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Key Points:

- Replacing irrigated by rainfed cereals has the highest potential in saving blue water
- Benchmarking water footprints and early-planting have promising, but lower effects
- The adaptation strategies cannot mitigate water scarcity in all provinces/months

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Agricultural Adaptation to Reconcile Food Security and Water Sustainability Under Climate Change: The Case of Cereals in Iran

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Abstract In this study, we simulate the crop yield and water footprint (WF) of major food crops of Iran on irrigated and rainfed croplands for the historical and the future climate. We assess the effects of three agricultural adaptation strategies to climate change in terms of potential blue water savings. We then evaluate to what extent these savings can reduce unsustainable blue WF. We find that cereal production increases under climate change in both irrigated and rainfed croplands (by 2.6–3.1 and 1.4–2.3 million t yr^{-1}, respectively) due to increased yields (6.6%–78.7%). Simultaneously, the unit WF (m^3 t^{-1}) tends to decrease in most scenarios. However, the annual consumptive water use increases in both irrigated and rainfed croplands (by 0.3–1.8 and 0.5–1.7 billion m^3 yr^{-1}, respectively). This is most noticeable in the arid regions, where consumptive water use increases by roughly 70% under climate change. Off-season cultivation is the most effective adaptation strategy to alleviate additional pressure on blue water resources with blue water savings of 14–15 billion m^3 yr^{-1}. The second most effective is WF benchmarking, which results in blue water savings of 1.1–3.5 billion m^3 yr^{-1}. The early planting strategy is less effective but still leads to blue water savings of 1.7–1.9 billion m^3 yr^{-1}. In the same order of effectiveness, these three strategies can reduce blue water scarcity and unsustainable blue water use in Iran under current conditions. However, we find that these strategies do not mitigate water scarcity in all provinces per se, nor all months of the year.

1. Introduction

Achieving food and nutritional security is one of the greatest challenges of our time, particularly in water-stressed nations. Unexpected disturbing phenomena such as pandemics (e.g., COVID19 in 2020 or Spanish influenza in 1918) can threaten food security not only in the water-scarce countries but worldwide (Galanakis, 2020; Torero, 2020). Climate change adds to this challenge through uncertain impacts on food production, crop water needs, and the availability of blue and green water resources. This paper explains this challenge and evaluates how adaptation strategies can enhance food security in water-scarce regions. We do this for the case of Iran, which faces significant challenges to reconcile food security and sustainable use of freshwater resources.

Food security of most countries in the Middle East and North Africa (MENA) region is at stake (Blatchford et al., 2018; Hameed et al., 2020; Nouri et al., 2019, 2020). In Iran, population growth (~1.3% annually; World Bank, 2020), changing diets (Matthee, 2020), limited arable land (~9% of the country; World Bank, 2020), low and erratic water availability (Madani, 2014) and poor water management, threaten the nation with a growing water crisis (Karandish & Hoekstra, 2017; Olen, 2021). Water scarcity and over-abstraction of water for irrigation purposes occur in most provinces (Faramarzi et al., 2010; Karandish & Hoekstra, 2017). A recent study claimed that sacrificing a degree of self-sufficiency is a must to minimize the over-abstraction of water for agriculture in Iran (Soltani et al., 2020).

The vulnerability of agricultural production to climate change in Iran is a threat to the sustainability of water resources and food security of over 80 million people. Several studies evaluated the effects of climate change on crop yields (t ha^{-1}) and crop water footprints (WF; m^3 ha^{-1} and/or m^3 t^{-1}) and reported different, and sometimes conflicting, outcomes in size and direction of the effects (Araya et al., 2017; Arunrat et al., 2020; Bocchiola et al., 2013; Darzi-Naftchali & Karandish, 2019; Karandish, Kalanaki, & Saberali, 2017; Karandish, Mousavi, & Tabari, 2017; Masud et al., 2018; Moradi et al., 2013; Shrestha et al., 2017; Tubiello et al., 2000; Zheng et al., 2020; Zhuo et al., 2016a). These differences were often rooted in differences in geographical locations, climate-change scenarios, crops, and watering systems (green or blue). This shows that it is crucial to distinguish along these lines when assessing the impacts of climate change and the effectiveness of adaptation strategies.

