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Assessment of the effect of climate change on the yields and water footprint of crops in arid area

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ABSTRACT

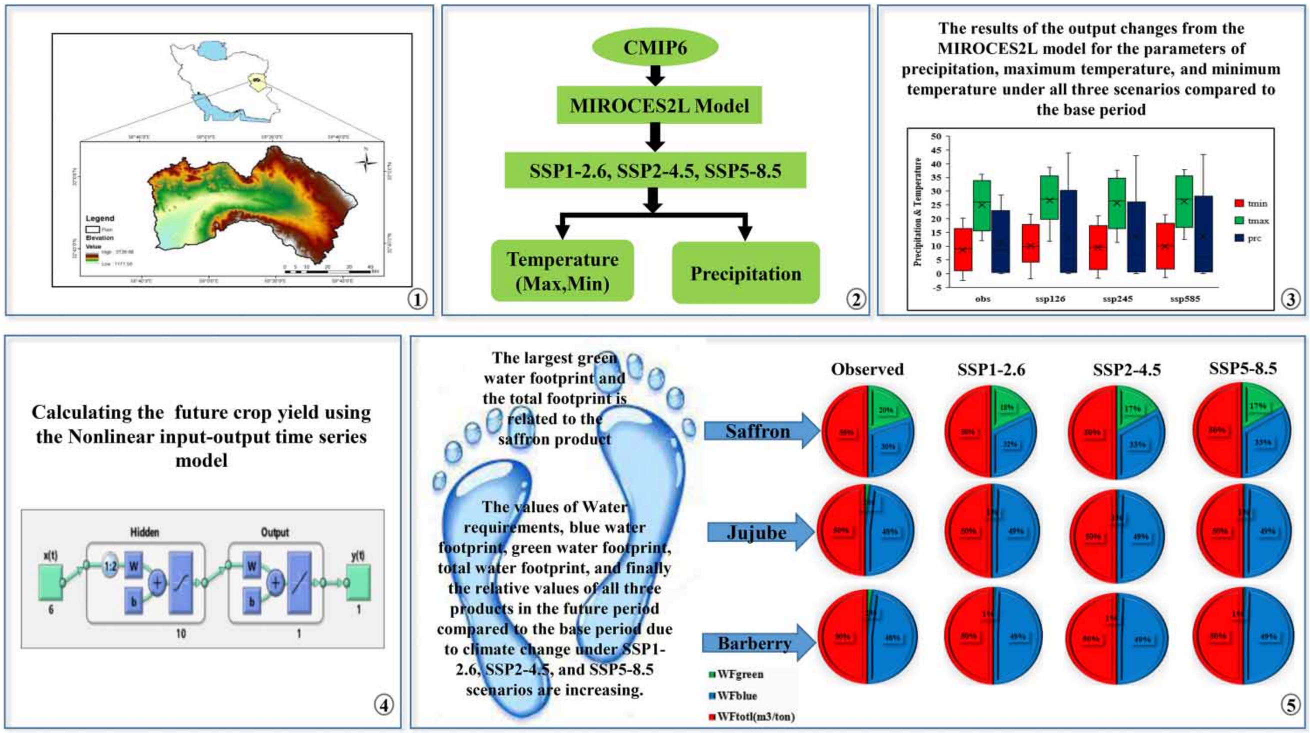
Investigating the actual amount of water used by agricultural crop yield is very important. This research evaluates the impact of climate change on water demand, yields, and green and blue water footprint of barberry and jujube plants under SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios. The results show that the amount of precipitation in the future under three scenarios varies from −13.08 to 5.13 mm during the future period. It shows maximum temperature changes from 1.07 to 1.25 °C and minimum temperature changes from 1.15 to 1.54 °C. The maximum and minimum temperatures under all three scenarios have an increasing trend compared to the base period. The results show that the values of water requirement, blue water footprint, green water footprint, total water footprint, and finally the relative values of both crop yields increase in all three scenarios in the future period (2022–2038) compared to the base period (2021–2005). Furthermore, according to the three proposed scenarios, the water footprint of the barberry crop in the future is estimated to be 98.74% blue water and 1.24% green water. The jujube crop's water footprint consists of 98.81% blue water and 1.20% green water.

Key words: climate change, CMIP6, crop yield, NIO model, water footprint

HIGHLIGHTS

- Crop performance and water footprint were assessed under CMIP6.
- The nonlinear input–output time series model is a good simulation tool for modeling the future performance of products based on SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios.
- An increase in water footprint (WF) is due to a decrease in crop yields and vice-versa.
- The increase in WF shows the high dependence of crops on surface and underground water resources.

