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RESEARCH ARTICLE

Water footprint of irrigated cotton production in Xinjiang under predicted climate change scenarios

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KEYWORDS

Xinjiang, cotton, climate change, water footprint

HIGHLIGHTS

- Increasing aridity in southern Xinjiang were predicted for various climate change scenarios.
- Water footprint of cotton is expected to decrease in these scenarios.
- Sprinkler irrigation was found to have the highest water-saving potential.

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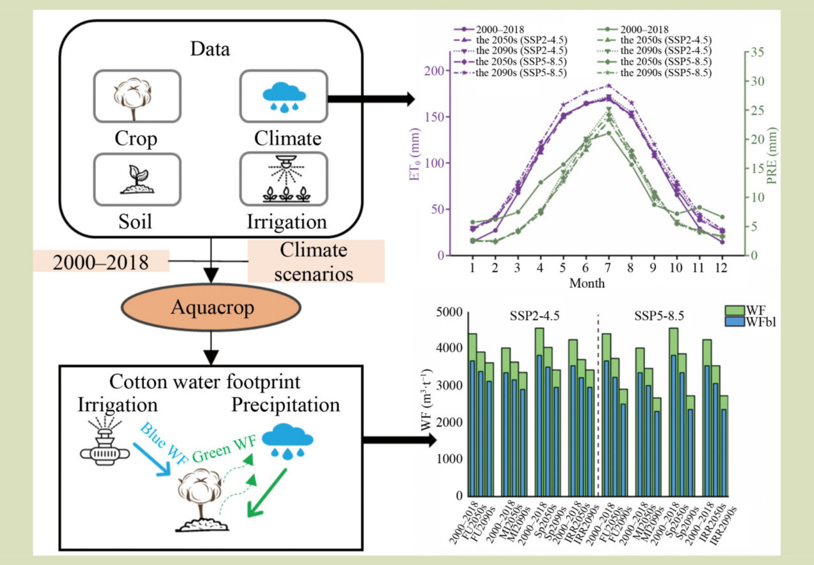
GRAPHICAL ABSTRACT



ABSTRACT

Xinjiang, one of China’s most water-scarce provinces, produces 25% of the world’s cotton. However, changes in water consumption of cotton production in Xinjiang under two climate change scenarios is unclear. This study considered three irrigation techniques (i.e., furrow, micro (drip) and sprinkler irrigation) and simulated the blue and green water footprints of cotton production in Xinjiang at a 5-arcmin grid level in response to climate change scenarios in the 2050s and 2090s. Taking the period 2000–2018 as the baseline, results showed that this footprint of cotton in Xinjiang for the baseline period was 4264 $m^3 \cdot t^{-1}$, with blue water accounting for 83%. Under climate change scenarios, Xinjiang was predicted to have an increasing drought trend and intensifying pressure on water resources. Owing to increased CO_2 concentrations, the water footprint of cotton tended to decrease by 19.3% and 35.7% under two Shared Socioeconomic Pathway scenarios—SSP2-4.5, representing a moderate socioeconomic development path with lower emissions, and SSP5-8.5, indicating a scenario of high growth with higher emissions—respectively, for the 2090s. The blue water footprint was predicted to have an overall decrease. However, its proportion of the total would increase slightly, with the highest increase being 3.4%. The green water footprint was also predicted to have decreasing trend, with reductions of 33.7% (SSP2-4.5) and 47.2% (SSP5-8.5), respectively. Of the three irrigation techniques, sprinkler irrigation was predicted to have the greatest water conservation potential, with a reduction of up to 40.1%.

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) stated that human activities have contributed to the increasing warmth of the atmosphere, oceans, and land[1]. Climate change has led to more frequent, intense, widespread and prolonged extreme weather events, thus posing a significant threat to crop production. Crop yields can decrease by up to 40% under drought conditions[2] and require increased water demand to sustain production[3]. For example, Bonetti et al.[4] predicted the national irrigation demand of South Africa to increase by 6.5%–32% by 2090 due to future climate impacts. Cotton is often grown in arid regions because of the favorable light and temperature conditions. However, this makes achieving a sufficient water supply in response to climate change a challenge for cotton-growing regions.

To achieve a fairer and more sustainable allocation of freshwater resources, Hoekstra & Hung[5] introduced the concept of a water footprint (WF) in 2002. The WF of crop production denotes the volume of freshwater used to produce crop during the growth period of the plant. The indicator is multidimensional, quantifying water usage volumes by source and contaminated volumes by pollution category; it meticulously maps every component of the overall WF across both geographical and temporal dimensions[6]. The WF includes the green WF (precipitation-derived soil moisture consumed by crops), blue WF (groundwater or surface water consumed by crops), and gray WF (freshwater needed to assimilate the load of pollutants discharged during crop production). The blue and green water footprints are collectively referred to as consumptive WF whereas the gray WF is also known as the degradative WF[7]. By measuring the WF of crop production, the water use and water quality impacts owing to crop production can be evaluated. The present study focused only on consumptive WF. The WF of crop production represents a further refinement of traditional water resource assessment indicators that primarily focus on blue water. Compared to traditional water resource assessment indicators, WF considers precipitation utilized during crop production[8].