Climate change projections indicate an increase in precipitation, air temperature and potential evapotranspiration in Iran (Karandish & Mousavi, 2018; Karandish, Mousavi, & Tabari, 2017; Paymard et al., 2019). A net result of these effects is an increase in the green water deficit—the difference between potential evapotranspiration and precipitation—mainly in the growing seasons of irrigated crops in the semi-arid zone (Karandish & Mousavi, 2018), which accounts for a considerable share of Iran's agricultural production (~25%; Karandish & Hoekstra, 2017).

Climate change is expected to impact agricultural production in Iran. A national study in Iran revealed that climate change causes about 0%–15% reduction in yield for irrigated cereals and 0%–30% increase in crop evapotranspiration (Karandish, Mousavi, & Tabari, 2017). However, this study left out effect of elevated CO_2 levels on simulated yields and adaptation scenarios on WFs. Drought and aridity have different effects on irrigated and rainfed crops (Meza et al., 2020). Likewise, possible adaptation strategies are different for rainfed and irrigated farmlands. For rainfed crops, early planting showed promising results to minimize the adverse impacts of drought (Rezaei & Lashkari, 2019; Yang et al., 2019). Early planting can match crops' growing needs with climate-change-induced shifts in the thermal and moisture regimes. These shifts can reduce yield loss and irrigation needs, which increases water productivity. Previous studies on maize production in Iran (Karandish, Kalanaki, & Saberali, 2017; Moradi et al., 2013) and Kansas, US (Araya et al., 2017), rice production in Iran (Darzi-Naftchali & Karandish, 2019) and Thailand (Arunrat et al., 2020) and several crops in Italy (Tubiello et al., 2000) asserted that early planting increases water productivity. The combination of early planting and choosing slow-maturing cultivars may also improve the water productivity of spring-summer crops under climate change (Tubiello et al., 2000).

Off-season cultivation is another promising strategy to alleviate blue water scarcity. In Iran and some other countries in the MENA region, the growing period of irrigated crops mostly falls during the dry season when blue water availability is the lowest (Karandish & Hoekstra, 2017; Nouri et al., 2019; Schyns & Hoekstra, 2014). Off-season cultivation of these crops in the wet season, under rainfed instead of irrigated conditions, may concurrently reduce blue water consumption and increase the contribution of green water in crop production. While there is a potential for expanding rainfed cropping under climate change in Iran (Shahsavari et al., 2019), its consequences have not been investigated yet.

Several studies show that formulating benchmark levels for crop WFs is a promising strategy to save water (Brauman et al., 2013; Chukalla et al., 2015; Karandish et al., 2018; Karandish & Šimůnek, 2018; Mekonnen and Hoekstra, 2011, 2014; Schyns & Hoekstra, 2014; Zhuo et al., 2016b; Zwart et al., 2010). By assuming producers can meet benchmark WF levels which are achieved by more efficient producers in similar circumstances, WF benchmarking counters the inefficient water use per unit of crop production. Therefore, less water is consumed through crop production. Karandish et al. (2018) found that WF benchmarking in Iran can lead to a 34% reduction in groundwater consumption within the irrigated croplands under the historical climate. The effects of WF benchmarking on blue water use in Iran under climate change have not been assessed.