GRAPHICAL ABSTRACT



INTRODUCTION

Given Iran's arid and semi-arid climate, water is a crucial resource and a major limiting factor for agricultural production. It is crucial to understand the water requirements for agricultural systems to ensure their success. This knowledge is essential for optimizing crop growth and yield. The amount of water needed and the water footprint of crop yield vary depending on the specific region and its climate. Furthermore, individual water usage patterns, agricultural practices, and water use efficiency in the region all contribute to this variation. As a result, it is essential to develop a framework that allows for an accurate estimation of water demands for each crop yield. For this purpose, the water footprint is used as a comprehensive index that shows the actual amount of water used by each crop in the situation and climate of each region. Hoekstra & Hung (2002) first introduced this index, and in recent years, it has attracted the attention of experts from different parts of the world. The water footprint of each crop includes three colored components: blue water, green water, and gray water. Blue-water refers to the water of rivers, lakes, groundwater sources, etc., which is used for irrigation. Green water is rainwater that is temporarily stored in saturated soil, on the soil surface, or coverage herbal. Gray water and its traces also indicate the volume of polluted water. Calculating the water footprint is used as a suitable method to check the water use of crops and measure the efficiency of agricultural water and crop production (Morillo *et al.* 2015). In recent years, this index has been widely assessed by researchers and experts around the world. The footprint of various crops has been calculated, including tea (Jefferies *et al.* 2012), rice (Chapagain & Hoekstra 2011), wheat (Hoekstra & Chapagain 2007; Aligholinya *et al.* 2019), cotton (Chico *et al.* 2013), grapes (Ene *et al.* 2013), corn (Nana *et al.* 2014), and potato (Herath *et al.* 2014; Rodriguez *et al.* 2015). In their 2006 study, Chapagain *et al.* (2006) investigated the water use footprint of cotton production worldwide. They categorized water usage into three types: green water (evaporation of infiltrated rainwater to cotton growth), blue water (surface water or groundwater used for irrigation), and water contamination during the cotton growth period. The study aims to assess the impact of cotton production on water resources and identify areas for improvement. Their study found that cotton requires 256 Gm^3 (a billion cubic meters) of water annually, with 42% coming from blue water, 39% from green water, and 19% from gray water. In their research, Ercin & Hoekstra (2014) examined various factors such as population growth, economic growth, production-business patterns, and technology development on a global scale to predict the water footprint scenario by 2050. Their study results showed that if the pattern of water use changes, the water footprint will also reduce despite the increase in population. Masud *et al.* (2018) simulated the yields and water consumption of the crop by using the soil and water evaluation tool along with the geographic information system (SWAT-GIS) model. Their findings showed that due to increased performance and reduced water consumption, the water footprint is also reduced. Fulton *et al.* (2019) conducted a study on the water footprint and economic value of almond production in 12 regions of California. Their findings revealed that the average water footprint for almonds was 10.24 m^3/kg, while the economic value was 0.42 \$/m^3. A comparison of these results with 43 other crops in California revealed that almonds have the highest economic value among nuts and berries. In a study conducted by Bazrafshan *et al.* (2019), the virtual water and water footprint of saffron production in Iran were examined. The study revealed that the average water footprint of saffron production in Iran is 4,659 m^3/kg, with green, blue, white, and gray water footprints accounting for 12, 42, 40, and 6%, respectively. Also, the total water footprint of saffron production was 1,541 million m^3 per year, the share of exported virtual water is 1,354.6 million m^3 per year, and the average economic water footprint of saffron production is 1.3 \$/m^3. Rahimipour Anaraki *et al.* (2020) in a study assessed the virtual water and water footprint of crops in Qalaganj. The results showed that the most cultivated area was related to cereals and vegetables, which covered more than half of the 48,000 hectares of cultivated area and more than 60% of the total water footprint, and their yields were low. Arunrat *et al.* (2022) addressed the effect of climate change on the water footprint and yields of major crops in Thailand. This study was conducted over three time periods: short term, medium term, and long term, and examined two different scenarios. The results revealed that both scenarios showed an increase in minimum and maximum temperatures and rainfall across all three time periods. In addition, the researchers predicted that rice crop yield will increase in all three periods under the SSP2.4.5 scenario and will also increase in the middle period under the SSP5.8.5 scenario. On the other hand, drought, climate change, and incorrect management policies have severely affected existing water sources and caused a negative balance in some parts of the world. This is in direct contradiction to the principles of sustainable water usage. The impact of climate change is felt across various sectors, including agriculture and water sources. As such, it is crucial to accurately predict these effects to minimize vulnerability and effectively adapt to them. Several studies have examined the changes in water footprints under the conditions of climate change. Pour Salehi *et al.* (2015) in a study calculated the virtual water value of eight crops in Birjand Plain and investigated the optimal cultivation pattern using the LINGO linear programming model. Their study results showed that in the study area, compared to other crops, saffron cultivation with an area equal to 2010 hectares under the first scenario and 12,188.65 hectares under the second scenario had a higher virtual water value and the cultivated area. Elbeltagi *et al.* (2020) in a study investigated the effect of climate change under RCP2.6, RCP4.5, and RCP8.5 scenarios on water footprint of wheat and corn in the Nile Delta in Egypt using a deep neural network model. The results showed that the coefficient of determination (R^2) of evapotranspiration for two crops varies from 0.92 to 0.97, and the prediction values of wheat and corn yields were in the range of −3.21 to 3.47% and −4.93 to 5.88%, respectively. Also, by reducing precipitation in the future, under three scenarios, the green water footprint is reduced. Kouzegaran *et al.* (2020) in a study predicted the effect of climate change on saffron yields. The results of predicting extreme climatic events in the future showed that the increase in minimum and maximum temperature and the decreasing trend in the precipitation parameter are among the factors reducing the yields of saffron. As a result, yield reduction during future periods under the RCP8.5 scenario was higher than the same periods under the RCP4.5 scenario. Mali *et al.* (2021) in a study assessed the effect of climate change on the water footprint of cereals in India. To assess the effect of climate change on water footprint, RCP4.5 and RCP6 scenarios were used by the hybrid-delta model. The results showed that the WF of cereals will change in the range of −2.3 to 6.3% under two scenarios. Govere *et al.* (2022) in that study assessed the effects of climate change under RCP4.5 and RCP8.5 scenarios on wheat yields, crop water use, and wheat water footprint in Zimbabwe using the AquaCrop model. The results showed that water footprint reduced under the scenarios in the future and wheat yields increased in the future, while water use reduced due to climate change. Pilevneli *et al.* (2023) investigated the effect of climate change on agricultural production and income in 25 river basins in Turkey. The results of this research showed that as a result of the increase in the need for irrigation water in the future, the risk of water shortage will decrease from an excess of 14.6 km^3 per year under the RCP8.5 scenario to 3.57 km^3. Also, the results indicate that the performance and income value of crop yield in this basin are associated with a 100% decrease. The review of the aforementioned research indicates the existence of increasing tension on freshwater sources in different parts of the world along with the increase in demand for agricultural crop yield and climate change. Therefore, the importance of a new attitude and the use of comprehensive criteria such as water footprint to determine the actual amount of water used by crops is necessary for planning and optimal management of water use in the agriculture sector. The main purpose of this research is to investigate the water footprint of barberry and jujube crop yield and to investigate the amount of water consumed by these two main crop yields of the agricultural sector in Birjand Plain. Also, in this research, the water footprint and amount of water consumed by these crop yields in the future will be calculated under three scenarios of the sixth climate change report SSP1-2.6, SSP2-4.5, and SSP5-8.5 during the statistical period of 2022–2038.

