CO_2]_{atm}$ fertilization might protect soil water and delay the onset of drought stress. Compared to the baseline period, the θ for all layers decreased by 0.4–0.7% under $S_{1.5/380}$ and $S_{2.0/380}$ scenarios, but increased by 0–0.9% in the 0–0.45 m soil layer under the $S_{1.5/490}$ and $S_{2.0/650}$ scenarios (Figure 2). These results concurred with those of Markelz et al. [56] and Manderscheid et al. [57], who reported that the effect of elevated $[CO_2]_{atm}$ significantly increased the θ in the surface soil layers. Based on field experiments, Bernacchi et al. [58] and Burkart et al. [59] also indicated that the lower water consumption and increased leaf area index caused by an elevated $[CO_2]_{atm}$ may result in conservation of soil moisture in the surface layers.

Global warming of 1.5 °C or 2.0 °C directly increased T°_{soil} overallthesoillayers in cotton fields by 1.19 °C–2.0 °C (4.2–7.4%) in the region under study. The magnitude of T°_{soil} increase under the $S_{1.5/490}$ and $S_{2.0/650}$ scenarios was less than that under the $S_{1.5/380}$ and $S_{2.0/380}$ scenarios. Changes in T°_{soil} and θ were coupled at the ecosystem level [60]. The lesser increase in T°_{soil} under the $S_{1.5/490}$ and $S_{2.0/650}$ scenarios (vs. $BL_{0/380}$) may be a benefit from the increased θ in the surface soil layer. Bond-Lamberty et al. [61] indicated that a lower T°_{soil} may be caused by an increased θ in poorly drained land. The increased (vs. $BL_{0/380}$) aboveground biomass of cotton under the $S_{1.5/490}$ and $S_{2.0/650}$ scenarios may also increase the shading effect of cotton leaves on the topsoil, thereby reducing soil evaporation and increasing θ. Al-Kayssi et al. [62] also reported that increased θ reduced T°_{soil} and provided protection to crop roots from sharp and abrupt changes in T°_{soil}. Warming conditions due to natural fluctuations in T°_{soil} can alter the optimal conditions for rapid cotton germination and seedling emergence [63]. Under the $S_{1.5/490}$ and $S_{2.0/650}$ scenarios, mean seed emergence occurred 1.8 and 2.3 days earlier, and the yield increased by 9.01% and 20.30%, respectively. Quisenberry and Gipson [64] and Kerby et al. [65] also indicated that post-planting warm T°_{soil} is critical to eventual crop yield.

4.2. Cotton Yield, ET and WUE under Future Climate Scenarios

The simulated seed cotton yield increase with the $S_{1.5/490}$ and $S_{2.0/650}$ scenarios was mainly influenced by the fertilization effect of a rise in $[CO_2]_{atm}$. Compared with $S_{1.5/380}$ and $S_{2.0/380}$ scenarios, the simulated seed cotton yield under the $S_{1.5/490}$ and $S_{2.0/650}$ scenarios increased by 19% and 36%, respectively. This concurred with the results of Adhikari et al. [5], who simulated a 14–29% increase in cotton yields based on the Intergovernmental Panel on Climate A2 emissions scenario. Using various crop models, Attavavich and Mc-

Carl [66] reported a 51% increase in cotton yield when $[CO_2]_{atm}$ increased by 183 ppm, due to abundant rainfall and fewer occurrences of extreme weather. Other studies have shown a strong positive effect of $[CO_2]_{atm}$ on cotton yield, and that the $[CO_2]_{atm}$ fertilization effect compensates for yield losses attributable to the direct effects of global warming [6,67–69]. However, based on the DSSAT model, Ayankojo et al. [70] indicated that seed cotton yields reduced by 40% and 51% in the mid-century and late-century, respectively, compared to baseline (1987–2011) in the Arizona low desert (ALD), USA. This may be that the daily maximum temperature for ALD (July and August) that regularly exceeds 38 °C, leading to advantages for CO_2 fertilization, would be negated by the disastrous effects of elevated temperature. Rahman et al. [46] indicated that the DSSAT model limited crop growth mainly based on temperature and was more sensitive to high temperatures than $[CO_2]_{atm}$ fertilization effects. Elevated temperatures above the optimum growth requirement would reduce seed cotton yields, and even a significant increase in $[CO_2]_{atm}$ would not fully compensate for the negative impact on yields [15]. Schauberger et al. [71] noted that high-temperature-induced crop yield decreases were usually the result of temperature-induced water stress.

In general, the cotton crop's water requirements would increase under higher temperatures. The simulated cotton E_p increased by 8.30% and 11.07% and ET_p increased by 3.58% and 4.88% under $S_{1.5/380}$ and $S_{2.0/380}$ (vs. $BL_{0/380}$) scenarios, respectively. Hall [72] reported that the greater ET_p of cotton plants caused by higher T°_{air} led to more intense water stress. Increased T°_{air} led to increased soil evaporation but shorter crop growth periods, thereby reducing transpiration. Walter et al. [73] also indicated that increased T°_{air} led to an increase in water vapor pressure deficit, which increased the atmospheric E_p and ET_p rates. These conclusions were consistent with the simulation results in this paper. However, due to the direct effect of global warming without a rise in $[CO_2]_{atm}$, simulated seed cotton yield and WUE significantly decreased (13.54% and 19.25%, respectively) in the $S_{1.5/380}$ and $S_{2.0/380}$ scenarios (Figure 3). In contrast, WUE of cotton increased due to an increased aboveground biomass and yield under $S_{1.5/490}$ and $S_{2.0/650}$ scenarios. The effects of eCO2 and shorter growth period on seed cotton yield offset the negative impacts of increased temperatures. Similarly, Ko and Piccinni [74] and Broughton [51] reported that cotton WUE would improve owing to the fact that elevated $[CO_2]_{atm}$ would increase aboveground biomass and reduce crop T_p.