This study assesses the effects of the latest IPCC scenarios on crop yields and WFs, complementing earlier studies using previous IPCC scenarios (Darzi-Naftchali & Karandish, 2019; Karandish, Kalanaki, & Saberali, 2017; Karandish & Mousavi, 2018; Karandish, Mousavi, & Tabari, 2017). We select major cereal crops in Iran—wheat, barley, maize, and rice to better understand the national food security challenges by building upon the available literature. Previous crop water productivity studies on Iran were limited in their scopes in different ways such as (a) they studied only one crop (Darzi-Naftchali & Karandish, 2019; Moradi et al., 2013; Paymard et al., 2019); (b) they did not distinguish between individual cereal crops (Karandish, Mousavi, & Tabari, 2017); (c) they studied only rainfed cereal (Paymard et al., 2019); or (d) they studied only irrigated crops (Darzi-Naftchali & Karandish, 2019; Karandish, Kalanaki, & Saberali, 2017; Karandish, Mousavi, & Tabari, 2017; Moradi et al., 2013). This study includes Iran's four major food crops, in both irrigated and rainfed systems, which are analyzed individually in different climate zones. We also report the effects of climate change on green and blue water footprints, separately. This comprehensive assessment provides an opportunity for water managers and decision-makers to oversee different water resources (precipitation water in the unsaturated zone, i.e., green water; and surface and groundwater, i.e., blue water), accordingly. After studying the climate change impacts on cereal production under

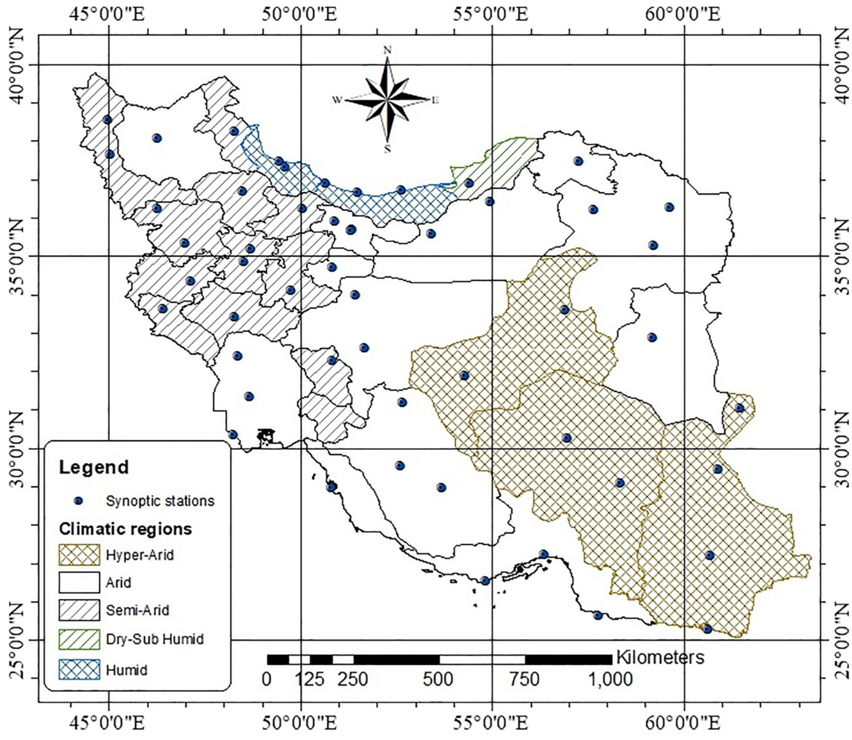

Figure 1. Study area with provinces classified into five climatic regions and the location of the 52 synoptic weather stations from which historical weather data were obtained.

current practices, we assess three adaptation strategies' effectiveness in terms of blue water savings: off-season cultivation, early planting, and WF benchmarking. As described, these adaptation strategies are promising for Iran's case but have not been studied sufficiently. Lastly, we assess to what degree the current blue water scarcity levels in Iran's provinces can be alleviated through these adaptation strategies.

2. Methods and Data

2.1. Study Area

Iran is one of the world's driest nations (Madani, 2014) with annual precipitation of 228 mm yr^{-1} and internal renewable freshwater resources of 129×10^9 m^3 yr^{-1} (AQUASTAT, 2020). Over the past 20 years, the per capita water availability has declined from 2194 m^3 cap^{-1} yr^{-1} to 1700 m^3 cap^{-1} yr^{-1} (AQUASTAT, 2020).