Assessing the influence of climate change on crop WFs has been a focus of research over the past 5 years[9–12]. Most studies have focused on the influence of climate change on the WF of crop production in a country or watershed. For example, Zhuo et al.[13], Yue et al.[14], and Jiang et al.[15] used the AquaCrop model to predict and quantify crop yields and WFs in China under various climate scenarios. Govere et al.[16] analyzed the influence of climate change on the blue WF of wheat in Zimbabwe, and concluded that agricultural management factors and climate change may bear equal responsibility for the increase in blue WF. Martins et al.[17] used crop simulation models to assess the changes in the WF of rice under future climate conditions, based on three distinct regional climate scenarios as well as predicted land and cover changes. They found that under most scenario predictions, the WF of irrigated rice planting with soil fertility management gradually decreased. Pilevneli et al.[18] investigated the influence of climate change on agricultural in 25 river basins in Turkey and found that the influence of climate change on water supply was the greatest from 2015 to 2040. Under Representative Concentration Pathway 8.5, which denotes a scenario characterized by elevated greenhouse gas emissions resulting in considerable climate change, from 2071 to 2100, there are risks of water shortages for irrigation water demand, and among the 12 priority products, maize and wheat are highly susceptible to the drought influence of climate change.

When studying the influence of climate change on agricultural production and water resources, researchers often excessively focus on food crops and neglect cash crops. Cash crops are crucial for the development of Chinese industry, especially light industry, and are also a major source of exports and foreign exchange earnings. Cotton accounts for 32.3% of total planted area of cash crops in China, ranking second only to peanuts in terms of planted area, highlighting its significance in Chinese agriculture. Given that cotton is a highly water-consuming cash crop, studying its water consumption structure would be beneficial for alleviating water resource pressure. Also, at a large regional scale, existing studies have overlooked the response of crop water consumption under different irrigation techniques to long-term climate change, concerning cash crops.

Recent studies have investigated the influence of climate change on cotton yield and water consumption at different regional scales. Li et al.[19] assessed the global impact of climate change on cotton yields, highlighting the universal sensitivity of the crop to temperature extremes and irregular precipitation. The study underscored the positive effects of elevated CO_2 and the critical role of adaptive measures in bolstering the crop resilience across diverse geographical locations. Jans et al.[20] used the Lund-Potsdam-Jena managed land model to investigate the influence of climate change on global cotton water use and yields. The study found that, accounting for climate change and CO_2 fertilization, cotton yields in most regions steadily increased. Han et al.[21] reported that climate variation significantly impacted cotton yield variability in major cotton-growing regions of China. The effects differed across regions; in the Yellow River basin, yield increases were primarily driven by rising temperatures and declining solar radiation whereas in the Yangtze River region, yield declines were mainly attributed to increased rainfall. In the arid north-western inland areas, yield decreases were linked to rising solar radiation.

Compared to previous research on the cotton yield and WF, the current study is the first to quantitatively assess the response of cotton water consumption intensity and structure to climate change under different irrigation techniques in Xinjiang. Xinjiang (73.40°–96.23° E, 34.25°–48.10° N) is the westernmost province in China and is one of the driest regions; however, it is responsible for 91.0% of Chinese cotton production[22], contributing 35% of farmer income, and 25% of global production[23]. Owing to severe water scarcity, the adoption rate of water-saving irrigation for cotton in Xinjiang has increased annually. However, the response of cotton water consumption to future climate changes using different irrigation methods remains unclear. Previous studies have indicated that the water resource situation in Xinjiang is unlikely to improve significantly in the future[24]. Cotton is primarily grown in northern, central and southern Xinjiang (Fig. 1). However, the spatial distributions of cotton fields and water resources in Xinjiang are not aligned. Additionally, the highly arid climatic conditions (mean annual precipitation of < 270 mm, and evaporation of > 1000 mm) make cotton production in Xinjiang heavily reliant on irrigation, with the water supply and demand being significantly constrained by climatic conditions. Understanding the water consumption of cotton production in Xinjiang, particularly the response of the WF to different future climate change scenarios, will contribute to achieving regional water conservation and economic benefits.

2 Method and data

This study used a crop WF calculation method based on the soil water dynamic balance[25] within the international

