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Accessing future crop yield and crop water productivity over the Heihe River basin in northwest China under a changing climate

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Abstract

Quantitative evaluation of the response of crop yield and crop water productivity (CWP) to future climate change is important to prevent or mitigate the adverse effects of climate change. This study made such an evaluation for the agricultural land over the Heihe River basin in northwest China. The ability of 31 climate models for simulating the precipitation, maximum temperature, and minimum temperature was evaluated for the studied area, and a multi-model ensemble was employed. Using the previously well-established Soil and Water Assessment Tool (SWAT), crop yield and crop water productivity of four major crops (corn, wheat, barley, and spring canola-Polish) in the Heihe River basin were simulated for three future time periods (2025–2049, 2050–2074, and 2075–2099) under two Representative Concentration Pathways (RCP4.5 and RCP8.5). The results revealed that the impacts of future climate change on crop yield and CWP of wheat, barley, and canola would all be negative, whereas the impact on corn in the eastern part of the middle reaches of the Heihe River basin would be positive. On the whole, climate change under RCP8.5 scenario would be more harmful to crops, while the corn crops in the Minle and Shandan counties have better ability to cope with climate change.

Keywords: Crop yield, Crop water productivity, Soil and water assessment tool, Representative concentration pathways, Heihe river basin

Introduction

The latest report of the Intergovernmental Panel on Climate Change (IPCC) points out that the concentration of greenhouse gases in the atmosphere will continue to rise in the future under the combined effects of natural factors and human activity and that the continuous warming of the global climate system has been an indisputable fact (IPCC 2013). Global warming has caused significant changes to the climate in some parts of China (Ji and Kang 2013; Zou and Zhou 2013; Wu et al. 2014; Qin and Xie 2016). Changes in the quantity, quality, and combination of climate variables, as well as the more frequent occurrence of extreme weather and natural disasters with greater magnitudes, will have a direct or indirect impact on food security, ecological and social security, and human health.

According to the recent FAO (Food and Agriculture Organization of the United Nations) report, climate change for high-emission climate scenarios by 2100 may result in production reduction with a rate of 20–45% for maize, 5–50% for wheat, 20–30% for rice, and 30–60% for soybean (FAO 2016). Climate change poses an unprecedented challenge to agricultural development and the security of agricultural production systems. Temperature, precipitation, and other climatic factors will directly lead to changes in light, heat, and water resources required for the growth of crops, thus resulting in changes not only in crop physiology but also in yield and quality. The degree of impact will vary with different crop types, but all are anticipated

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to reach a significant level (Ambardekar et al. 2011; Zhao et al. 2007). As a result, agriculture is the industry that will be most directly and most severely affected by climate change (Fisher et al. 2012). Global warming will advance the time of soil thawing in spring and the sowing time of spring-sown crops (Yang et al. 2019; Wang et al. 2004). Further, the rising temperature in the growing period will accelerate the growth and development of some crops, shorten the phenological stage, and reduce the time for photosynthesis and dry matter accumulation (Eamus 1991; Polley et al. 1993). Nevertheless, the increase in CO_2 concentration in the atmosphere will stimulate the photosynthesis of crops, leading to improvement in photosynthesis efficiency and water use efficiency (Schmidhuber and Tubiello 2007). Accumulating evidence suggests that the overall impact of climate change on crop yields is positive in some agricultural areas and negative in others (Parry et al. 2004; Lobell et al. 2011; He et al. 2018). Therefore, it is necessary to quantitatively assess the response of crop yields to future climate on a regional scale and to use scientific and technological developments to mitigate any adverse impacts.

The rapid development of crop growth models has led to their wide applications to simulate the biomass and yield of different crops, especially in the study of climate change impacts (Challinor et al. 2010; Chen et al. 2013; Wang et al. 2018). Marin et al. (2013) simulated the sugarcane yield in southern Brazil using the calibrated DSSAT/CANEGRO model. The results showed that sugarcane yield was sensitive to temperature, CO_2 concentration, and rainfall; the sugarcane yield and water use efficiency showed an increasing trend when all of temperature, CO_2 concentration, and rainfall increased.

The crop growth module of the Soil and Water Assessment Tool (SWAT) was derived from the simplified EPIC module (Neitsch et al. 2011), which has successfully simulated crop growth processes under different crop types, diverse management measures, and various climatic conditions (Shahvari et al. 2019; Wu et al. 2012; Sun and Ren, 2014; Marek et al. 2017). Fu et al. (2019) adopted SWAT to simulate the effect of 16 kinds of irrigation schemes on crop yield and water use efficiency in the downstream of the Songhua River Basin in China, and determined the optimum irrigation schemes of corn and soybean crops by means of Analytic Hierarchy Process (AHP) and Gray Interconnect Degree Analysis (GIDA). Uniyal et al. (2019) calibrated SWAT in four catchments of different agro-climatic zones/countries to simulate the crop growth under deficit irrigation, and found that deficit irrigation (25–48%) achieved substantial water savings with only a small decrease in annual average crop yield in all climatic zones.

Crop yield and crop water productivity (CWP) are important indicators that can reflect regional agricultural production level and evaluate food sustainability. The CWP is defined as the marketable crop yield over the water use by actual evapotranspiration (Kijne et al. 2003). Increasing crop yields while also increasing crop water productivity to relieve pressure on water resources and reduce conflicts in water use is an important challenge faced by China. Sun et al. (2017) found, by comparing the effects of agricultural management measures on crop water productivity of wheat, that CWP is more sensitive to irrigation efficiency when compared to the amount of fertilizer. Vaghefi et al. (2017) used a coupled SWAT–MODSIM model to simulate the CWP of irrigated wheat and maize in the Karkheh River Basin (KRB) in the semi-arid region of Iran. The results showed that there was a close linear relationship between crop yield and CWP, which first increased and then decreased with the continuous rise of consumptive water use. These studies and their outcomes indicate that exploring crop water productivity helps understand the tradeoff between food production and water consumption and helps find effective ways to improve CWP under climate change conditions.

The Heihe River basin is an important commercial grain base, located in an arid region in northwest China. The runoff generation and crop production for the region were simulated in the study of Niu et al. (2018). Li et al. (2016) applied AquaCrop model to quantify the impact of climate change on water consumption and water use efficiency of maize and spring wheat for a sub-region. Han et al. (2017) analyzed the effect of climate change on phenological stages and water requirement of spring wheat during growing season. However, to the best of our knowledge, the previous studies did not systematically evaluate the possible effects of climate change on the local major crops (four crop types) with the crop distribution data (Zhong et al. 2015) and GCM products for the whole agricultural land in the middle reaches of the basin. Encouraged by the advances made by the above studies, the present study attempted to assess the impact of climate change on crop yield and crop water productivity in the Heihe River basin in northwest China (Fig. 1).

The latest generation of coupled climate models included in the Coupled Model Intercomparison Project Phase 5 (CMIP5) have been widely used to assess the impact of climate change on crop yield at the regional scales (Rowhani et al. 2011). Combined with future meteorological data, the present study aims to use SWAT model to simulate the temporal and spatial changes in crop yield and CWP of major crops in the upper-middle Heihe River basin under future climate change conditions (see Fig. 2).