According to the national data reported by the Iranian Ministry of Agriculture Jihad (IMAJ, 2019), 73% of the agricultural lands have been allocated to cereal production: 53.1% for wheat, 14.8% for barley, 3.5% for rice, and 1.6% for maize. Cereal production comprises about 32.6% of Iran's total crop production, from which 23% is rain-fed. Together, the four crops contribute to about half of Iran's domestic food supply (in calories; FAOSTAT, 2013; WFP, 2016). We limit our study to these four main staple crops of Iran, wheat, maize, barley, and rice.

With an area of 1,640,195 km^2, Iran is divided into 30 provinces, illustrated in Figure 1. Based on the De-Martonne climate classification (De Martonne, 1926), there are five climatic regions in Iran, namely hyper-arid, arid, semi-arid, dry-sub-humid and humid (Figure 1), of which arid and semi-arid are prevailing (Karandish, Mousavi, & Tabari, 2017). We assess the green and blue water footprints of these crops in all 30 provinces of Iran—encompassing five climate zones—under current (1980–2010) and future (2041–2070) climate for three different Representative Concentration Pathways (RCPs).

2.2. WF of Cereal Production

The WF of each crop (wheat, barley, maize, rice) has been estimated per province for each year in the historical period (1980–2010) and the future period (2041–2070) for three RCP scenarios. The WF of each cereal crop was calculated on a daily time step based on the WF accounting framework by Hoekstra et al. (2011). The weighted average WF of cereals was then calculated based on each crop's proportion in the historical period. After that, weighted average values were calculated for all five climatic regions.

For each crop, the green and blue WF of crop production (green or blue WF_{prod}, m^3 t^{-1}) were calculated by separating the daily total (green + blue) evapotranspiration ($ET_{green+blue}$) into green and blue compartments (ET_{green} or ET_{blue}, m^3 ha^{-1}), which have been aggregated over the full growing period and subsequently divided by the harvested yield (Y, t ha^{-1}). Green WF refers to the consumption of rainwater, while blue WF refers to the consumption of irrigation water that is supplied from the surface and/or groundwater resources (Karandish & Hoekstra, 2017). ET and Y were simulated using the FAO water balance and crop growth model; AquaCrop, version 6.0 (Steduto et al., 2012). The model simulates a daily soil water balance for the root zone:

$$S_{[t]} = S_{[t-1]} + P_{[t]} + I_{[t]} + \mathrm{CR}_{[t]} - \mathrm{ET}_{[t]} - \mathrm{RO}_{[t]} - \mathrm{DP}_{[t]} \quad (1)$$

in which $S_{[t]}$ and $S_{[t-1]}$ are the soil water content at the end of day t and t – 1, respectively, P is precipitation, I is irrigation, CR is capillary rise, ET is evapotranspiration, RO is surface runoff, and DP is deep percolation on day t. All variables are expressed in mm da yr^{-1}. Following Karandish and Hoekstra (2017), the initial soil moisture content was estimated by running the model for several consecutive years (5 years in this study) and taking the outcome as the initial value for the calculation. CR is assumed to be zero since groundwater is deeper than one m below the rooting zone all over Iran (Karandish & Hoekstra, 2017). This assumption may result in underestimating (blue) ET in regions where shallow groundwater can occur, such as humid regions. However, this climatic region only covers 2.3% of Iran. The Soil Conservation Service curve-number equation was used when estimating the RO by the model. P and I were considered as green and blue water, respectively. The contributions of green (P) and blue (I) water to RO were calculated based on the ratio of P and I, respectively, to the sum of P and I. The fraction of green and blue water in the total soil water content at the end of the previous day was applied to calculate green and blue DP and ET. Following Zhuo, Mekonnen, Hoekstra, and Wada (2016), green soil water content (S_{green}) and blue soil water content (S_{blue}) were calculated as:

$$S_{\mathrm{green}[t]} = S_{\mathrm{green}[t-1]} + P_{[t]} - \mathrm{RO}_{[t]} \times \frac{P_{[t]}}{P_{[t]} + I_{[t]}} - (\mathrm{DP}_{[t]} + \mathrm{ET}_{[t]}) \times \frac{S_{\mathrm{green}[t-1]}}{S_{[t-1]}} \quad (2)$$

$$S_{\mathrm{blue}[t]} = S_{\mathrm{blue}[t-1]} + I_{[t]} - \mathrm{RO}_{[t]} \times \frac{I_{[t]}}{P_{[t]} + I_{[t]}} - (\mathrm{DP}_{[t]} + \mathrm{ET}_{[t]}) \times \frac{S_{\mathrm{blue}[t-1]}}{S_{[t-1]}} \quad (3)$$

The overall green, blue and total (green + blue) water consumption (green, blue or total $WF_{overall}$, m^3 yr^{-1}) for a specific crop was calculated by multiplying its green or blue WF_{prod} by the crop's total production (t yr^{-1}).

The calibrated and validated model was further used to estimate climate change projections into crop yield and water consumption. Similar to previous studies (e.g., Alvar-Beltran et al., 2021; Bouras et al., 2019; Li et al., 2016; Yawson & AduArmah, 2020; Yu et al., 2018), crop-related parameters for the future periods were set to those calibrated and validated over the historical period (1980–2010). Annual simulations were run until the end of mid-21st century using the downscaled meteorological inputs obtained from different GCMs under three climate change scenarios, RCP2.6, RCP4.5 and RCP8.5.

2.3. AquaCrop Model Calibration and Validation

Per crop, per province, the AquaCrop model was calibrated and validated to simulate crop growth against the experimental data involving a wide range of observed yields and total biomass collected by IMAJ (2019) over 1980–2010. To find the most sensitive parameters prior to the calibration and validation process, a sensitivity analysis was first carried out. The AquaCrop model includes 42 crop parameters which are summarized in Table 1. Following Hui-Min et al. (2017) and, the relative change in crop yield and water requirement was determined after adjusting each of these 42 crop parameters one by one by ±20% compared to their initial value. More details are available in Karandish et al. (2018). The parameters that caused the largest relative changes

Table 1
Crop Parameters Embedded in the AquaCrop Model

a: Canopy and phenological development	
mat	Total length of crop cycle in growing degree-days (GDD)
ccs	Soil surface covered by an individual seedling at 90% emergence
den	Number of plants per hectare
mcc	Maximum canopy cover in fraction soil cover
eme	GDD from sowing to emergence
sen	GDD from sowing to start senescence
flo	GDD from sowing to flowering
flolen	Length of the flowering stage
cgc	GDD—increase in canopy cover
cdc	GDD—decrease in canopy cover
hilen	Building-up of harvest index during yield formation
b: Root development	
root	GDD from sowing to maximum rooting depth
rtnx	Minimum effective rooting depth
rtx	Maximum effective rooting depth
rtexup	Maximum root water extraction in top quarter of root zone
rtexlw	Maximum root water extraction in bottom quarter of root zone
rtshp	Shape factor describing root zone expansion
c: Transpiration	
kcdcl	Decline of crop coefficient as a result of aging, nitrogen deficiency, etc.
kcb	Crop coefficient when canopy is complete but prior to senescence
evladc	Effect of canopy cover in reducing soil evaporation in late season
d: Biomass and yield production	
wp	Normalized water productivity
hi	Reference harvest index
exc	Excess of potential fruits
e: Water and temperature stress	
puexp	Upper threshold of soil water depletion factor for canopy expansion
Plexp	Lower threshold of soil water depletion factor for canopy expansion
pexshp	Shape factor for water stress coefficient for canopy expansion
Psto	Upper threshold of soil water depletion fraction for stomatal control
pstoshp	Shape factor for water stress coefficient for stomatal control
Psen	Upper threshold of soil water depletion factor for canopy senescence
psenshp	Shape factor for water stress coefficient for canopy senescence
Ppol	Upper threshold for soil water depletion factor for pollination
Anaer	Anaerobiotic point at which deficient aeration occurs
polmn	Minimum air temperature below which pollination starts to fail
polmx	Maximum air temperature above which pollination starts to fail
Stbio	Minimum growing degrees required for full biomass production
hipsveg	Coefficient describing positive impact on HI of restricted vegetative growth during yield formation
hinsveg	Coefficient describing negative impact on HI of stomatal closure during yield formation
Hinc	Allowable maximum increase of specified