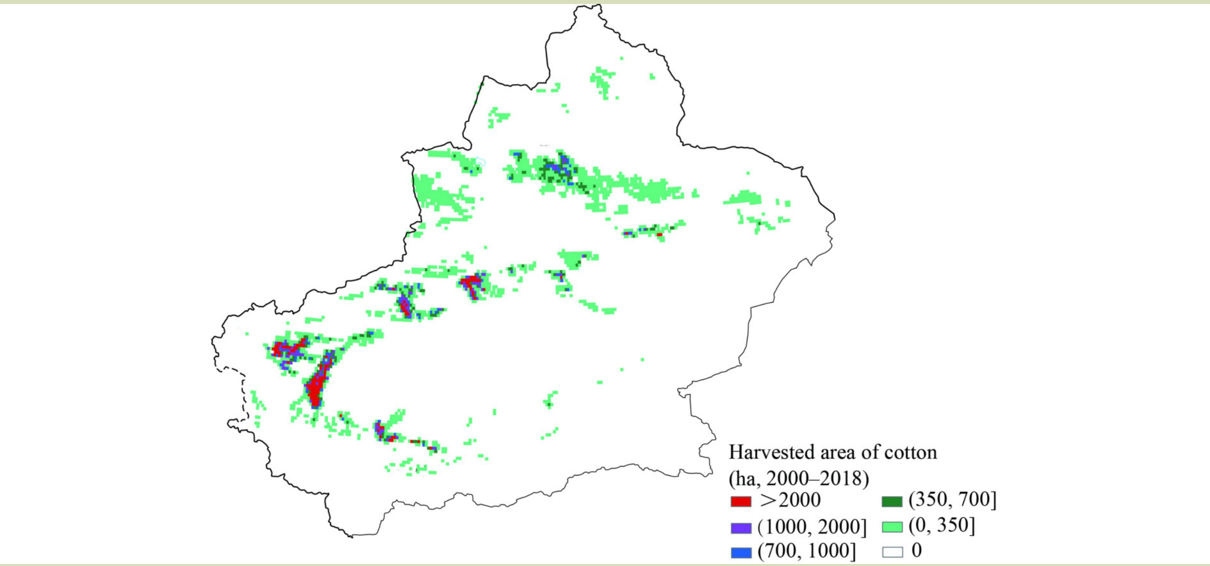


Fig. 1 Cotton planting area in Xinjiang from 2000 to 2018 (审图号：新 S（2025）016 号).

standard calculation framework for WF[6]. AquaCrop was used to calculate the cotton WF in Xinjiang, with 5-arcmin grid cells as spatial units[14]. The blue and green WFs of cotton production in Xinjiang were calculated for the baseline period and future climate scenarios of the 2050s and 2090s, respectively. The climate change scenarios are based on the outputs from the Coupled Model Intercomparison Project Phase 6. Specifically, the medium-resolution climate system model BCC-CSM2-MR, released by the Beijing Climate Center, was used to simulate the climate under two future climate change scenarios: SSP2-4.5 and SSP5-8.5[26].

2.1 Meteorological data processing

Monthly meteorological data from the CRU-TS4.04 database for 2000 to 2018, including maximum temperature, minimum temperature, precipitation and reference evapotranspiration. However, monthly meteorological data for the 2050s and 2090s downloaded from the WorldClim database[26] did not include reference evapotranspiration data. Therefore, the Penman formula provided by the Food and Agriculture Organization of the United Nations was used to calculate the missing reference evapotranspiration data based on the input temperature data[27]. By summing the monthly meteorological data to obtain annual data, we then calculated the averages of the monthly and yearly meteorological data for each year to obtain the monthly and yearly meteorological data for the baseline period, 2050s, and 2090s.

2.2 Water footprint per unit crop calculation

The WF of crop production denotes the total water resources consumed in the production of a unit of a product (typically an economic product) within a specific area[6].

The WF of crop production includes blue, green, and gray WFs[6]. Since our study is solely concerned with the irrigation WF of economic crop production ($\mathrm{WF_{proc,irr}}$), which does not entail the creation of gray WF, we have limited our considerations to the blue and green WFs only. $\mathrm{WF_{proc,irr}}$ was calculated as:

$$\mathrm{WF_{proc,irr}}=\mathrm{WF_{proc,green}}+\mathrm{WF_{proc,blue}} \tag{1}$$

where, $\mathrm{WF_{proc,green}}$ and $\mathrm{WF_{proc,blue}}$ ($\mathrm{m^3{\cdot}t^{-1}}$) are the green and blue WFs during the growth process of crops or trees, respectively, and calculated as:

$$\begin{cases} \mathrm{WF_{proc,green}} = \dfrac{\mathrm{CWU_{green}}}{\mathrm{Y}} \\ \mathrm{WF_{proc,blue}} = \dfrac{\mathrm{CWU_{blue}}}{\mathrm{Y}} \end{cases} \tag{2}$$

where, $\mathrm{CWU_{green}}$ and $\mathrm{CWU_{blue}}$ ($\mathrm{m^3{\cdot}ha^{-1}}$) are the green and blue crop water use (CWU), respectively, and Y ($\mathrm{t{\cdot}ha^{-1}}$) is the crop yield per unit area.

The green and blue components of the crop water consumption are equal to the cumulative daily evapotranspiration over the entire growth period[6] and were calculated as:

$$\begin{cases} \mathrm{CWU_{green}} = 10\times\sum_{d=1}^{lgp}\mathrm{ET_{green}} \\ \mathrm{CWU_{blue}} = 10\times\sum_{d=1}^{lgp}\mathrm{ET_{blue}} \end{cases} \tag{3}$$

where, $\mathrm{ET_{green}}$ and $\mathrm{ET_{blue}}$ (mm) are green and blue components of the total evapotranspiration (ET), respectively, the constant, 10, serves as a unit conversion factor, converting the water depth of ET (mm) into the volume of water per unit of land area for CWU ($\mathrm{m^3{\cdot}ha^{-1}}$) and lg p is the length of the growth period (days).