STUDY AREA

Birjand is the capital of South Khorasan Province, which is located in the Bagheran mountains at a longitude of 59 degrees and 13 s and a latitude of 32 degrees and 53 s. This city has an area of 42.7 km^2, which is divided into 2 parts and 10 villages and has a minimum temperature of 8 °C and a maximum temperature of 24 °C. The annual rainfall is 152 mm, and the height above sea level is 1,491 m. The evaporation capacity of Birjand Plain has been calculated to be 1,745.38 mm (Jafarzadeh *et al.* 2019). Figure 1 shows the location of Birjand Plain.

METHODOLOGY

Birjand plain was assessed during the basic period and climate change using the CropWat 8.0 model to calculate water requirement and evapotranspiration of selected crops in this study (barberry and jujube). Also, to investigate the yields of crops in the future under the influence of climate change, the nonlinear input–output (NIO) time series model was used. Meteorological data including precipitation, minimum temperature, maximum temperature, sunny hours, and relative humidity were prepared from the Birjand synoptic station and sorted for the basic statistical period (2005–2021). The yield data were prepared from the site of the Agricultural Jihad Organization of South Khorasan Province.

PROVIDING METEOROLOGICAL DATA FOR FUTURE YEARS

The main objectives of CMIP6 models are to assess organized models, investigate the responses of the earth's structure to various forces regarding the origin and quantification of climate changes, and assess the uncertainty of scenarios. The reason for the improvement of CMIP6 models compared to CMIP5 models is the improvement of the number of vertical layers, which have a more accurate perspective in the stratosphere, and in these models, the number of scenarios for

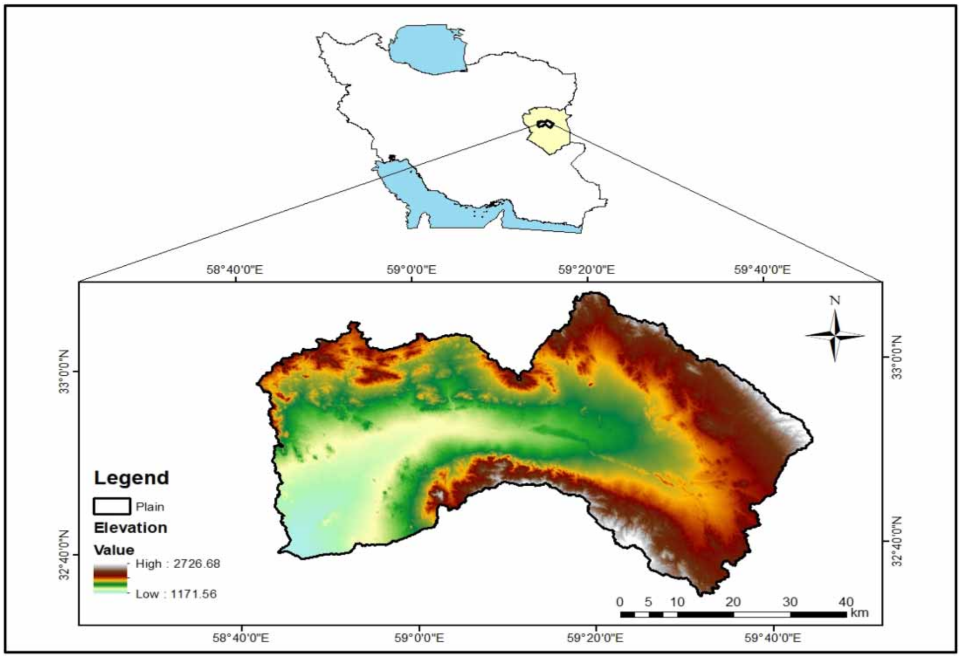


Figure 1 | Study area of Birjand plain.

future periods has been considerably increased (Gupta *et al.* 2020; Su *et al.* 2021). In this study, first, the minimum temperature, maximum temperature, and precipitation data for Birjand Station in the future daily time series were downloaded by the MIROC-ES2L model under three scenarios SSP1-2.6, SSP2-4.5 and SSP5-8.5 from the site https://cds.climate.copernicus.eu/cdsapp#!/dataset/projections-cmip6?tab=form, and the specifications are presented in Table 1. Given that to assess the predicted global climates in hydrological systems, different methods and exponential downscale models are used, and in this study, the climate model data for hydrologic modeling (CMhyd) were used for the parameters of minimum and maximum temperature and precipitation. This model has eight different methods of downscaling for temperature and precipitation data. Some of the methods available in this software are not suitable for the exponential downscaling of precipitation or temperature, so the downscaling method should be selected according to the objective. This model includes three data inputs, which include observation data, data from the past period of the climate model (historical), and scenario data (future) of the climate model. In this model, the data can be used in two formats, NetCDF and text or ASCII, which downscale the data at the station level. In this study, the exponential downscaling of data was done in ASCII format daily, and the linear scaling method was also used for exponential downscaling. The historical data are from 1990 to 2014, and the simulated output of meteorological parameters for the future under three scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5 is considered during 2022–2050.

WATER REQUIREMENT AND WATER FOOTPRINT

Given that the main part of water use is by the agriculture sector and for crops, the water footprint index is a comprehensive index that shows the total amount of water that is used in two parts, directly (water requirement of plants) and indirectly (hidden water used for the crop processing) for the final production of that crop. Therefore, to check the water footprint of a crop, both direct and indirect use parts should be considered. First, to calculate the water requirement of plants, it is necessary to estimate the exact amount of reference evapotranspiration. Accurate calculation and prediction of the amount of daily evapotranspiration and further accurate calculation of water requirement of plants provide the conditions for the design of new irrigation systems, and by reducing the implementation costs, it provides a suitable program for the exploitation of water sources in the irrigation and agriculture sector. In this study, CropWat 8.0 was used to calculate evapotranspiration and water demand. Input data to the model include monthly data of minimum temperature, maximum temperature, wind speed, sunshine hours, and precipitation. For the characteristics of plants and soil, the studies conducted in the Birjand Plain and the South Khorasan Agricultural Jihad Organization, as well as the suggested values of FAO, which are included as defaults in the model, were used (FAO 2006, 2009, 2010). The CropWat 8.0 model uses the FAO-Penman-Monteith equation to calculate evapotranspiration, which is the most accurate and standard method for estimating plant evapotranspiration. The FAO-Penman-Mantith equation is also given in the form of Equation (1):