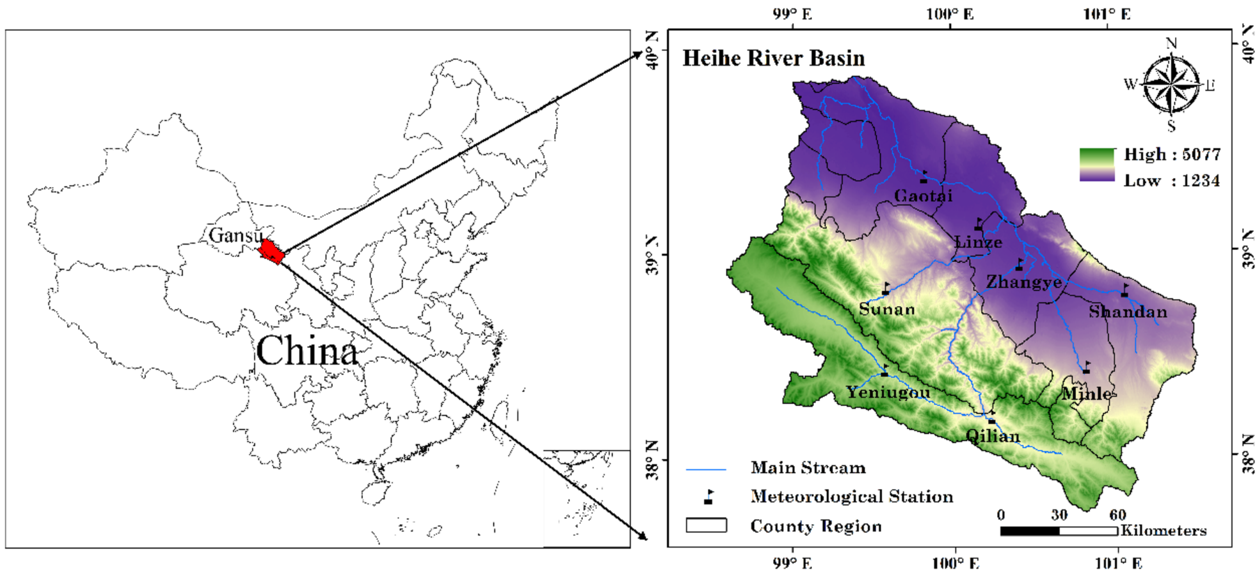


Fig. 1 Location of the upper and middle reaches of the Heihe River basin, the river network, DEM, meteorological stations, and the main counties in the study area

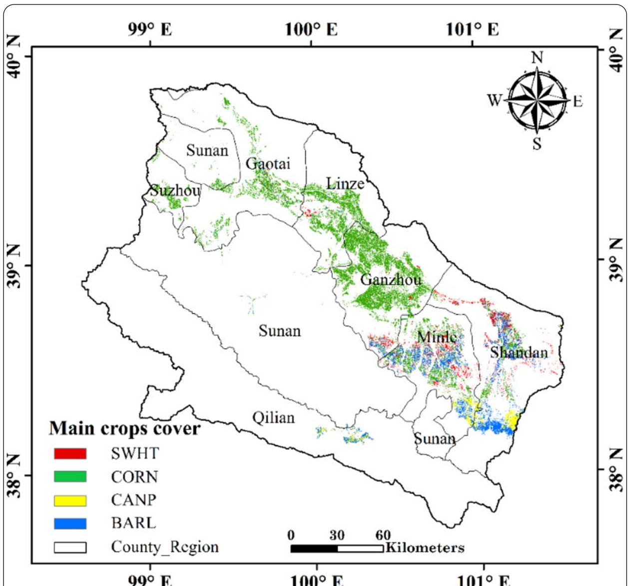


Fig. 2 Planting distribution of four main crops (corn, spring wheat, spring barley, and spring canola-Polish) in the upper and middle reaches of the Heihe River basin

The flowchart of the performed study is shown in Fig. 3. The rest of this paper is organized as follows: "Materials and methods" introduces the study area, relevant data, and methods used in this study. The ability of climate models to simulate climate variables is briefly assessed before their outputs are incorporated into SWAT, for predicting the potential effects of future climate change on crop yield and CWP. The results from the analysis of spatial–temporal characteristics of major crops at different time periods in the future are presented in "Results and discussion." "Limitation and future studies" explains the study limitations and what we can do in the next step. "Conclusions" draws some conclusions and highlights the implications of the present study toward responding effectively to climate change.

Materials and methods

Study area and established SWAT

The Heihe River basin, with an area of 14.2×10^4 km^2, is the second largest inland river basin in northwest China. The basin is located between 98° E and 102° E longitude and between 38° N and 42° N latitude (Fig. 1). The Heihe River originates in the Qilian Mountains and flows through Qinghai, Gansu, and Inner Mongolia provinces (Cheng et al. 2014). The Qilian Mountains in the south of the Yingluo gorge is the upper reach of the Heihe River basin, with a large area of water conservation forests. The middle reach is between the Yingluo gorge and the Zhengyi gorge, which is a typical agricultural area. The upper and middle reaches of the Heihe River basin is the area considered in the present study (see Fig. 1).

Located in the hinterland of the Eurasian continent, the Heihe River basin has a typical temperate continental climate with dry climate, less and concentrated precipitation, windy weather, and strong solar radiation. The middle reaches of the Heihe River, located in the middle of the Hexi corridor, is not only a primary irrigated agricultural area in northwest China but also an important commercial grain base in China. According to the statistical yearbook 2012 of the Zhangye Municipal Bureau of Statistics (ZMBS), the planting area of corn, wheat, barley, and spring canola-Polish in the middle reaches of the Heihe River basin accounted for 63% of the total agricultural planting area, with an annual output of 9.9×10^5 tons, accounting for more than 80% of the total crop output (ZMBS 2012). Therefore, corn, spring wheat, spring barley, and spring canola-Polish are the main cultivated crops in this region.

In a previous study, Niu et al. (2018) successfully developed a distributed hydrological model for the upper-middle Heihe River basin using SWAT. In their study, the study area was divided into 34 sub-basins and 1613 hydrological response units. The model parameter values used in the present study were obtained from Niu et al. (2018) using the observed evapotranspiration, detrending crop yield data, and the optimization algorithm of the Sequential Uncertainty Fitting Algorithm Version 2 (SUFI-2) (Abbaspour et al. 2004).

Climate data

The 31 climates models used in this study were obtained from the CMIP5 under the World Climate Research Program (WCRP). Table 1 presents the details of these models (Taylor et al. 2012). The fifth Assessment Report (AR5) of the IPCC adopted the Representative Concentration Pathways (RCPs) integrated into policy factors, which have a stronger capability to simulate extreme weather (Moss et al. 2008). The RCPs are a new scenario characterized by stable concentration, including four typical concentration paths: RCP2.6, RCP4.5, RCP6.0, and RCP8.5. The radiative forcing values of four RCPs range from 2.6 to 8.5 W/m^2 by 2010. RCP8.5 is the highest emission scenario, without any mitigation policy to greenhouse gas (GHG) emissions. The lower scenarios (RCP2.6, RCP4.5, and RCP6.0) have adopted some mitigation measures to control GHG emissions (van Vuuren et al. 2011). RCP4.5 is the medium stabilization scenarios and has a higher priority than RCP6.0 (Han et al. 2018). Considering the increasing CO_2 concentration in the future, emission modes RCP4.5 and RCP8.5, which are relatively close to the current social and ecological environment (Meinshausen et al. 2011; Wang et al. 2015), were selected for this study.