The daily crop ET and yield per unit during the growing season were simulated using the AquaCrop model. AquaCrop is a soil moisture-driven crop productivity model based on dynamic daily soil water balance[28]. The balance equation is:

$$\mathrm{S}_{[t]} = \mathrm{S}_{[t-1]}+\mathrm{IRR}_{[t]}+\mathrm{PR}_{[t]}+\mathrm{CR}_{[t]}-\mathrm{ET}_{[t]}-\mathrm{RO}_{[t]}-\mathrm{DP}_{[t]} \tag{4}$$

where, $\mathrm{S}_{[t]}$ (mm) is the soil water content at the end of day t, $\mathrm{S}_{[t-1]}$ (mm) is the soil moisture state at the start of day t, $\mathrm{IRR}_{[t]}$ (mm) is the total water applied in irrigation on day t, $\mathrm{PR}_{[t]}$ (mm) is the amount of precipitation on day t, $\mathrm{CR}_{[t]}$ (mm) is the amount of water that rises from the groundwater table through capillary action on day t, $\mathrm{ET}_{[t]}$ (mm) is the total amount of water lost through the processes of evaporation and transpiration on day t, $\mathrm{RO}_{[t]}$ (mm) is the amount of water that flows over the land surface as runoff on day t, and $\mathrm{DP}_{[t]}$ (mm) is the quantity of water that percolates deep into the soil beyond the root zone on day t.

During the initial growth stage of crops, the soil water is considered green. During the growth period, the blue and green WFs originated from irrigation and rainfall, respectively. The daily input of rainfall and irrigation to various components of the soil water balance was monitored, allowing for the determination of daily $\mathrm{ET_{green}}$ and $\mathrm{ET_{blue}}$ values. This allowed the blue and green WFs of irrigation production for major cereal crops in China to be quantified. Monitoring the daily water movement entering and leaving the crop root zone enables the differentiation between blue and green water[25]. The blue and green water in soil was calculated as:

$$\mathrm{S}_{\mathrm{g}[t]} = \mathrm{S}_{\mathrm{g}[t-1]}+(\mathrm{PR}_{[t]}+\mathrm{IRR}_{[t]}-\mathrm{RO}_{[t]})\times\frac{\mathrm{PR}_{[t]}}{\mathrm{PR}_{[t]}+\mathrm{IRR}_{[t]}}-(\mathrm{DP}_{[t]}+\mathrm{ET}_{[t]})\times\frac{\mathrm{S}_{\mathrm{g}[t-1]}}{\mathrm{S}_{[t-1]}} \tag{5}$$

$$S_{b[t]} = S_{b[t-1]} + (PR_{[t]} + IRR_{[t]} - RO_{[t]}) \times \frac{IRR_{[t]}}{PR_{[t]} + IRR_{[t]}} - (DP_{[t]} + ET_{[t]}) \times \frac{S_{b[t-1]}}{S_{[t-1]}} \tag{6}$$

where, $S_{g[t]}$ and $S_{g[t-1]}$ (mm) are the green water content of the soil at the end and start of the day respectively, and $S_{b[t]}$ and $S_{b[t-1]}$ (mm) are the blue water content of the soil at the end and start of the day, respectively. The soil moisture content before to the crop growth period was presumed to be entirely composed of green water.

The three main irrigation techniques were considered in the simulation, namely furrow irrigation, micro-irrigation, and sprinkler irrigation. The soil surface wetted percentages for furrow irrigation, micro-irrigation and sprinkler irrigation are 80%, 40%, and 100%, respectively. Parameters for other irrigation techniques, such as time criteria, depth criteria and water quality, were referenced from Yue et al.[14]

2.3 Data sources

The meteorological data for the baseline period (2000–2018) in Xinjiang, including annual precipitation and reference evapotranspiration (ET_0), were sourced from the CRU-TS4.04 database[29], the 5 × 5-arcmin monthly meteorological data forecast for the 2050s and 2090s under the SSP scenarios from the BCC-CSM2-MR climate model were sourced from the WorldClim database[26], soil type and moisture data were sourced from the ISRIC SoilGrids database[30], crop irrigation and planting area distribution data were sourced from the MIRCA2000 data set[31], provincial statistics on crop yields were sourced from the National Bureau of Statistics of China's national database[22], the annual average atmospheric CO_2 concentration data for the baseline period were sourced from the Mauna Loa Observatory in Hawaii[32], the annual average atmospheric CO_2 concentration data for the SSP scenarios were sourced from Meinshausen et al.[33], crop parameters in the AquaCrop model, including the harvest index (the proportion of aboveground biomass allocated to the harvestable yield) and maximum rooting depth, were sourced from Allen et al.[27], and other parameters were obtained from the AquaCrop model user reference manual[34].