Table 1
Continued

hipsflo	Possible increase of HI due to water stress before flowering
lelecon	Electrical conductivity of soil saturation extract at crop starts to be affected
Uelecon	Electrical conductivity of soil saturation extract at crop no longer grow

Note. These parameters were involved through the sensitivity analysis.

were incorporated in the calibration process. They were adjusted to achieve an acceptable agreement between the model-simulated and observed data. The model was calibrated against observed yield and total biomass collected over the period 1980–2000. The calibrated model was subsequently validated against observed data collected during 2001–2010.

The normalized root mean square error (nRMSE), normalized mean bias error (nMBE), and Nash-Sutcliffe model efficiency coefficient (NSE) were calculated to provide a quantitative assessment of the correspondence between the model-estimated and observed data as follows:

$$\mathrm{nRMSE} = \frac{\sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}}}{\overline{O}} \times 100\% \tag{4}$$

$$\mathrm{nMBE} = \frac{\sum_{i=1}^{n}(O_i - P_i)}{n \times \overline{O}} \times 100\% \tag{5}$$

$$\mathrm{NSE} = \left(1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2}\right) \times 100\% \tag{6}$$

where O_i, P_i, and $\bar{O}$ are, respectively, the observed, model-simulated and average of the observed data; and n is the number of the observations.

2.4. Adaptation Strategies

After analyzing the probable consequences of climate change on cereal production in the study area, we assess three adaptation strategies to reduce the negative impacts of climate change on cereal production. These adaptation strategies include off-season cultivation (rainfed-cropping substitution), early planting, and WF benchmarking. We evaluate the effects of these strategies on reducing the overall green and blue water use, separately, for the base period (1980–2010) and three climate change scenarios (2041–2074). Since these solutions' main purpose is to reduce blue water consumption, we applied these solutions only to the irrigated cereals.

In off-season cultivation, we assumed to replace irrigated cereal production with rainfed cereal. In this substitution, the harvested area for each specific crop was kept the same as in the base case (i.e., the current condition). In contrast, irrigated crops were replaced by their rainfed equivalents, grown in another part of the year (the wet season). In doing so, the irrigated yield was substituted by the rainfed yield. We did this for wheat, barley and maize. Rice was excluded here since its rainfed cultivation is not feasible in Iran.

For early planting, each crop's planting date was brought forward by 2 weeks compared to the baseline. The logic behind this strategy was that the cropping date might affect the length of the growing period on the one hand and the daily evapotranspiration on the other hand. Hence, such a strategy may affect the total blue water consumption of these crops.