Table 1 Summary of the 31 climate models from CMIP5 used in this study

No	Model	Unit, Country	Resolution[a]
1	IPSL-CM5B-LR	IPSL, France	3.750° × 1.895°
2	IPSL-CM5A-LR	IPSL, France	3.750° × 1.895°
3	IPSL-CM5A-MR	IPSL, France	2.500° × 1.268°
4	CNRM-CM5	CNRM-CERFACS, France	1.407° × 1.401°
5	CCSM4	NCAR, America	1.250° × 0.942°
6	GFDL-CM3	NOAA GFDL, America	2.500° × 2.000°
7	GFDL-ESM2G	NOAA GFDL, America	2.500° × 2.000°
8	GFDL-ESM2M	NOAA GFDL, America	2.500° × 2.000°
9	GISS-E2-R	NASA GISS, America	2.500° × 2.000°
10	CESM1-BGC	NSF-DOE-NCAR, America	1.250° × 0.942°
11	CESM1-CAM5	NSF-DOE-NCAR, America	1.250° × 0.942°
12	MIROC5	MIROC, Japan	1.407° × 1.401°
13	MIROC-ESM	MIROC, Japan	2.813° × 2.791°
14	MIROC-ESM-CHEM	MIROC, Japan	2.813° × 2.791°
15	MRI-CGCM3	MRI, Japan	1.125° × 1.125°
16	BNU-ESM	GCESS, China	2.813° × 2.791°
17	BCC-CSM1-1	BCC, China	2.813° × 2.791°
18	BCC-CSM1-1-M	BCC, China	1.125° × 1.125°
19	FGOALS-g2	LASG-CESS, China	2.813° × 2.791°
20	FIO-ESM	FIO, China	2.813° × 2.791°
21	HadGEM2-AO	NIMR, England	1.875° × 1.250°
22	HadGEM2-CC	MOHC, England	1.875° × 1.250°
23	HadGEM2-ES	MOHC, England	1.875° × 1.250°
24	ACCESS1-0	CSIRO-BOM, Australia	1.875° × 1.250°
25	CSIRO-Mk3-6-0	CSIRO-QCCCE, Australia	1.875° × 1.865°
26	MPI-ESM-LR	MPI-M, Germany	1.875° × 1.865°
27	MPI-ESM-MR	MPI-M, Germany	1.875° × 1.865°
28	CanESM2	CCCMA, Canada	2.813° × 2.791°
29	CMCC-CM	CMCC, Italy	0.750° × 0.750°
30	INMCM4	INM, Russia	2.000° × 1.500°
31	NorESM1-M	NCC, Norway	2.500° × 1.895°

[a] The format of resolution is longitude × latitude

Correlation coefficient (R) and centered root-mean-squared difference (cRMS) (Sukanta et al. 2015) are important indexes to evaluate the simulation performance of the models. They are expressed as follows:

$$R = \frac{\frac{1}{N}\sum_{n=1}^{N}(f_n - \overline{f})(r_n - \overline{r})}{\sigma_f \sigma_r} = \frac{\frac{1}{N}\sum_{n=1}^{N}(f_n - \overline{f})(r_n - \overline{r})}{\sqrt{\frac{1}{N}\sum_{n=1}^{N}(f_n - \overline{f})^2}\sqrt{\frac{1}{N}\sum_{n=1}^{N}(r_n - \overline{r})^2}}, \quad (1)$$

$$\mathrm{cRMS} = \left\{ \frac{1}{N} \sum_{n=1}^{N} \left[(f_n - \bar{f}) - (r_n - \bar{r}) \right]^2 \right\}^{\frac{1}{2}}, \quad (2)$$

where f_n and r_n are the simulated and observed sequence values, $\bar{f}$ and $\bar{r}$ are the simulated and observed mean values, and n is the number of time positions.

Based on the correlation coefficient and cRMS between the simulated and observed values, the 31 climate models were ranked, and the multi-model ensemble (MME) result is selected to project future climate change. In the present study, the MME result was the equally weighted mean of the top three climate models in the evaluation results, so as to reduce the uncertainty of global climate model simulation.

The Delta method (Dubey and Sharma 2018) was used in this study for bias correction of the estimated future meteorological data, i.e., 2025–2099. For the convenience of macro statistics, the entire future time period 2025–2099 was divided into three sub-periods: short term (2025–2049), medium term (2050–2074), and long term (2075–2099).

The downloaded climate model data were on a monthly timescale. In order to meet the requirements of meteorological data input in SWAT, the bias-corrected data were converted to daily timescale. The detailed theory and description of temporal downscaling for each station have been reported by Jin and Sridhar (2012).

Crop information

Due to the prevailing characteristics of water and heat conditions, the study area is suitable mainly for two types of crops: summer harvesting crop (wheat and barley) and autumn harvesting crop (corn and spring canola-Polish). Corn is a C4 plant (Arrivault et al. 2017), whose growing period is from April to September. As the main food crops in the Heihe River basin, corn is planted in large areas in the north of the Minle, Shandan, Gaotai, Linze, Ganzhou, and Suzhou counties, among which Ganzhou county has the largest planting density. Wheat and barley

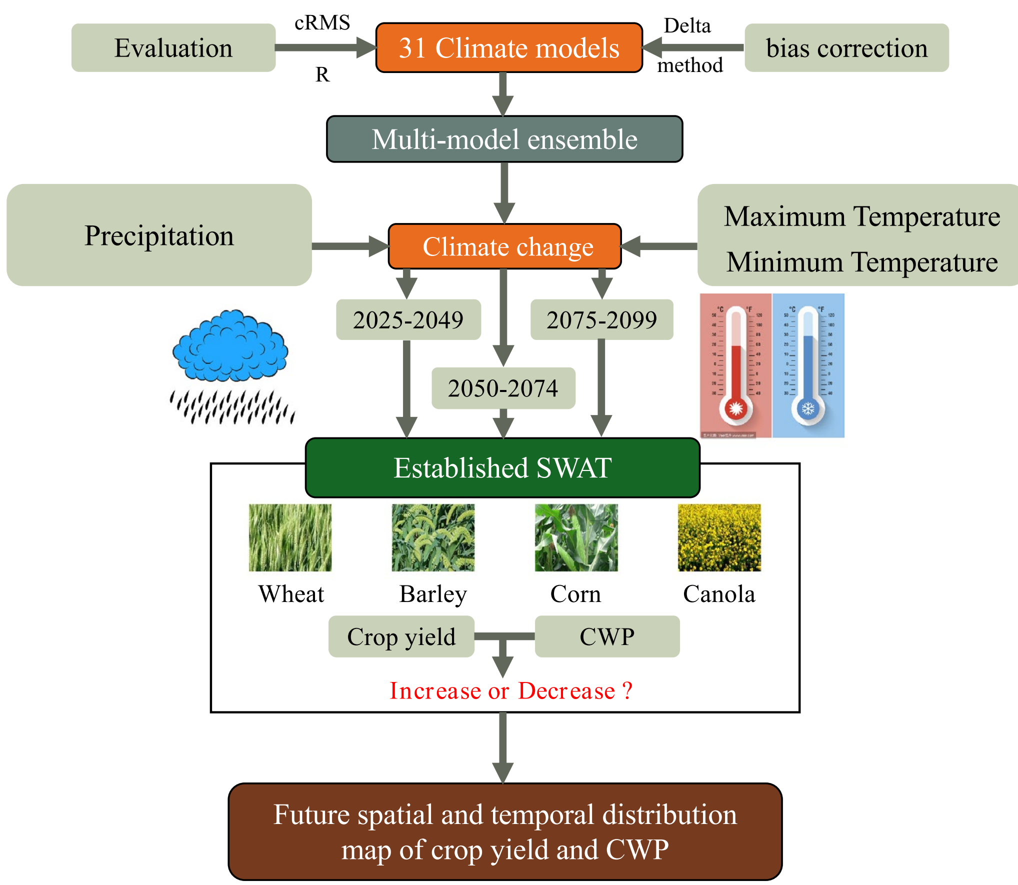


Fig. 3 Flowchart of the performed study

are C3 plants (Janjua et al. 2014; Cunniff et al. 2017), the growth period of both is similar, from April to July. Wheat cultivation is relatively scattered, mainly distributed in the Shandan, Minle, and Ganzhou counties. Barley is mainly planted in the south of the Ganzhou, Minle, and Shandan counties, with the most intensive cultivation in the south of the Shandan county. Spring canola-Polish, whose growth stage is from May to September, is also a C3 plant (Franzaring et al. 2011) and the main cash crop and oil crop in the study area.

Results and discussion

Climate model evaluation

Based on the historical observation data and model simulation data over the period 1980–2004 at the meteorological stations, the correlation coefficient and cRMS were calculated, and the climate models were sorted according to the order of the correlation coefficient from high to low and the cRMS from low to high.