3 Results

3.1 Future climate change trends in Xinjiang

Within Xinjiang, the average annual ET_0 increased under both the future scenarios compared to the baseline level of 1080 mm. In the 2090s (SSP5-8.5), ET_0 was predicted to have the most significant increase, with an annual growth rate of 14.3% (Fig. 2). The increase in ET_0 was particularly pronounced in winter and early spring (e.g., January and November), with growth rates reaching up to 93% and 53%, respectively, in the 2090s (SSP5-8.5), while the increase in summer (e.g., July) was smaller, at only about 8%, indicating a substantial rise in evaporative demand during the dry season. The changes in precipitation relative to the baseline period of 135 mm were similar in the two future scenarios, with higher precipitation from July to September compared to the baseline period and lower precipitation in other months. Overall, the annual precipitation was predicted to have a decreasing trend, with an average decrease of 15.1%. The highest decrease in the 2090s (SSP5-8.5) was 16.4%. Regardless of the scenario, ET_0 in the 2090s would be higher than that in the 2050s, while the changes in precipitation were similar and decreasing.

3.2 Impact of future climate change on the spatiotemporal distribution of cotton water footprint

3.2.1 Baseline and forecast spatiotemporal distribution of cotton water footprint

From a temporal-scale perspective, in future scenarios, irrespective of furrow irrigation, micro-irrigation or sprinkler irrigation, the irrigation WF in the 2090s would be relatively low. Under the SSP2-4.5 and SSP5-8.5 scenarios, the irrigation

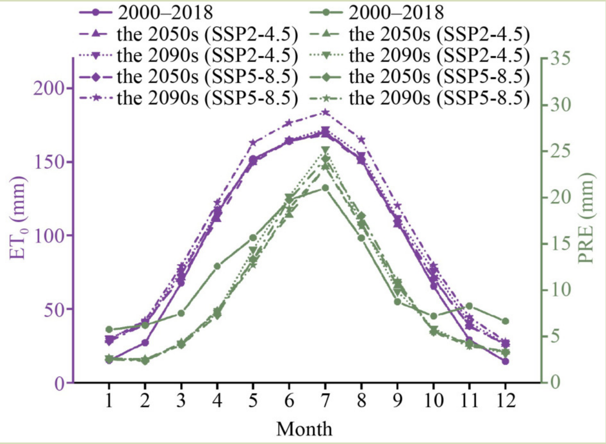


Fig. 2 Monthly crop reference evapotranspiration and precipitation under scenarios. The purple line with different point shapes represents the variation of ET_0, while the green line with distinct point shapes indicates the variation of precipitation (PRE).

WFs of furrow irrigation, micro-irrigation and sprinkler irrigation in the 2090s would have decrease by 17.8%, 16.5%, 24.8% (SSP2-4.5) and 34.1%, 33.7%, 40.1% (SSP5-8.5), respectively, compared with the baseline period. In addition, the proportion of blue WF in the total WF of cotton irrigation production would have increased by 3.4% and 3.0% in the 2050s and 3.1% and 3.0% in the 2090s, respectively, compared to the baseline period (Fig. 3).

From a spatial-scale perspective, in the baseline period, the average irrigation WF of cotton in Xinjiang was 4260 $m^3 \cdot t^{-1}$, with a blue WF of 3560 $m^3 \cdot t^{-1}$, accounting for 83% of the total WF. The WF of cotton had significant regional differences in spatial distribution, with higher values mainly in northern Xinjiang and lower values in southern and south-western regions (Fig. 4). When considering the blue and green WFs of cotton production, the blue WF of Xinjiang cotton had a north–south gradient. The green WF of cotton had large spatial distribution differences with no clear pattern, and overall, the green WF values of cotton in Xinjiang were low. Under the SSP2-4.5 and SSP5-8.5 scenarios, the IRR of cotton in the 2090s was predicted to have an overall decreasing trend, with reductions of 19.3% and 35.7%, respectively, and significant differences in spatial distribution. Under the two future climate scenarios, the relative changes in the 2090s would have similar spatial distributions, with some regions, mainly in northern Xinjiang, having significant decreases in the WF, and others, mainly in south and west, having lower rates of reduction rates. Under SSP5-8.5, the decreasing trend of cotton WF in the 2090s would be greater than that under SSP2-4.5, and in most regions, the reduction ratio of the WF relative to the baseline period would be 1.5 times that under the SSP2-4.5 scenario, with the majority of areas in the north experiencing a relative decrease the WF of more than 40%.

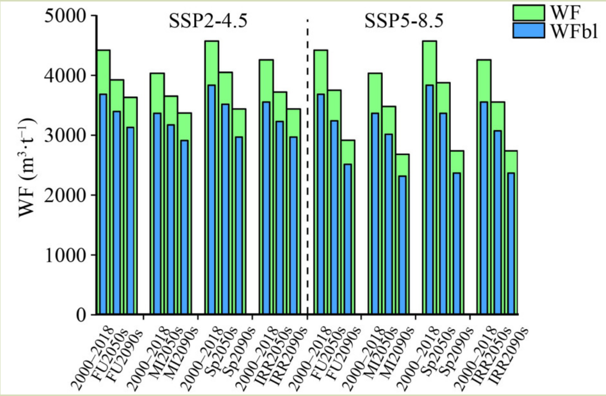


Fig. 3 Blue and green water footprints for three irrigation techniques used for cotton production in Xinjiang. FU, MI, and Sp represent Furrow irrigation, Micro-irrigation, and Sprinkler irrigation, respectively. FU2050s refers to furrow irrigation in the 2050s, with similar meanings for the other abbreviations.