$$\mathrm{ET}_0 = \frac{0.408\Delta(R_n - G) + \gamma\dfrac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.4U_2)} \quad (1)$$

where ET_0 is reference evapotranspiration (mmday^{-1}); R_n is net radiation at the level of coverage of herbal ($\mathrm{MJm}^{-2}\mathrm{day}^{-1}$); T is the average air temperature at a height of 2 m above the ground (°C); U_2 is the average wind speed at a height of 2 m above the ground (ms^{-1}); $e_s - e_a$ is vapor pressure deficiency at a height of 2 m (kpa), Δ is the slope of the vapor pressure curve ($\mathrm{kpa}^\circ\mathrm{C}^{-1}$); γ is the psychrometric coefficient (kpa $^\circ\mathrm{C}^{-1}$); and G is the heat flux into the soil ($\mathrm{MJm}^{-2}\mathrm{day}^{-1}$).

Table 1 | Specifications of selected models from CMIP6 models

Horizontal resolution	Simulation scenarios	Founder's name	Model name
250 km	SSP1-2.6 SSP2-4.5 SSP5-8.5	Model for Interdisciplinary Research on Climate (MIROC), Japan	MIROC-ES2L

WATER FOOTPRINT

In this study, to calculate the footprint of barberry and jujube, blue and green water footprints are used, and the total footprint is obtained from the sum of these two footprints, blue water and green water.

$$\mathrm{WF}_i = \mathrm{WF}_{i\mathrm{blue}} + \mathrm{WF}_{i\mathrm{green}} \tag{2}$$

where WF_i is the total water footprint of a crop i. $\mathrm{WF}_{i\mathrm{blue}}$ is a blue water footprint that is calculated for water used in surface water and groundwater sources. $\mathrm{WF}_{i\mathrm{green}}$ is green water footprint, which includes a volume of effective rainwater that is stored in the soil as sediment. In Equation (2), water footprint is expressed as a unit of the crop, i.e., the volume of water in the mass of the crop, which is usually used as (m^3/ton) to express the trend of the water footprint in the agriculture sector. For this purpose, the result of dividing the water footprint intensity of each crop yield by its yield value is used (Montaseri *et al.* 2016).

$$\mathrm{WF} = \frac{\mathrm{WF}_i}{Y} \tag{3}$$

The footprint of each component is calculated with Equations (4) and (5).

$$\mathrm{WF}_{i\mathrm{blue}} = \frac{\mathrm{CWU}_{\mathrm{blue}}}{Y} \tag{4}$$

$$\mathrm{WF}_{i\mathrm{green}} = \frac{\mathrm{CWU}_{\mathrm{green}}}{Y} \tag{5}$$

where $\mathrm{CWU}_{\mathrm{blue}}$ and $\mathrm{CWU}_{\mathrm{green}}$ are blue water and green water components of the crop (m^3/ton), respectively, and Y is the yields of crops (ton/ha). Blue and green water components (CWU) are calculated by Equations (6) and (7) with the sum of daily evapotranspiration during the growth period of a plant.

$$\mathrm{CWU}_{\mathrm{blue}} = 10 \times \sum_{d=1}^{\mathrm{lag}} \mathrm{ET}_{\mathrm{blue}} \tag{6}$$

$$\mathrm{CWU}_{\mathrm{green}} = 10 \times \sum_{d=1}^{\mathrm{lag}} \mathrm{ET}_{\mathrm{green}} \tag{7}$$

where $\mathrm{ET}_{\mathrm{blue}}$ is the evapotranspiration of blue water (evapotranspiration from irrigation water used by plants) (mm/year) and $\mathrm{ET}_{\mathrm{green}}$ is the evapotranspiration of green water (evapotranspiration from rainwater used by plants) (mm/year). The number 10 is used to convert the water depth in millimeters to the volume of water on the ground (m^3/ha). Also, LGP is the length of the growth period (day). Therefore, the sum of evapotranspiration data during the growth period means the calculation of the total daily evapotranspiration of the plant from the first day of planting the plant to the day of its harvest. The water component used by the plants ($\mathrm{CWU}_{\mathrm{blue}}$) shows the amount of water that is used directly (water requirement of the plant) through irrigation. During irrigation, some water is also used indirectly, including soil washing, irrigation to prevent frost, and overirrigation due to low irrigation efficiency.

CALCULATE FUTURE CROP YIELD BY THE NIO MODEL

Nonlinear input–output time series

The input–output time series has a considerable similarity with the nonlinear auto-regression model (NARX), with the difference that in the NIO time series, only the values of the previous time series are used as the input, and the output is used for the prediction disregarding the previous values. In the NARX model, the values of the previous input and output time series are used for prediction. Therefore, the input–output time series includes two-time series: one is the input series $X_{(t)}$, and the other is the output (target) series $Y_{(t)}$. $Y_{(t)}$ values are predicted by the values of the previous time series $X_{(t)}$ disregarding the values of

$Y_{(t)}$.The general equation of the NIO network is as follows (Omolaye & Badmos 2017):

$$Y_{(t)} = f(X_{(t-1)} \dots X_{(t-d)}) \tag{8}$$

We considered minimum, maximum, and average temperatures and precipitation for input. We used crop yield data for output (target) data. The NIO time series model shows the future yields of barberry and jujube under three scenarios: SSP1-2.6, SSP2-4.5, and SSP5-8.5. The NIO model and MATLAB performed the calculations related to this section.

ESTIMATION OF RELATIVE HUMIDITY IN THE FUTURE

Since Cmhyd does not simulate the humidity values for future periods and the relative humidity is one of the inputs required by CropWat 8.0 to calculate evapotranspiration, the Minitab model was used to estimate the relative humidity in the future period. Then, using the linear regression relationship obtained between the minimum temperature, maximum temperature and average temperature, and relative humidity, the relative humidity in the future under the influence of three scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5 was calculated and considered an input to the CropWat 8.0 model for the future period.