The results of comprehensive ranking are presented in Fig. 4. The models GFDL-CM3, BCC-CSM1-1-m, and MPI-ESM-MR occupy the top three positions in the ranked results. The equally weighted mean of the three models outputs was used to project the future climate.

Precipitation and temperature

As predicted by the multi-model ensemble, the average annual rainfall during the short-term period increased by 22.29 mm and 16.75 mm for RCP4.5 and RCP8.5, respectively, compared with that during the baseline period. The increase was found to be 23.33 mm and 25.72 mm during the medium term, and 29.04 mm and 37.06 mm during the long term. These results indicate that, when the time period goes farther and farther in the future, the growth rate of rainfall with the RCP8.5 scenario becomes significantly higher than that with the RCP 4.5 scenario.

Figure 5 presents the monthly precipitation change. With scenario RCP4.5, the change in precipitation was mainly concentrated between May and August for the three different time periods, and the maximum precipitation change was in May. Consistent with the variation trend for scenario RCP4.5, the multi-year mean monthly precipitation for scenario RCP8.5 in the future was also found to increase compared to that during baseline period. For the periods 2025–2049 and 2050–2074, the maximum precipitation increase occurred in August and May, respectively. However, for 2075–2099, the precipitation increase exhibited a bimodal distribution. In general, the average annual precipitation with RCP8.5 scenario had a faster increasing trend than that for the RCP4.5 scenario.

By contrast, the maximum temperature was found to increase more rapidly than the minimum temperature in either scenario. The gradually widening distance over time between the maximum and minimum temperature curves also supported these observations, as summarized in Fig. 6. All in all, in the future, both the maximum and minimum temperatures will have a significant increasing trend.

Spatial and temporal distribution of crop water productivity

Based on the calibrated SWAT, the growth of corn, spring wheat, spring barley, and spring canola-Polish for the short, medium, and long terms, over the upper-middle

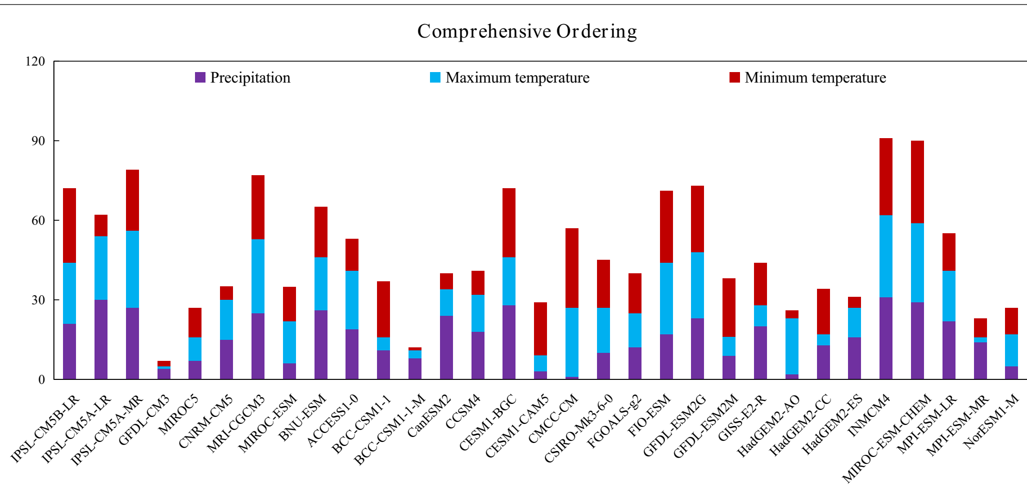


Fig. 4 Ranking of 31 climate models according to their comprehensive abilities to simulate precipitation, maximum temperature, and minimum temperature

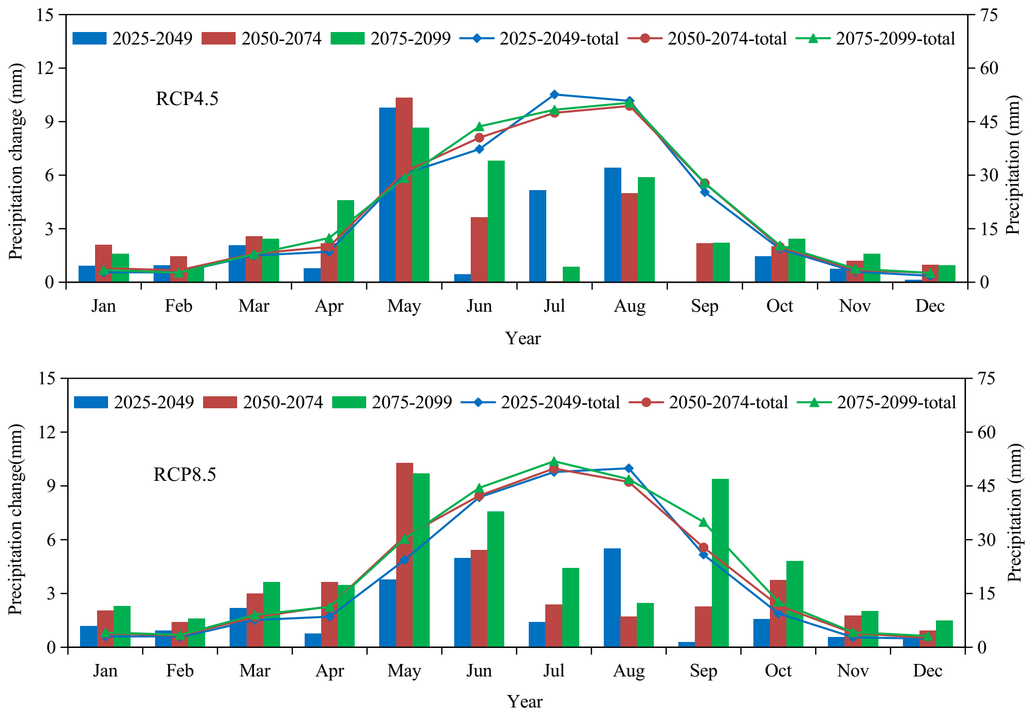


Fig. 5 Precipitation change of future precipitation data under RCP4.5 and RCP8.5 scenarios with respect to the historical period (1980–2004)

Heihe River basin, was simulated with future climate change conditions.

It is important to note that the crop growing conditions are different in different counties for the upper-middle reaches of the Heihe River basin. The crop yield and CWP present spatial differences. Figures 7 and 8 display the change in short-term crop yields and CWP of the four main crops relative to the historical baseline period, respectively, for the climate scenarios RCP4.5 and RCP8.5, respectively. Figure 7 shows that, for scenario RCP4.5, climate change would reduce the yield of spring wheat, spring barley, and spring canola-Polish in varying degrees. The decrease in wheat yield was found to be most significant in Gaotai, Suzhou, and Sunan (west) counties. Different from the distribution of yield change, the regions with the most significant drop in CWP were Shandan, Minle, and Sunan counties. The decrease in CWP in these counties was found to be in the range 0.21–0.23 kg m^{-3} compared to the baseline period, while in the western regions, the drop in CWP of wheat was found to be below 0.15 kg m^{-3}. Temperature was found to be the main reason for the decrease in wheat yield. The loss of wheat yield caused by heat stress could be attributed to the shortening of the growth period induced by high temperature and the interference of carbon assimilation (Stone 2001). In short, the results suggested that the impact of future climate change on crop yield and CWP would be negative. The temperature increase is gradually getting greater from east region to west region, and this distribution characteristic determines the regional difference in crop yield decline. The results are summarized in Table 2.