Formulating benchmark levels for green and blue WFs is a promising strategy to reduce consumptive water use per unit of harvested crop (Brauman et al., 2013; Mekonnen & Hoekstra, 2011; Zhuo, Mekonnen, Hoekstra, & Wada, 2016; Zwart et al., 2010). WF benchmarking implies defining a reasonable WF per activity or product; a WF larger than the benchmark indicates inefficient resource use. A reasonable benchmark depends on environmental

Table 2
The Type and Sources of Data Sets Used in This Study

Type of data	Sources
Agricultural data including rainfed and irrigated cropping system information (i.e., total production, harvested area, and yield and total biomass), cropping calendar and agricultural practices	IMAJ (2019)
Irrigation timing, depth, and duration	WRM (2016)
Weather data, including minimum and maximum temperature, relative humidity, sunshine hours, wind speed, and precipitation	IRIMO (2016)
Reference evapotranspiration (ETo)	Estimated based on FAO-Penman-Monteith equation (Allen et al., 1998)
Soil data, including soil texture and total soil water holding capacity	Batjes (2012)
Soil water parameters including soil water content at field capacity, permanent wilting point, saturated soil water content, total available water, and saturated hydraulic conductivity	Steduto et al. (2012)

conditions and managerial factors (Hoekstra, 2013, 2014). For example, benchmarks can be derived by taking the WF level that is not being exceeded by the best 20%–25% of producers in an area (Mekonnen & Hoekstra, 2014; Zhuo et al., 2016b). We evaluate the effects of reducing the WF_{prod} of wheat, barley, maize and rice to benchmark levels for two alternatives WF benchmarking options. In option 1, we set the benchmark at the WF level that is achieved by the 25% most efficient producers of each crop in each climatic zone in the study area according to Karandish et al. (2018). They did a grid-based assessment in which climate-specific WF benchmark levels were calculated for 26 crops for 30 years in the period 1980–2010, at $5' \times 5'$ spatial resolution. In option 2, we assume a case in which crop yields can be increased by 10% through better technology, cultivars and management practices without affecting crop water use. This results in setting the WF benchmark at 91% (=1/1.1) of the original estimated value for each crop (in all location and years). The 10% criterion is selected only as an instance; indeed, WF directly reduces with yield improvement; hence, more yield improvement ends up with more reduction in the WF.

2.5. Blue Water Scarcity

We assess the effects of the three adaptation strategies on monthly blue water scarcity (BWS) in every province and climatic zone by dividing the monthly blue WF by monthly blue water availability. To estimate the total blue WF, blue WF estimates of crops other than those considered in this study were obtained from Karandish and Hoekstra (2017). Because data on the water availability and the WF of other crops pertain to the current climate, we only do this analysis for the base period.

Per province, blue water availability was calculated as the natural runoff minus environmental flow requirements, all on monthly basis (Hoekstra et al., 2011). Data on monthly natural runoff per province (i.e., natural runoff generated within the selected province plus water entered from upstream) were obtained from Iran's Water Resource Management Company (WRM, 2016). Environmental flow requirements were assumed at 80% of natural runoff, according to the presumptive standard proposed by Richter et al. (2012), which has been adopted in several other water scarcity assessments (Hoekstra et al., 2012; Mekonnen & Hoekstra, 2016)

Following Mekonnen and Hoekstra (2016), we categorized the BWS into four groups of no scarcity with $BWS \leq 1$, moderate scarcity with $1 < BWS < 1.5$, significant scarcity with $1.5 \leq BWS < 2$, and severe scarcity with $BWS \geq 2$. $BWS > 1$ implies that the blue WF is beyond the sustainable blue water availability in the month/province and taps into environmental flows. Therefore, a month/province with $BWS > 1$ is considered an "environmental hotspot'' and any blue WF there as "unsustainable'' (Hoekstra et al., 2011). In such a hotspot, the contribution of the specific blue water-consuming activity (e.g., growing a particular crop) towards the total unsustainable blue water footprint is calculated based on the ratio of the blue water footprint of the activity to the total blue water footprint.