3.2.2 Response of cotton blue and green water footprints to future climate change

Under the SSP2-4.5 and SSP5-8.5 scenarios, the proportion of blue WF in the 2090s would be 86.4%, higher than that in the base period, which was 83%. Additionally, the blue WF of cotton was predicted to have an overall decreasing trend in the 2090s, with reductions of 16.5% and 33.4%, respectively. Spatial distribution of WF was predicted to have significant differences. Under SSP2-4.5, regions with larger decreases in the 2090s would be mainly in northern Xinjiang whereas regions with smaller reductions would be mainly in southern Xinjiang, with only a few areas in western and south-western parts predicted to have an increasing trend in the blue WF. Under the SSP5-8.5 scenario, there was no region that would have an increasing trend in the blue WF in the 2090s and the decrease was more pronounced, with significant reductions predicted for southern Xinjiang exceeding 40% in some areas (Fig. 5). Under both future climate scenarios, the reductions in the green WF of cotton production in Xinjiang in the 2090s were 33.7% (SSP2-4.5) and 47.2% (SSP5-8.5), respectively. In both scenarios, the green WF of cotton production was predicted to have a spatially decreasing trend in the 2090s, with larger reductions in southern Xinjiang and smaller reductions in northern regions. However, some areas were predicted to have a rising trend. Under SSP5-8.5, the green WF of cotton production in Xinjiang in the 2090s would have an overall decreasing trend, with more significant reductions in each region compared with SSP2-4.5, with the largest reduction exceeding 60%.

4 Discussion

This research calculated the cotton WF of Xinjiang by the dynamic soil water balance method. It used the output results of the BCC-CSM2-MR climate system model released by the Beijing Climate Center with a 5-arcmin grid level as the spatial unit[26]. We calculated the relative changes and spatiotemporal distribution of the blue and green WFs of cotton in Xinjiang in the baseline period, the 2050s and 2090s under the SSP2-4.5 and SSP5-8.5 future climate scenarios, analyzing the response of the cotton WF to future climate change. Under the two climate scenario models, at the temporal scale, predicted ET_0 had an increasing trend whereas precipitation was predicted to to have a decreasing trend, indicating that Xinjiang would