High temperatures have been shown to reduce tillering stage, grain number, and grain weight, thereby further leading to reduction in crop yield. High maximum temperature can shorten the duration of grain fill and/or lower grain weight, which can reduce yield (Hakala et al. 2012). Moreover, high minimum temperature may increase the night-time respiration, thus reducing the amount of organic substances available for plant growth and development (Klink et al. 2014). Therefore, under future climate change conditions, Gaotai county with higher temperature would become a major disaster area of barley production decline. June is close to the barley harvest time in the Heihe River basin. Peltonen-Sainio et al. (2011) found that increased precipitation in the phase close to maturity is a strong contributor to reduced yield. Table 3 shows that except Qilian county, Minle and Shandan have a higher increase in precipitation in June (close to maturity for barley in all county except Qilian) than other counties, which is the main reason for the 300–400 kg ha^{-1} decrease in barley yield. In Sunan, close to the south, the yield was found to be less sensitive to climate change, and the level of decline was found

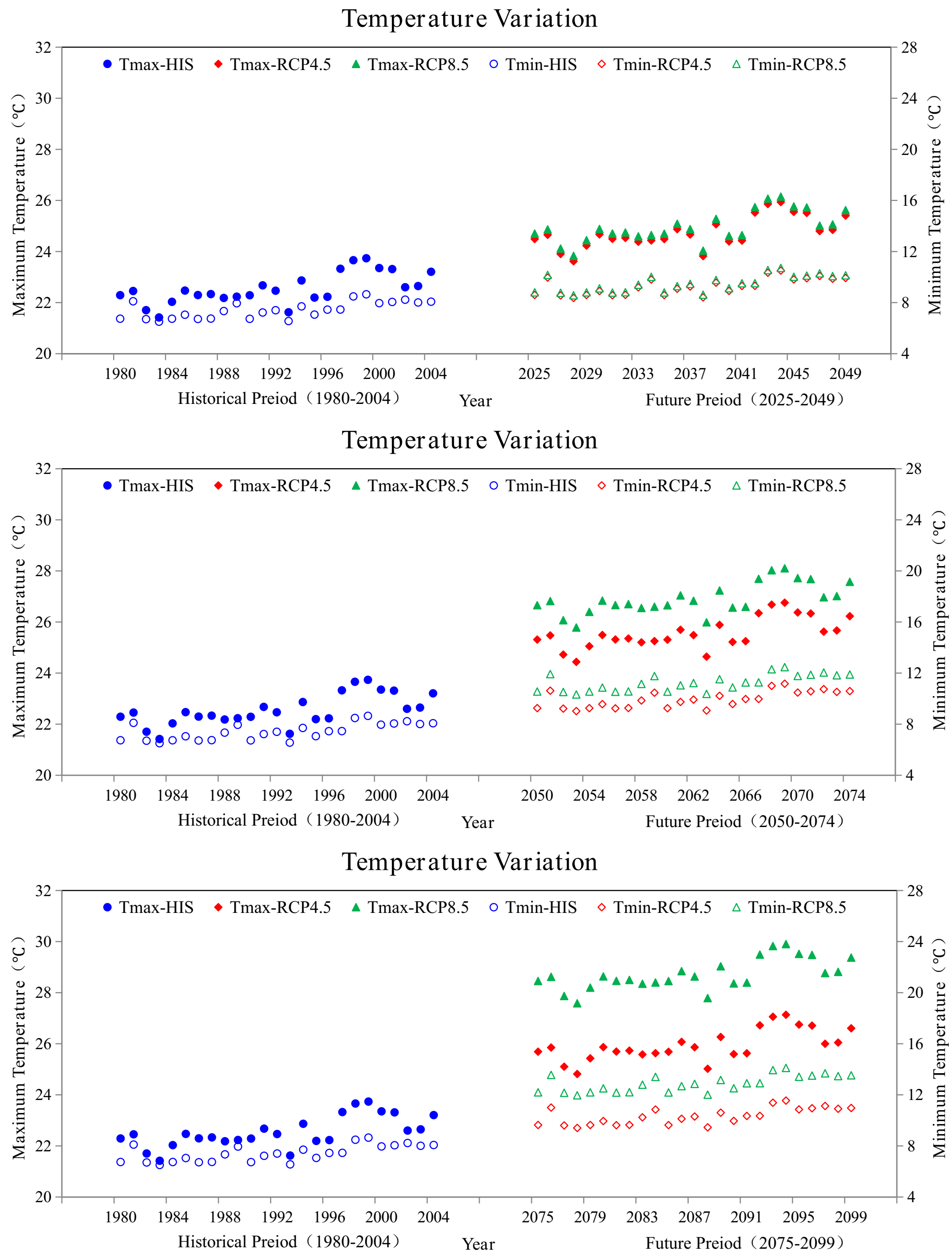


Fig. 6 The change tendency of maximum and minimum temperatures in the historical baseline period and in three future periods, i.e., 2025–2049 (top), 2050–2074 (middle), and 2075–2099 (bottom), with RCP4.5 and RCP8.5 scenarios

to be less than 250 kg ha^{-1}. As for the CWP, the level of decline in the eastern region was found to be significantly higher than that in the western region; the CWP reduction was found to be the most serious in Minle and Shandan counties, with a decline of about 8.5% compared with the baseline period. The degree of decrease in spring canola-Polish crop yield and CWP of spring canola-Polish indicated the trend of gradual increase from west to east in the future climate change.

Warming will not only inhibit the development of meristems in C3 plants but also enhance their photorespiration. However, for C4 crops, a slight increase in temperature will make the meristems more active to some extent, promoting the growth of crops (Ghannoum et al.

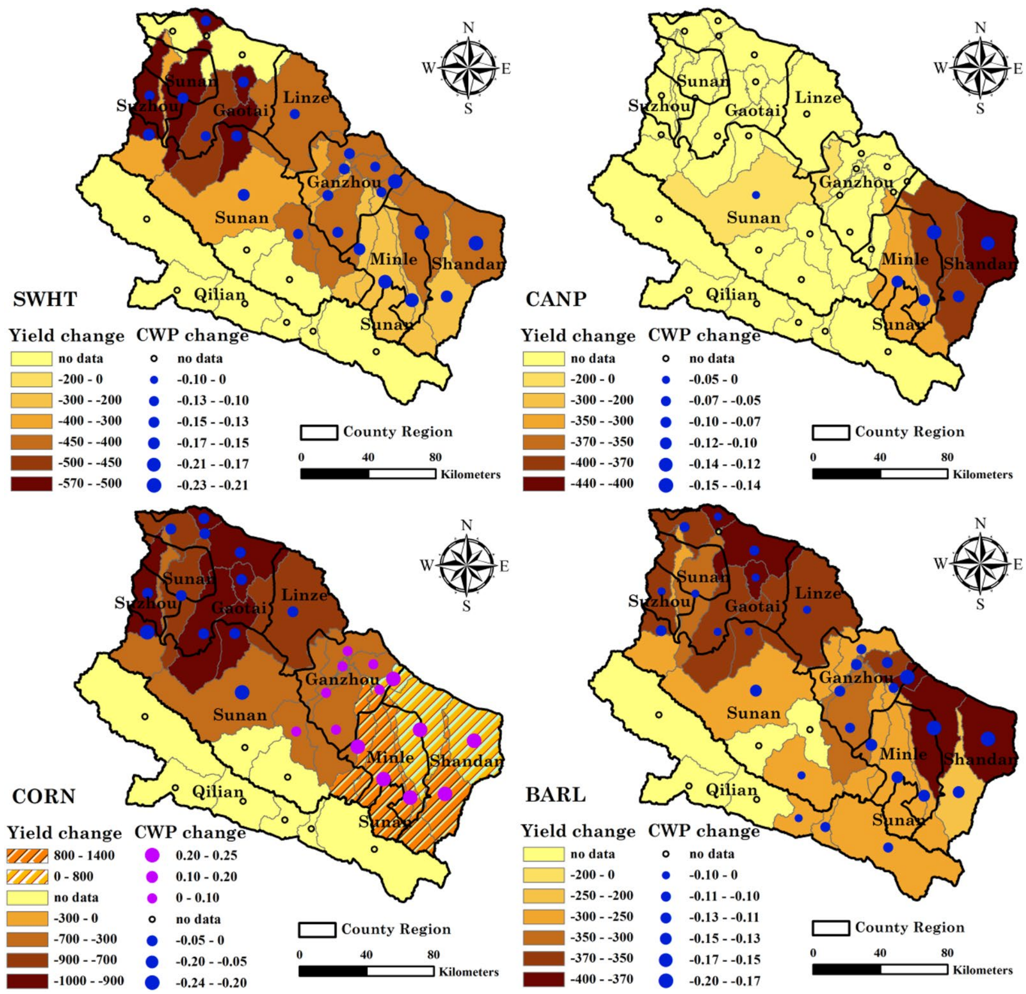


Fig. 7 The change of short-term crop yields and CWP of wheat (SWHT), canola (CANP), corn (CORN), and barley (BARL) relative to the historical baseline period in the climate scenario RCP4.5