EVALUATION CRITERIA OF MODELS

In this study, R^2, root-mean-square error (RMSE), and Kling–Gupta efficiency (KGE) were used to assess the data of minimum temperature, maximum temperature, and precipitation of the sixth climate change report, which is shown in Equations (9)–(11). Also, to assess the performance of NIO models in the simulation of the crop yield, R^2, RMSE and Nash–Sutcliffe efficiency (NSE) were used. R^2 and NSE are shown in Equations (12) and (13). The RMSE is based on assessing the prediction accuracy of a model by observational data (Raziei & Sotoudeh 2017). A low KGE for outputs near zero means there is less error in the data. KGE is a standard measure of error. Researchers use this to determine the similarity between predicted and observed data (Gupta *et al.* 2009). The NSE includes values between −∞ and 1, the value of 1 is the most optimal state of this criterion, and negative values indicate that the measured values are better than the simulated values. Using these evaluation criteria for hydrological modeling have also been investigated (Xu *et al.* 2015; Rajaee *et al.* 2019):

$$R = \frac{\sum_{i=1}^{n} (X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum_{i=1}^{n} (X_i - \overline{X})^2 \sum_{i=1}^{n} (Y_i - \overline{Y})^2}} \tag{9}$$

$$\text{RMSE} = \sqrt{\sum_{i=1}^{n} \frac{(X_i - Y_i)^2}{n}} \tag{10}$$

$$\text{KGE} = 1 - \sqrt{(r-1)^2 + \left(\frac{\sigma_{\text{sim}}}{\sigma_{\text{obs}}}\right)^2 + \left(\frac{\mu_{\text{sim}}}{\mu_{\text{obs}}} - 1\right)^2} \tag{11}$$

$$R^2 = \frac{\left[\sum_{i=1}^{n} (X_i - \overline{X})(Y_i - \overline{Y})\right]^2}{\left[\left[\sum_{i=1}^{n} (X_i - \overline{X})^2\right]^{0.5} \left[\sum_{i=1}^{n} (Y_i - \overline{Y})^2\right]^{0.5}\right]^2} \tag{12}$$

$$\text{NSE} = 1 - \left[\frac{\sum_{i=1}^{n} (X_i - Y_i)^2}{\sum_{i-1}^{n} (X_i - \overline{X})^2}\right] \tag{13}$$

where Y_i and X_i are the predicted and observed values by the model, respectively, and $\overline{Y}$, $\overline{X}_,$ and n represent the average of the predicted data, the average of the observed data, and the number of input data, respectively. sim and obs represent the predicted and observed values of the model, respectively. σ is the standard deviation, μ is the mean, and r is the linear correlation between observed and modeled data.

Therefore, in this study, first, the average minimum temperature, maximum temperature, sunny hours, relative humidity and precipitation data, water requirement, blue water footprint, green water footprint, and finally the total footprint during the observation period (2005–2021) were calculated by the CropWat 8.0 model. Then, using the CMhyd model, daily data (rainfall, minimum temperature, and maximum temperature) were downscaled by the linear scaling method during the future period under the three scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5. The average temperature, precipitation, and relative humidity data calculated in the future along with sunny hours and wind speed similar to the base period as input are entered into the CropWat 8.0 model, and water requirement, blue water footprint, green water footprint, and finally the total footprint of the barberry and jujube in the future were calculated and compared with the base period. Figure 2 shows a flowchart of the steps of the water footprint calculation method.

RESULTS AND DISCUSSION

The results include two parts. The first part includes the results related to the prediction of meteorological parameters by the CMhyd model and then compared with the data of the base period, and in the second part, the results of the water footprint during the two future and base periods are presented and assessed.

Predicted meteorological data

The study results of the MIROC-ES2L model in the exponential downscaling of parameters of precipitation, maximum temperature, and minimum temperature during the base period indicate that the model was able to predict the climatic changes in the study area well (Table 2). Figure 3 shows the results of the output changes by the MIROC-ES2L model for parameters of precipitation, maximum temperature, and minimum temperature under all three scenarios compared to the base period. Figure 3 shows that the range of parameters of maximum temperature and minimum temperature during the simulated period under three scenarios does not change much compared to the base period. But for the simulation of precipitation parameters during the future period under three scenarios, considerable changes are observed compared to the base period, and the model has good certainty (Barangi 2012).

For precipitation, maximum temperature, and minimum temperature in the future under the three scenarios SSP1-2.6, SSP2-4.5, and, SSP5-8.5 compared to the base period, the change in these parameters has been calculated based on the total and annual average during the future period compared to the base period, the results of which are given in Table 3. As shown, the average rain is rising in the future (2022–2050) compared to the base (1990–2014) under SSP1-2.6 and

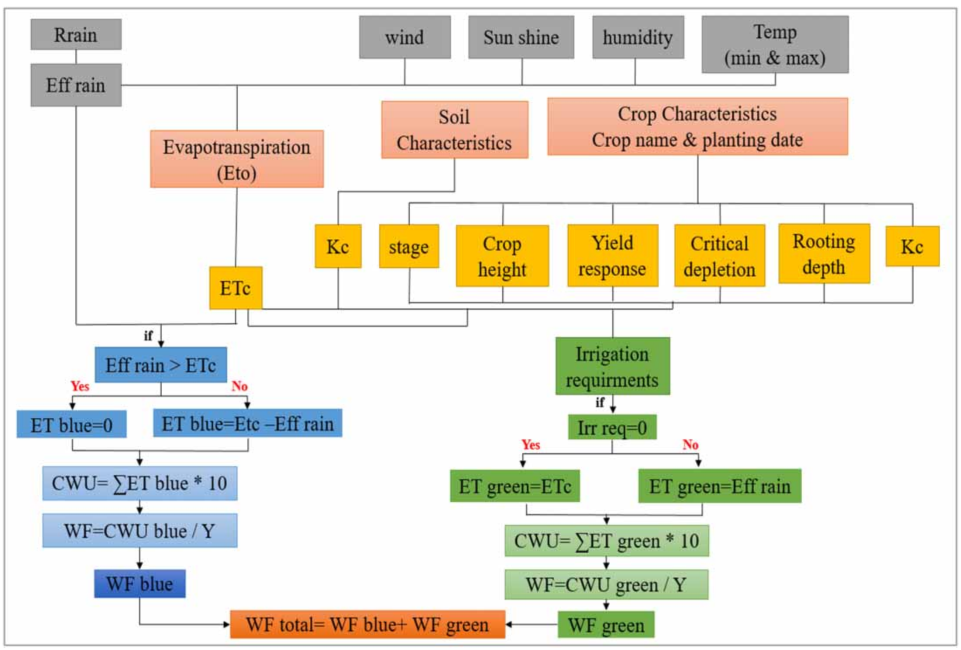


Figure 2 | Flowchart of the method of calculating the water footprint of crops for green water and blue water.