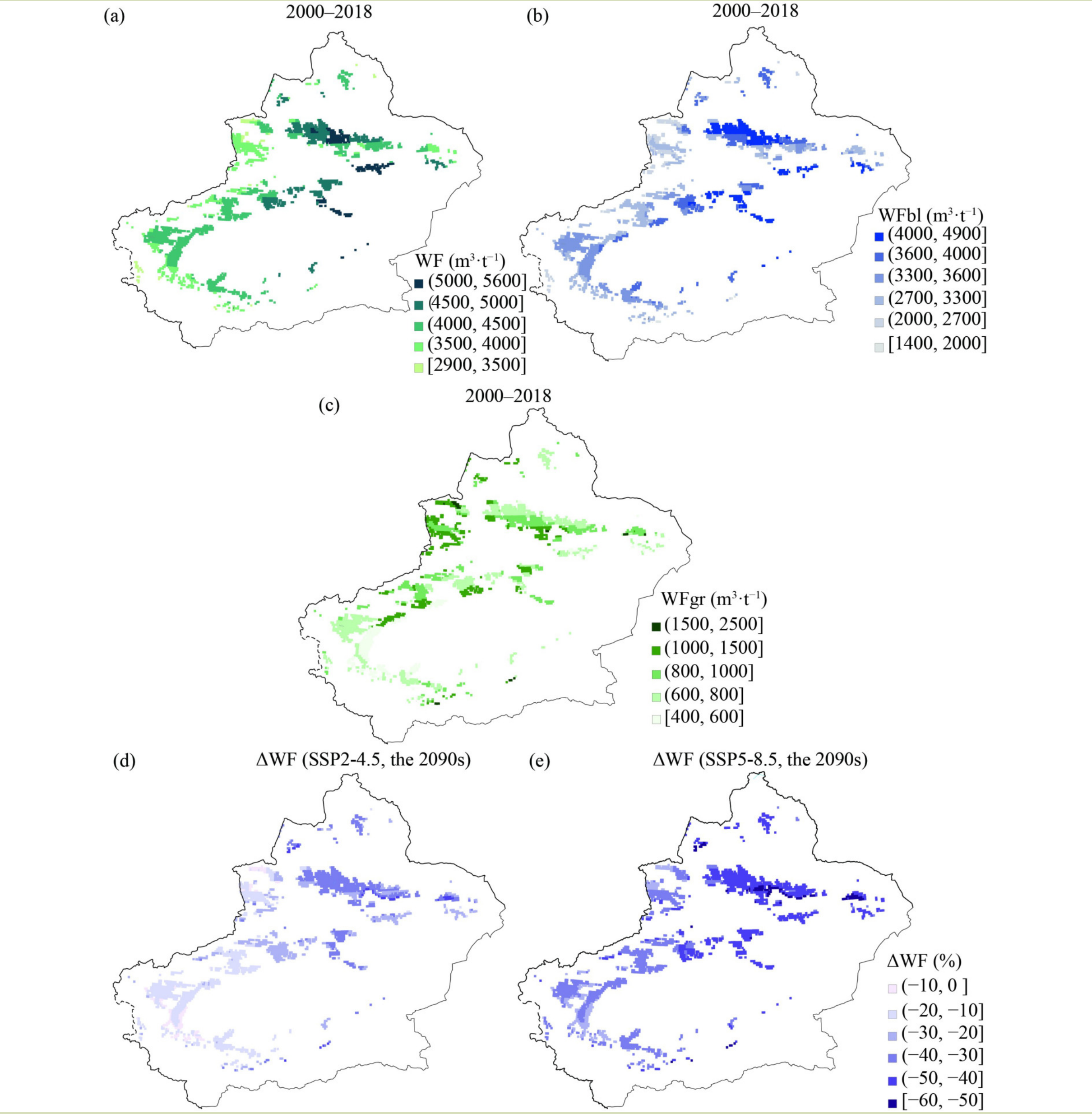


Fig. 4 Baseline and forecast relative changes in cotton water footprint in Xinjiang (审图号：新S（2025）016号). (a–c) The spatial distribution of total, blue, and green water footprints in Xinjiang from 2000 to 2018; (d, e) the relative changes in total water footprint for the 2090s compared to 2000–2018 under the SSP2-4.5 and SSP5-8.5 scenarios, respectively.

become drier in the future. Specifically, during the cotton growing season (mid-April to mid-October), ET_0 was projected to increase significantly from April to June, while precipitation was expected to decline. The intensification of drought conditions could affect the germination stage of cotton, potentially leading to delayed or failed seed germination. Although precipitation was projected to increase to some extent from July to October, the rate of increase remained substantially lower than that of ET_0. As a result, Xinjiang would continue to rely heavily on irrigation in the future, which is consistent with the conclusions drawn by Wang[35].

Li & Deng[36] studied the economic benefits of the WF of various crops in Xinjiang for 2006 to 2018. They found that the WF economic benefit of cotton was the lowest at about 1530 m^3 per 10^4 yuan, whereas that of potatoes was the highest at about 11 m^3 per 10^4 yuan. Although the WF economic benefit of cotton is the lowest, Xinjiang has the highest cotton production in China, which is important for Xinjiang's economic development. Therefore, giving attention to the water requirements of cotton production is crucial for reducing its WF and increasing its economic benefits. During the baseline period, the average WF of irrigated cotton was 4260 $m^3 \cdot t^{-1}$, with a blue WF of 3560 $m^3 \cdot t^{-1}$, which is consistent with the results of Li & Deng[36] and Hossain and Khan[37]. In diverse climatic zones and irrigation regimes, the responses of WF benchmarks to future climate change may have discrepancies[14]. Therefore, this study distinguished the changes in WFs under three irrigation techniques in the future. In the future, the WF under these irrigation techniques would have a decreasing trend. Of these, sprinkler irrigation would have the largest decrease in both scenarios, with reductions of 24.8% and 40.1%, respectively, whereas furrow irrigation and micro-irrigation were predicted to have similar decreases. This indicates that sprinkler irrigation has the highest water-saving potential, consistent with the conclusions of Yue et al.[14]. Also, under SSP5-8.5, the WF of cotton in the 2090s would be significantly lower than that under SSP2-4.5. Although the former predicts higher temperatures and lower precipitation compared to the latter, the CO_2 concentration in the SSP5-8.5 scenario (0.999%) is substantially higher than that in the SSP2-4.5 scenario (0.596%). Li et al.[19] has indicated that increased temperatures and reduced precipitation can have adverse effects on cotton yield. However, these negative impacts would be counterbalanced by the beneficial effects of elevated CO_2 concentrations, which is consistent with the findings of this study.

Under both climate scenarios, the spatial distribution of both blue and green WFs primarily would have a downward trend, with the decline in both blue and green WFs for being greater in the 2090s than in the 2050s. This is likely to due to the CO_2 fertilization effect. Additionally, the proportion of blue WF relative to the total WF is expected to be higher in both future scenarios compared to the baseline period. This may be attributed to the predicted changes in annual ET_0, which is