2000; Morgan et al. 2001; Hatch 1987). Thus, unlike the response of barley, wheat, and canola to climate change, corn yield and CWP displayed obvious increase in some areas of the Heihe River basin. The spatial distribution of maize yield change showed significant difference between the east and the west, and the dividing line was along the administrative boundary between Ganzhou and Minle, Shandan counties. The corn yield of Suzhou, Gaotai, Linze, and Ganzhou counties located to the east of the boundary presented an obvious downward trend, with the yield decreasing by 900–1000 kg ha^{-1} in severely affected areas. However, in Minle, Shandan, and Sunan (east) counties to the east of the dividing line, the corn yield increased significantly, especially in the southwest of Minle, the north of Shandan, and Sunan (east). Consequently, the increase in temperature in the western area of the Heihe River basin had evidently exceeded the tolerance range of corn crops, resulting in a decline in the crop yield. However, different with the negative effect of single temperature increase on crop, simultaneous increase in temperature and precipitation exerted a positive effect on crop, and this was why the corn yield in eastern region showed an increasing tendency. The dividing line for CWP was found to be to the west of that for corn yield, which is the administrative boundary between Linze and Ganzhou counties. To the west of the dividing line, the CWP in short term tended to decrease when compared to that during the historical base period, while to the east of the dividing line, the increase of CWP rose from west to east.

For the climate scenario RCP8.5, regions of severe output reduction showed a significant extension compared to that under the scenario RCP4.5. The areas of severe output reduction in wheat and barley basically covered the northwest region of the middle reaches of the Heihe River basin. Moreover, in the central and

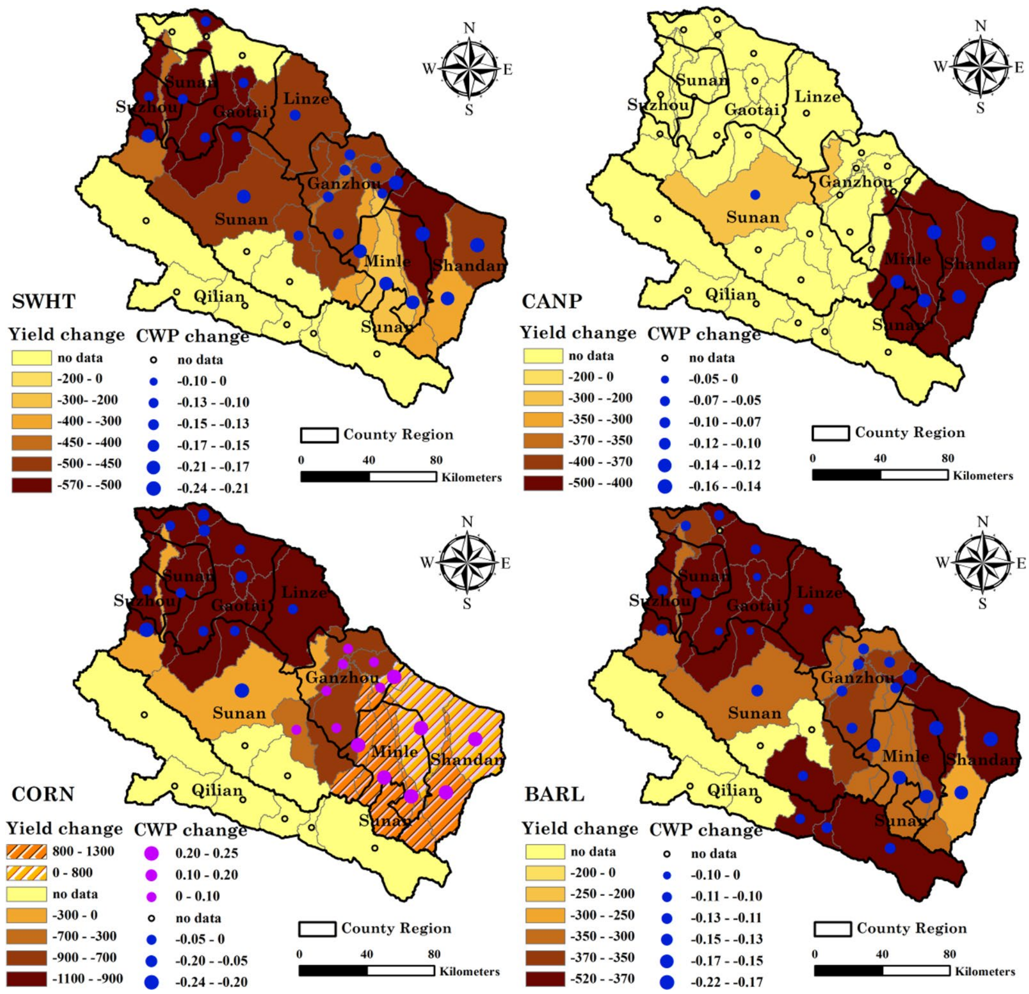


Fig. 8 The change of short-term crop yields and CWP of wheat (SWHT), canola (CANP), corn (CORN), and barley (BARL) relative to the historical baseline period in the climate scenario RCP8.5

Table 2 Increase in precipitation, maximum temperature, and minimum temperature in the short term (2025–2049), medium term (2050–2074), and long term (2075–2099) under scenario RCP4.5/ RCP8.5 relative to the historical baseline period in each county in the upper and middle reaches of the Heihe River basin

Region	Precipitation			Maximum temperature			Minimum temperature		
	Short	Medium	Long	Short	Medium	Long	Short	Medium	Long
Ganzhou	2.37/1.70	2.50/2.62	3.04/4.08	2.19/2.41	3.00/4.33	3.37/6.13	1.85/2.08	2.54/3.86	2.93/5.51
Gaotai	2.26/1.68	2.53/2.60	3.02/3.90	2.21/2.43	3.02/4.41	3.42/6.19	1.97/2.18	2.64/3.97	3.03/5.62
Linze	2.72/2.03	2.92/3.15	3.57/4.60	2.21/2.42	3.03/4.40	3.42/6.19	1.91/2.12	2.56/3.87	2.95/5.50
Minle	2.52/1.79	2.65/2.76	3.20/4.41	2.18/2.39	2.97/4.27	3.33/6.09	1.80/2.03	2.50/3.84	2.90/5.50
Qilian	6.58/5.05	6.67/7.69	8.57/10.53	2.20/2.41	3.05/4.37	3.41/6.18	1.75/1.94	2.37/3.62	2.74/5.25
Shandan	2.65/1.89	2.83/2.90	3.35/4.75	2.17/2.39	2.97/4.26	3.32/6.08	1.81/2.04	2.52/3.86	2.92/5.52
Sunan	2.91/2.17	3.11/3.34	3.82/4.89	2.20/2.42	3.02/4.37	3.40/6.17	1.90/2.11	2.57/3.88	2.95/5.53
Suzhou	2.56/1.91	2.80/2.98	3.39/4.35	2.21/2.42	3.03/4.41	3.42/6.19	1.94/2.15	2.60/3.92	2.99/5.56