Table 2 | Results of the MIROC-ES2L model during 1990–2014

		Assessment criteria		
Station	**Parameter**	***R***	**RMSE (mm,°c)**	**KGE**
Birjand	Precipitation	0.56	17.14	0.56
	Maximum temperature	0.95	2.58	0.95
	Minimum temperature	0.96	2.01	0.96

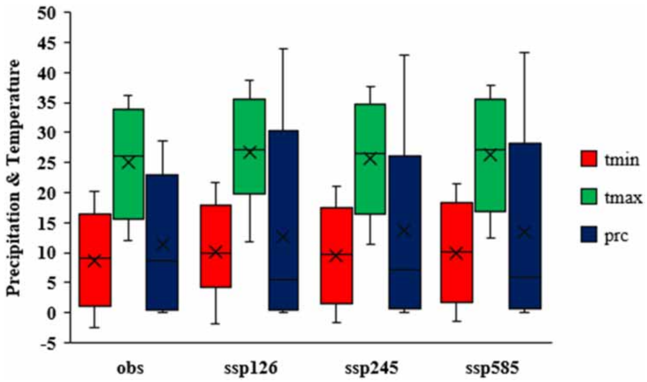


Figure 3 | Changes in parameters of precipitation and temperature in the future under the SSP scenarios compared to the base period.

SSP2-4.5. But, it decreased under the SSP5-8.5. The highest increase in precipitation under the SSP2-4.5 scenario is 144.85 mm per year. It can also be seen that the amount of precipitation in the future under three scenarios varies from −13.08 to 5.13 mm per year. The maximum temperature and the minimum temperature are increasing in the future compared to the base period under all three scenarios, and the highest increase in the maximum temperature compared to the base period under the SSP5-8.5 scenario is 26.22 °C on average during 2022–2050. Also, it is observed that the maximum temperature changes vary from 1.07 to 1.25 °C. The minimum temperature values in the future compared to the base period under the SSP5-8.5 scenario had the highest increase by 10.16 °C, and its changes ranged from 1.15 to 1.54 °C under all three scenarios compared to the base period.

During the recorded statistical period (1990–2021), wind speed data have been available, but climate change models cannot predict this parameter for future periods. Therefore, it is necessary to consider the same values of wind speed during the base and future periods when calculating changes in evapotranspiration. This ensures that any increase or reduction in evapotranspiration is not attributed to changes in wind speed. Furthermore, similar considerations were made for sunny hours in the future period in comparison to the base period (Montaseri *et al.*, 2016).

Prediction of yields and water footprint of crops

The study calculated the future values of relative humidity under three scenarios using the Minitab model. This was done by considering the linear regression relationship between meteorological parameters and relative humidity during the base period. Furthermore, the study determined the green water footprint, blue water footprint, and total water footprint of

Table 3 | Changes in precipitation, maximum temperature, and minimum temperature under three scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5 in the future compared to the base period

	Precipitation (mm year^{-1})			Maximum temperature (°C)			Minimum temperature (°C)		
Time period	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**
Historical period (2002–2021)		134.39			24.97			8.61	
Future period (2022–2050)	139.53	144.85	121.30	26.04	26.15	26.22	9.77	10.00	10.16
Change (2022–2050)	5.13	10.46	−13.08	1.07	1.18	1.25	1.15	1.38	1.54
%Change (2022–2050)	3.82	7.78	−9.73	4.31	4.74	5.02	13.43	16.08	17.94

barberry and jujube by incorporating the values of water requirement and evapotranspiration potential of crops in the future under the three scenarios. The volume of water use per unit weight of the crop (m^3 per ton) was then calculated using Equations (4)–(7). The results of these calculations are provided in Table 4. The results of Table 4 show that the values of water requirement, blue water footprint, green water footprint, total water footprint, and finally the relative values of both crops have increased during the future period (2022–2038) compared to the base period (2005–2021) due to climate change under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios. The water requirements for barberry and jujube have increased from 468.90 to 950.81 mm per year and from 483.58 to 992.40 mm per year, respectively. Also, the water footprint results in Table 4 show that out of the total footprint of 3,784.1 m^3/ton in the base period of the barberry crop, 96.36% of it includes a blue water footprint and 3.63% green water footprint. In the future period, under the SSP1-2.6 scenario, out of the total footprint of barberry 7,392.9 m^3/ton, 98.98% is blue water footprint and 1.1% is green water footprint. The total water footprint of the barberry crop yield under the SSP2-4.5 scenario was calculated as 8,033 m^3/ton, of which 98.67% includes the blue water footprint and 1.32% green water footprint of this crop yield. In the SSP5-8.5 scenario, the total footprint is 7,691.7 m^3/ton, of which 98.68 and 1.31% are blue water footprint and green water footprint, respectively. The amount of water footprint in the Jujube crop yield is 2,244 m^3/ton in the base period, of which 96.46% is blue water footprint and 3.53% is green water footprint. In the SSP1-2.6 scenario, the total footprint of jujube is calculated to be 4,525.8 m^3/ton, and its blue water footprint and green water footprint are 99 and 1.06%, respectively. The total footprint of jujube in the SSP2-4.5 scenario is 4,372.1 m^3/ton, of which 98.71% includes blue water footprint and 1.28% includes green water footprint. Finally, it can be seen that the total water footprint of the jujube crop yield under the SSP5-8.5 scenario is calculated to be 4,465.6 m^3/ton, of which 98.71% is the blue water footprint and 1.27% is the green water footprint. The results of water footprint calculation in two crop yield barberry and jujube under the influence of climate change and three scenarios of Shared Socioeconomic Pathways (SSPs) and increasing temperature and increasing water demand indicate that the amount of total water footprint has increased. Most types of water footprints include blue water footprints. The table results indicate a high dependence of two crop yields, barberry and jujube, on surface and groundwater resources, as seen in the green water footprint and total footprint. Therefore, according to the study results of water requirement and water footprint in the future, it can be concluded that climate change in the future in Birjand Plain will lead to the instability of water and its higher use, which can be attributed to the excessive use of surface water and groundwater sources due to the increase in water use (water footprint) that is caused by changes in water requirement of crops in the study area. The results of this section are similar to the study results of Montaseri *et al.* (2016). Therefore, the reduction in surface water and groundwater sources affected by climate change leads to the intensification of water stress in the Birjand Plain. For this reason, one of the most important solutions is to reduce and balance water use according to the potential of water sources in the region. In this context, the factors that reduce water footprint in the study area include low irrigation methods, reducing cultivated area, changing the agricultural calendar, and changing the crop cultivation pattern.