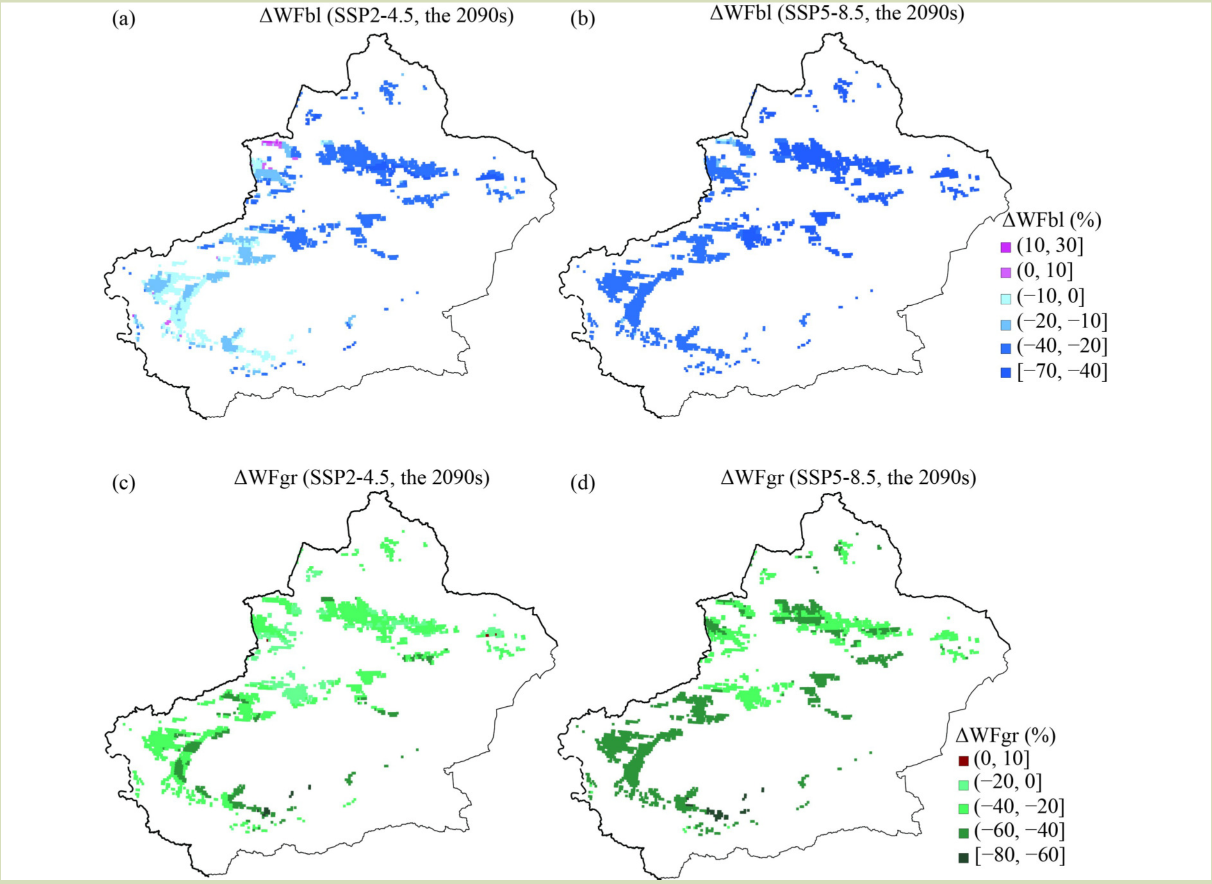


Fig. 5 Predicted relative changes in blue (△WFbl) and green (△WFgr) water footprints of cotton in Xinjiang (审图号：新S（2025）016号). (a, b) The spatial distribution of relative changes in blue water footprint for Xinjiang Province in the 2090s compared to 2000–2018 under SSP2-4.5 and SSP5-8.5, respectively; (c, d) the same for green water footprint.

expected to increase, and precipitation, which is anticipated to decrease. These changes lead to a reduction in the green WF while simultaneously causing an increase in the proportion of the blue WF. The green WF was predicted to have a downward trend across most of Xinjiang, with a few areas having an increasing trend, possibly due to increased precipitation in those areas under the scenarios.

Although this study has explored the influence of future climate change on cotton production WF, it has only considered the effects of ET_0, precipitation and CO_2. Additionally, the model used assumes that irrigation technology, cotton cultivars and agronomic practices remain unchanged. However, Song et al.[38] predicted that crop water requirements for cotton would increase under all future scenarios. With improvements in water-saving irrigation technologies, it is expected that the water consumption associated with the three main irrigation techniques would be significantly reduced. Zhang et al.[39] suggest that the intensification of drought conditions would lead to an expansion of the areas suitable for cotton production in Xinjiang, a reduction in areas unsuitable for cotton and a shift of some cotton-suitable areas toward higher-yielding cultivars, which would result in an increase in cotton production. Zhang et al.[40] posit that high-yielding and high-quality cotton cultivars will gradually replace existing lower-quality ones, thereby increasing the cotton yield per unit area in the future. Therefore, it is necessary to consider these factors in further research to enhance the credibility of our findings.

5 Conclusions

This research analyzed the spatial and temporal dynamics of cotton WF and the temporal changes in precipitation and ET_0 under two future climate scenarios in Xinjiang. The conclusions were as follows: ET_0 and precipitation were predicted to increase and decrease, respectively, suggesting that Xinjiang will increasingly rely on irrigation to meet its water demands, thereby intensifying the pressure on water resources. Under SSP2-4.5 and SSP5-8.5, the overall cotton irrigation WF was predicted to decrease by 19.3% and 35.7%, respectively. The proportion of the blue WF was predicted to increase slightly but the overall blue WF was predicted to decrease by 16.5% and 33.4%, respectively. The green WF was predicted to decrease by 33.7% and 47.2%. The spatial distribution of the blue WF was predicted to decline more reductions in the north than in the south whereas the green WF reduction would have the converse trend. Of the three irrigation techniques, sprinkler irrigation had the greatest potential for water conservation, with a reduction of up to 40.1%.

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Compliance with ethics guidelines

Pengcheng Tian, Zhiwei Yue, Xiangxiang Ji, Ning Yao, Pute Wu, and La Zhuo declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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