4.3. Optimal Irrigation Strategy for Cotton under Future Climate Scenarios

The present simulations showed that irrigation amount of 650 mm–750 mm would provide the greatest cotton seed yield, gross and net income, whereas irrigation amounts of 500 mm–550 mm resulted in the greatest Nwp when T°_{air} increased in the regions by 1.5 °C or 2.0 °C (Table 4). Wang et al. [75] reported that the average water requirement of cotton (WRC) in southern Xinjiang from 1963 to 2012 ranged from 726 to 810 mm, with a decreasing trend in WRC at different cotton growth stages over the past 50 years. This trend was a similar trend in cotton water demand under warming of 1.5 °C and 2.0 °C. Compared to the results of Chen et al. [42] in the same region, the optimal total irrigation amount for cotton under future climate scenarios would be reduced by 9% (50 mm). Adhikari et al. [5] reported that elevated $[CO_2]_{atm}$ enhances crop photosynthesis, and this effect may reduce the effect of water stress on cotton yield. Moreover, Wang [76] reported that, to implement deficit irrigation and adapt to future climate scenarios in northwest China without significantly reducing cotton yield, one must implement optimal irrigation scheduling. Owing to no significant reduction in cotton yield and the higher net income values obtained with lower irrigation amounts, the Irr_{550} treatment was the optimal irrigation scheduling to cope with future climate scenarios in this region. Although the Irr_{500} treatment attained the highest Nwp under the $S_{2.0/650}$ scenario, it failed to maintain seed cotton yield and lower net income.

4.4. Uncertainty in Optimizing Irrigation Amount under Future Climate Scenarios

The optimization of irrigation amount in hyper–arid areas under future climate scenarios are influenced by many factors, such as crop models, irrigation methods and sowing time. The single crop model led to the uncertainty in predicting the effects of future climate change on crop growth and yield [77]. Most crop models are radiation-driven, placing insufficient emphasis on responses to environmental stress, thus limiting their application in crop management research [47]. Due to uncertainty in future climate scenarios, Tenreiro et al. [78] indicated that crop modeling is likely to be required to improve the integration of more moisture-driven mechanisms under water-limited conditions and to improve the accuracy of simulations. In this paper, the limited observational soil and crop parameters used for calibration and validation in the model and the use of trial and error methods may also affect the simulation results and lead to uncertainty. Chen et al. [79] indicated that the current crop datasets may lead to new uncertainties when optimizing irrigation regimes under future climate scenarios. Ma et al. [80] showed that incorporating Parameter Estimation Software (PEST) in the model to calibrate parameters is superior to the commonly used trial-and-error calibration methods, as PEST provides parameter sensitivity and uncertainty analysis that should help users in selecting the correct parameters for calibration. Therefore, field and laboratory experiments are critical for developing models and improving simulation accuracy [81]. In addition, the improvement in drought tolerance of cotton varieties in the future may also have some uncertainties, especially for the simulated irrigation amount. Yang et al. [82] reported that the combination of transgenic cotton (the application of improving crop drought tolerance) could reduce the water demand of cotton while maintaining yields. Furthermore, there may be uncertainties in optimizing irrigation scheduling under future climate scenarios based on local traditional irrigation time and amount. Using the automatic irrigation method based on RZWQM2 model may be more beneficial to finding out the optimal irrigation amount [41,82–84].

5. Conclusions

In the present study, the calibrated and validated RZWQM2 model was used to simulate θ and $\mathring{T}_{soil}$, ET_p, aboveground biomass and cotton seed yield in hyper–arid areas under global warming scenarios of 1.5 °C and 2.0 °C, with or without increased $[CO_2]_{atm}$. In addition, an economic analysis methodology for mitigating the impact of future climate scenarios on cotton yield and WUE using different irrigation amount was proposed based on RZWQM2 simulations. Under the $S_{1.5/380}$ and $S_{2.0/380}$ scenarios, the average simulated surface layer (0–0.45 m) soil moisture declined by 0.38–0.67%, whereas under $S_{1.5/490}$ and $S_{2.0/650}$ scenarios it increased by 0.03–0.92%. The increased θ in the lower layer maybe benefit from an increased $[CO_2]_{atm}$, which increased the aboveground biomass of cotton and reduced leaf transpiration. A decrease of 13% and 12% in the simulated average aboveground biomass and seed cotton yield were found with global warming of 1.5 °C and 2.0 °C without increased $[CO_2]_{atm}$, respectively. However, the simulated average aboveground biomass and seed cotton yield increased by 21% and 15% with increased $[CO_2]_{atm}$, respectively. An appropriate increase in irrigation amount may be an effective measure to improve cotton yields and net income under future climate scenarios. However, as the Irr_{550} treatment can maintain crop yield along with a greater IWUE, to save water in hyper-arid areas, it may prove to be the optimal irrigation depth and scheduling for local producers.

Author Contributions: Conceptualization, X.C. and Z.Q.; methodology, H.D.; software, Z.Q.; validation, X.C., S.F. and H.W.; data curation, H.D.; writing—original draft preparation, X.C. and H.D.; writing—review and editing, D.G., L.M., K.R.T. and B.L. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financially supported by the Open Project Program of Engineering Research Center of High-efficiency and Energy-saving Large Axial Flow Pumping Station, Jiangsu Province, Yangzhou University (grant number ECHEAP2022-016) and the Natural Science Foundation of Jiangsu Province, China (grant number BK20210825).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available on request from all authors.

Conflicts of Interest: The authors declare no conflict of interest.

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