In this research, a NIO time series model was used to predict the performance of barberry and jujube crop yield in the future under the influence of climate change. The results of the evaluation of the predicted performance values of the mentioned crop yield in the future are presented in Table 5. It can be seen that the model has been able to predict the performance values well in all stages of training, validation, and testing. Also, there is a good correlation coefficient between the observed and calculated values in all two crop yield, so the model has been able to predict the yield values in the future under the influence of climate change. Figure 4 shows the predicted yields of barberry and jujube during the future period by the NIO model

Table 4 | Historical and estimated water footprint values under scenarios SSPs

Crop	Scenarios	Crop water requirement (mm/year)	Blue WF (m^3/ton)	Green WF (m^3/ton)	Total WF (m^3/ton)	Blue WF (%)	Green WF (%)	Ratio of blue WF to green WF (%)
Barberry	Baseline	468.90	3,652.8	131.3	3,784.1	96.36	3.63	45.34
	SSP1-2.6	955.65	7,308.5	84.4	7,392.9	98.89	1.10	121.38
	SSP2-4.5	949.87	7,923.5	109.4	8,033.0	98.67	1.32	84.71
	SSP5-8.5	950.81	7,587.0	104.6	7,691.7	98.68	1.31	85.09
Jujbe	Baseline	483.58	2,167.8	76.1	2,244.0	96.46	3.53	46.69
	SSP1-2.6	992.40	4,525.8	46.6	4,570.3	99.00	1.06	125.89
	SSP2-4.5	930.79	4,316.6	55.5	4,372.1	98.71	1.28	87.40
	SSP5-8.5	980.38	4,410.0	55.6	4,465.6	98.72	1.27	87.72

Table 5 | Results of the NIO model for predicting crop yield

Crop	Scenarios	Train			Validation			Test			All		
		R^2	RMSE (kg/ha)	NSE	R^2	RMSE (kg/ha)	NSE	R^2	RMSE (kg/ha)	NSE	R^2	RMSE (kg/ha)	NSE
Barberry	SSP1-2.6	0.92	64.5	0.91	0.99	31.3	0.82	0.99	80.1	0.95	0.98	89.2	0.97
	SSP2-4.5	0.68	115.4	0.63	0.88	89.2	0.65	0.98	40.7	0.96	0.94	125.4	0.93
	SSP5-8.5	0.83	102.5	0.80	0.84	52.0	67.3	0.98	0.01	0.98	0.99	83.4	0.98
Jujube	SSP1-2.6	0.97	112.3	0.96	0.75	95.4	0.78	0.88	52.0	0.74	0.96	108.7	0.95
	SSP2-4.5	0.97	112.6	0.95	0.86	81.7	0.81	0.77	105.2	0.69	0.96	113.9	0.94
	SSP5-8.5	0.97	112.7	0.97	0.98	43.8	0.90	0.78	30.9	0.69	0.97	94.8	0.97

under three scenarios of the sixth climate change report. The yields of barberry in the future under the SSP1-2.6 scenario have increased by 28.61 kg per hectare and under the two scenarios SSP2-4.5 and SSP5-8.5 have reduced by 56.22 and 26.74 kg per hectare compared to the base period. The yields of jujube under the SSP1-2.6 scenario were reduced by 34.12 kg/ha compared to the base period and increased by 19.37 and 3.03 kg/ha under the two scenarios SSP2-4.5 and SSP5-8.5, respectively. The results of predicting crop yield in the future indicate that due to climate change, temperature increase, and evapotranspiration, the water requirement of crops has increased, and finally, the water footprint in all the crops studied in this study has also increased in the future compared to the base period.

Figure 5 shows the green water, blue water, and total water footprints of barberry and jujube in the future. It shows them under three climate change scenarios: SSP1-2.6, SSP2-4.5, and SSP5-8.5. The blue and total water footprints have both risen for both crops in all three scenarios. The green footprint has changed the least. Overall, the total footprint of both crops in Birjand Plain increased. This will happen in the future period (2022–2038) compared to the base period (2005–2021).