Table 3 Change in precipitation in June in three different periods in the future relative to the historical baseline period (1980–2004) in each county in the Heihe River basin

Region	RCP4.5			RCP8.5		
	Short	Medium	Long	Short	Medium	Long
Ganzhou	0.14	2.15	4.49	3.13	3.52	5.66
Gaotai	− 0.52	1.47	3.57	2.47	1.95	4.49
Linze	− 0.17	2.20	4.59	3.32	3.06	5.43
Minle	0.56	2.60	5.19	3.53	4.78	6.70
Qilian	1.86	7.46	12.50	9.41	10.84	12.36
Shandan	0.49	2.70	5.48	3.77	5.11	7.33
Sunan	0.06	2.55	5.12	3.65	3.75	5.94
Suzhou	− 0.35	1.88	4.12	2.94	2.53	4.95

northeast regions, there had also been a significant increase in the number of production cuts. Further, the CWP of barley crops in the upper-middle reaches of the Heihe River basin decreased significantly, as shown in Fig. 8. The difference was that, in Suzhou, Gaotai, and Sunan (west) counties, where the yield of wheat crops decreased more significantly, the decline in CWP was alleviated instead. The main cause of the phenomenon was that wheat was a high water-consuming crop compared to the other three crops. A further increase in temperature reduced the yield of wheat; at the same time, however, it could improve the water use efficiency of plants by increasing the leaf transpiration (Williams and Baeza 2007), while the higher precipitation in the east masked this feature. Therefore, there was a greater decrease in CWP in Ganzhou, Minle, and Shandan counties. The change in corn yield also showed the marked difference between the east and the west. The western region had all evolved into a severe output reduction area, with the decline in yield reaching more than 900 kg ha^{-1}. Clearly, when the temperature increases too much, even with high rainfall, the damage due to high temperature on crops cannot be prevented. Nevertheless, the distribution of CWP for corn was not significantly different from that in scenario RCP4.5.

Figures 9 and 10 show the changes in crop yield and CWP. It could be seen that in scenario RCP4.5, the crop yield and CWP of spring wheat, spring barley, and spring canola-Polish decreased continuously with the passage of time. The corn yield and CWP in Minle and Shandan counties over the medium term and long term remained higher than that during the baseline period, but the increase would be less over time, which meant the corn yield and CWP presented downward trend under future climate change conditions. In addition, the corn yield and CWP in the other counties indicated continued declines during the entire future time period. In RCP8.5 climate scenario, the yield and CWP of spring barley, spring wheat, and spring canola-Polish decreased at a higher rate. In Minle and Shandan counties, where the corn yield showed an increasing trend in the short term, the yield decreased sharply because of a further increase in temperature in the medium term and long term. Furthermore, it was found that the area with the most serious decline in wheat crop yield was Gaotai county, while Shandan county had the largest decline in CWP. The severe corn output reduction area appeared in Gaotai county in the east, and the barley yield and CWP decreased in Qilian county, where the temperature was projected to be low.

Obviously, reducing the barley planting area in Qilian county and transferring the barley and wheat crops planted in Gaotai and Suzhou counties to Ganzhou, Linze, and other central regions can reduce the decline in yield, to some extent. However, this is not the best way to solve the decline in barley and wheat crop yield and CWP. Accordingly, we need to explore better agricultural management measures to effectively deal with the negative impact of future climate change on these two crops. Although the yield of canola in Sunan county was projected to result in only a small reduction in future climate, its total yield was found to be about 1000 kg ha^{-1} lower than that in Minle and Shandan counties, on average. Hence, changing the planting area is not an effective way to mitigate the decline in canola yield in the Heihe River basin, which should be more dependent on the selection of new varieties. The significant difference in corn yield and CWP between the east and the west demonstrated that expanding the crop planting area of Minle and Shandan counties could reduce the declining rate of corn yield in the watershed. This method can effectively alleviate the negative impacts of climate change on corn yield.

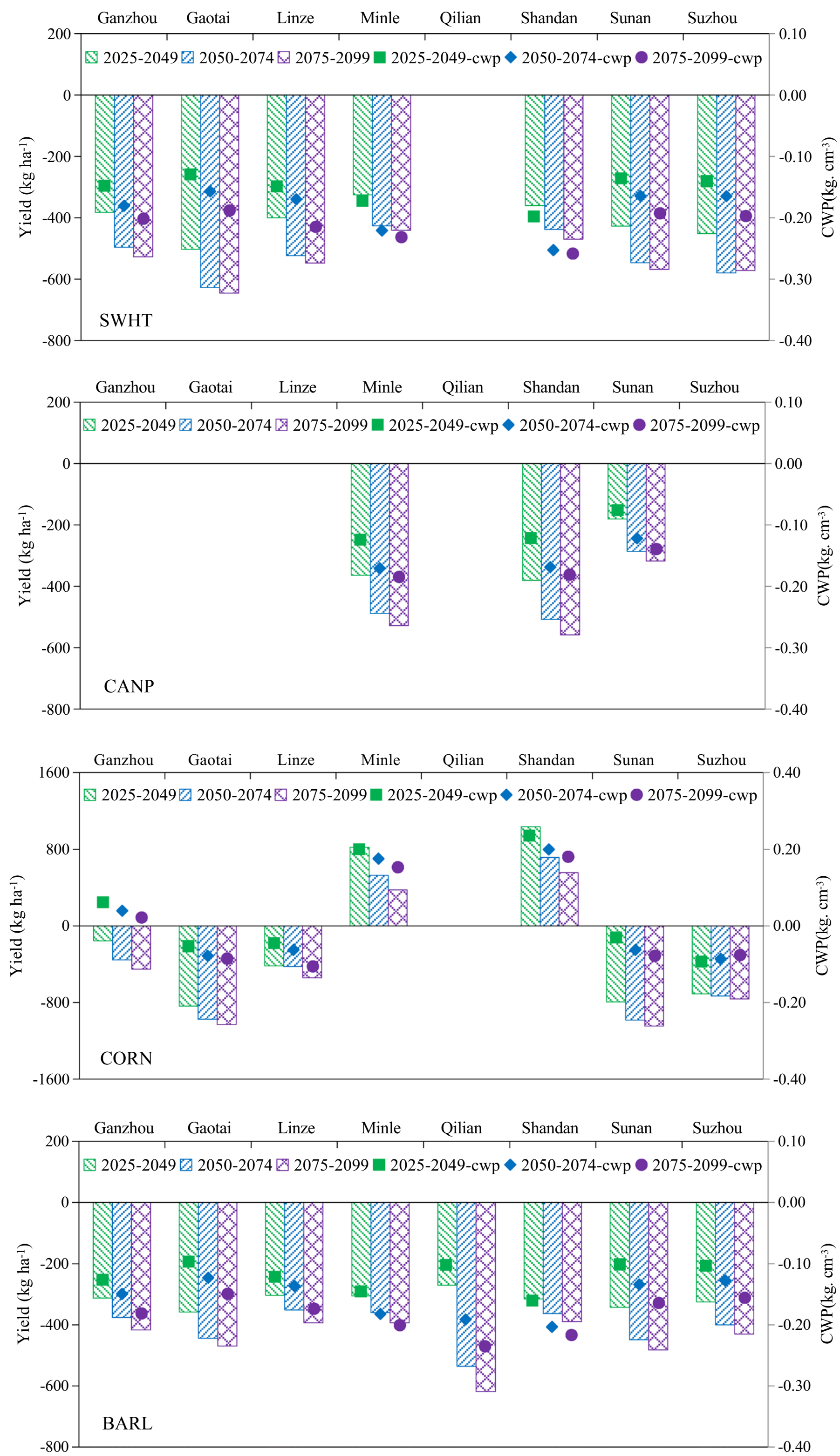
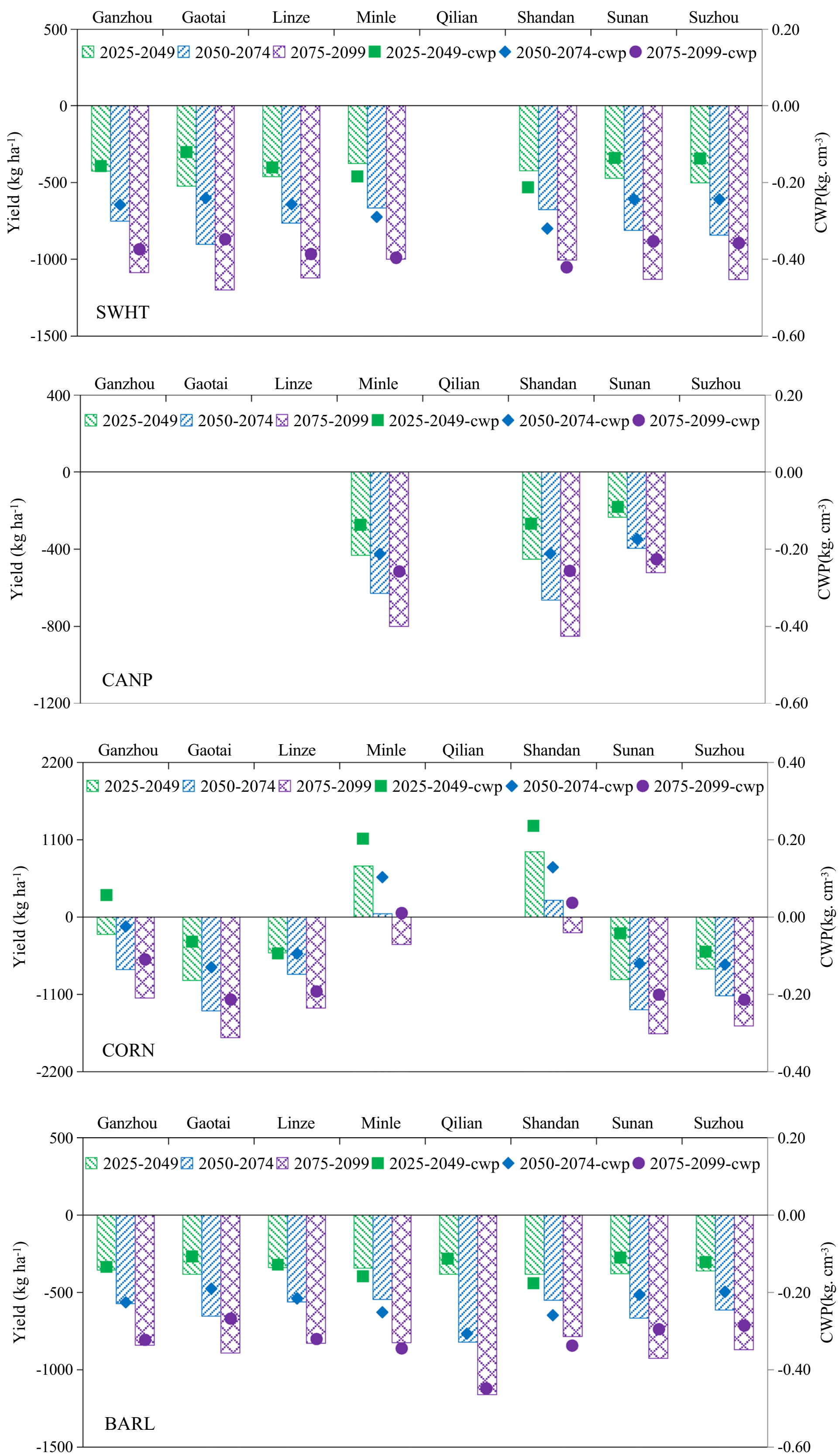