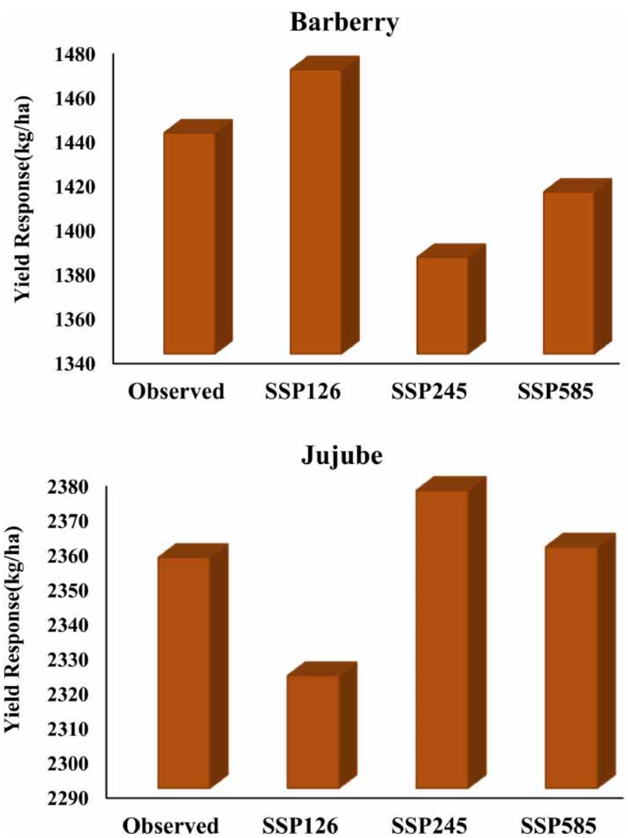


Figure 4 | Prediction of the yields of barberry and jujube by the NIO model under the SSP scenarios in the future compared to the base period.

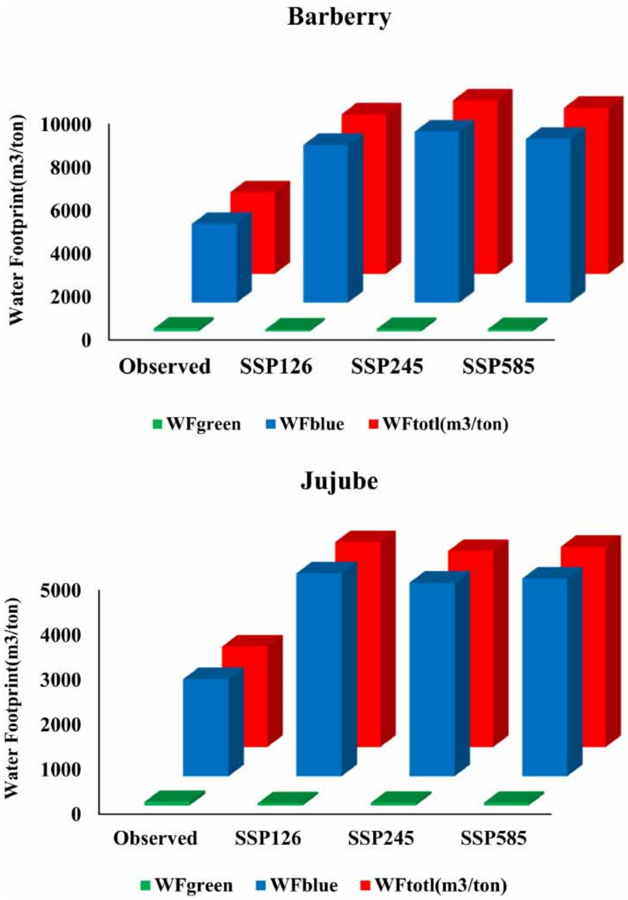


Figure 5 | Prediction of the water footprint of barberry and jujube by the NIO model under the SSP scenarios in the future compared to the base period.

CONCLUSION

The main factors influencing water demand in the agricultural sector are climate changes, which have a significant impact on crop yield and global food security. It is crucial to evaluate the effects of climate change on the green and blue water footprints of crop yield to make informed decisions about climate adaptation strategies and mitigate its consequences. In this study, we aimed to investigate the impact of climate change on the water footprint in Birjand Plain. We extracted meteorological data, including minimum and maximum temperatures and precipitation, from the sixth climate change report using the MIROC-ES2L model. These data were then downscaled at the station level using the Cmhyd exponential downscale model and the linear scaling method under three scenarios: SSP1-2.6, SSP2-4.5, and SSP5-8.5 for the future period (2022–2050). We then compared the simulated meteorological parameters with the base period and found that the model accurately predicted the values of these parameters for the future period.

The results of the study investigating minimum temperature, maximum temperature, and precipitation indicate that precipitation is predicted to increase in the SSP1-2.6 and SSP2-4.5 scenarios, while it is expected to decrease in the SSP5-8.5 scenario. The changes in precipitation range from −13.08 to 5.13 mm per year in the future under all three scenarios. In addition, the study found that both minimum and maximum temperatures are projected to increase under all three scenarios. Specifically, the maximum temperature is expected to rise by 1.07–1.25 °C, and the minimum temperature is predicted to increase by 1.15–1.54 °C compared to the base period.

The evapotranspiration and water requirement values for the years 2022–2038, which will be affected by climate change, were calculated using the CropWat 8.0 model. The green and blue water footprint, total footprint, and yields of barberry and jujube, which are the most widely cultivated crops in the Birjand plain, were then calculated using an input–output nonlinear time series model. The results of the yield prediction for the future showed that barberry yields are expected to increase in the SSP1-2.6 scenario but decrease in the other two scenarios. On the other hand, jujube yields are predicted to increase in the SSP2-4.5 and SSP5-8.5 scenarios but decrease in the SSP1-2.6 scenario.

The results of calculating the water consumption for two crop yields, barberry and jujube, indicate that the ratio of blue water to green water in barberry crops has increased from 45.34 in the base period to 121.38 in the future period. The largest increase in this ratio was observed under the SSP1-2.6 scenario. Similarly, the ratio of blue water to green water in jujube crops has also increased from 46.69 in the base period to 125.89 in the future period. The highest ratio of blue water to green water for jujube crops was found under the SSP1-2.6 scenario.

Based on the investigation of water requirements and water footprint in the future, it can be concluded that climate change in the Birjand Plain will result in water instability and increased consumption. This is due to the excessive use of surface and groundwater resources, driven by changes in water demand for agricultural crop yield in the area. To address this issue, it is necessary to propose and implement methods such as reducing the area under cultivation, implementing less irrigation, changing cultivation patterns, and adjusting the agricultural calendar. In addition, improving irrigation systems and replacing traditional methods with modern ones can increase irrigation efficiency and reduce the water footprint of crops in the Birjand Plain. As climate change is inevitable, it is crucial to focus on efficient irrigation and optimal water management to decrease the water footprint of crops.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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