Fig. 9 The changes of crop yield and CWP in three future periods compared with the baseline period in the RCP4.5 scenario

(See figure on next page.)
Fig. 10 The changes of crop yield and CWP in three future periods compared with the baseline period in the RCP8.5 scenario


Ganzhou
Gaotai
Linze
Minle
Qilian
Shandan
Sunan
Suzhou
2025-2049
2050-2074
2075-2099
2025-2049-cwp
2050-2074-cwp
2075-2099-cwp
Yield (kg ha-1)
CWP(kg. cm-3)
SWHT
CANP
CORN
BARL
500
0
-500
-1000
-1500
400
-400
-800
-1200
2200
1100
-1100
-2200
0.40
0.20
0.00
-0.20
-0.40
-0.60

Limitation and future studies

The dynamic changes of agricultural management measures (e.g., irrigation and fertilization) are affecting crop yields and CWP (Sun and Ren 2014; Zou et al. 2020) and can mitigate to some extent the negative effects of climate change on crop production (Okada et al. 2018). However, the present study focuses on the effects of future precipitation and temperature on crop yield and crop water production in the basin. The possible water-saving agricultural management practices can be integrated into the SWAT model in the future to more accurately simulate the temporal and spatial distribution of CWP in the region.

Apart from climate change, land use types, which are affected by the regional climate and the economic values of crop, also impact the agricultural production. Therefore, the prediction of agricultural land use changes can provide a better understanding of future food production and food security. Future land use simulation model [e.g., the model proposed by Liu et al. (2017)] may be an approach to describe the possible changes. The further study can be carried out by collectively using land use simulation model and SWAT model for production simulation.

Conclusions

This study explored the temporal and spatial variations of crop yield and crop water productivity in the upper and middle reaches of the Heihe River basin under future climate change conditions. The ranking method was used to evaluate the ability of 31 climate models in CMIP5 to simulate the meteorological factors in the study area, which identified that GFDL-CM3, BCC-CSM1-1-M, and MPI-ESM-MR were the top three climate models in simulation. The coupling of these three models for a multi-model ensemble was done to project future climate change. Then, this study was using calibrated SWAT model to investigate the impacts of precipitation, maximum temperature, and minimum temperature in future period on yield and CWP of four major crops.

The simulation results for future climate change indicated that precipitation would have a gradual increasing trend, and the average annual precipitation in the RCP8.5 scenario would have a faster increasing rate than that in the RCP4.5 scenario. In addition, in the RCP8.5 scenario, the increase in the maximum and minimum temperatures in the future three periods considered would be higher than that in the RCP 4.5 climate scenario. Furthermore, in both RCP4.5 and RCP8.5 scenarios, the maximum temperature would have a faster increase rate than the minimum temperature.

The results revealed that the impacts of future climate change on crop yield and CWP of wheat, barley, and canola would all be negative. Due to the different characteristics of regional climate change, the extent of decline in crop yield and CWP would vary from county to county. For example, barley and wheat yield in Linze and Gaotai counties would have a large decline, while the extent of decrease in the yield and CWP of canola would gradually increase from the western parts to the eastern parts. In contrast to that, corn yields and CWP in the eastern part of the middle reaches of the Heihe River basin would have a positive response to climate change in the short term. Nevertheless, as the temperature continues to increase, the positive effects of climate change on crop growth would diminish or even disappear. On the whole, climate change under RCP8.5 scenario would be more harmful to crops. However, the corn crops in Minle and Shandan counties would have better ability to cope with climate change, so it is suggested to expand the corn planting area in Minle and Shandan counties. In order to better adapt to future climate change, barley, wheat, and canola crops should rely on the exploration of better agricultural management practices and the selection of new breeding.

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Authors' contributions
JN contributed to conceptualization and supervision; QL contributed to data curation and writing—original draft; JN and QL were involved in investigation and methodology; JN, RD, and SL were involved in writing—review and editing. All the authors read and approved the final manuscript.

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Availability of data and materials
The data supporting our analyses can be accessed publicly from the link provided in this paper, and the simulation data are available from the corresponding author on reasonable request.

Competing interests
The authors declare that they have no competing interests.

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