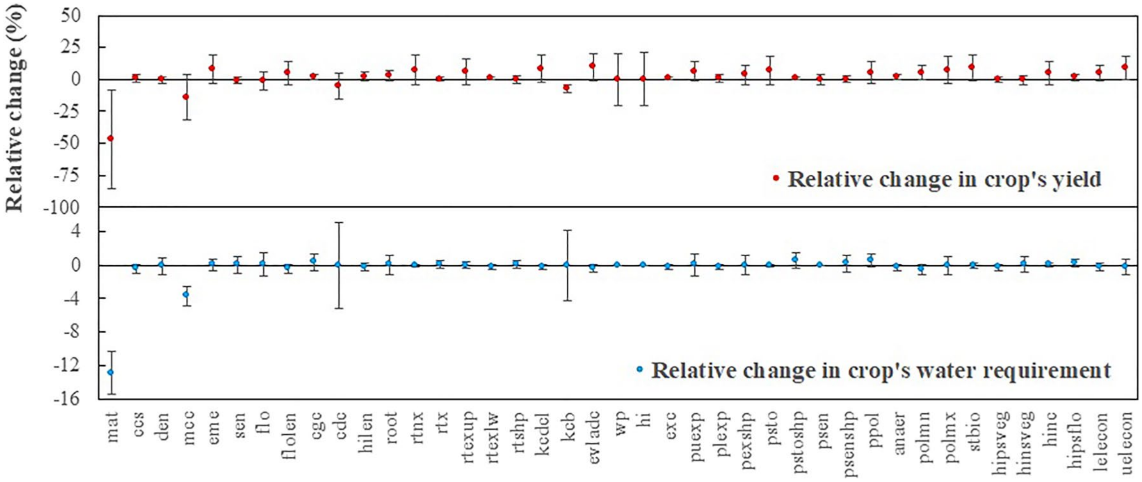

Figure 2. Relative change in crop yield and net irrigation water requirement and an adjustment in different crop parameters in the sensitivity analysis process. The whiskers denote the variations in sensitivities across different crops and regions.

2.6. Data

Table 2 shows the type and source of datasets used in this study. Meteorological data for 1980–2010 were collected from 52 weather stations spread out over the country and the five climatic regions (IRIMO, 2016) as presented in Figure 1. Daily values of reference evapotranspiration (ET_o) were calculated using the FAO-Penman-Monteith equation (Allen et al., 1998). Soil properties were obtained from Batjes (2012). Soil water parameters (e.g., soil water content at field capacity, permanent wilting point, saturated soil water content, total available water, and saturated hydraulic conductivity) for each soil type were extracted from the manual of the AquaCrop model (Steduto et al., 2012). The agricultural data, including crop sowing area (ha), irrigated area (ha), plantation date, harvesting date, and yield (kg ha^{-1}), were collected per crop per province per year for the period 1980–2010 (IMAJ, 2019).

The projections of future climate variables were obtained from 20 General Circulation Models described in the Coupled Model Intercomparison Project, Phase 5 (Miao et al., 2014) for three different Representative Concentration Pathways (RCPs): RCP2.6, RCP4.5 and RCP8.5. The properties of applied GCMs can be found in Shahsavari et al. (2019). The RCPs represent possible changes in future anthropogenic greenhouse gas emissions and are consistent with underlying socioeconomic assumptions. According to IPCC (2014), in RCP2.6, the CO_2 emission follows a decreasing trend and is supposed to reach zero by 2100. In RCP4.5, as an intermediate scenario, the highest CO_2 emission is supposed to occur around 2040, after which emissions will decline toward 2100. In RCP8.5, which indicates the most extreme climate-change scenario, emissions consistently increase throughout the 21st century.

3. Results and Discussion

3.1. Model Calibration and Validation Results

Figure 2 shows the relative change in crop yield and water requirement along with a ±20% adjustment in the model's crop parameters. While the sensitivities vary per crop per region, our results demonstrate that eight parameters have the largest effects on the model outputs: flo, psen, mat, kcb, wp, hi, mcc and cdc (see Table 1 for definitions). The same parameters have been found to be the most sensitive parameters for winter wheat in a global assessment carried out by Hui-Min et al. (2017).

The outcomes of the model calibration based on these eight parameters are summarized in Table 3. During the calibration period (1980–2000), the model simulated different crop yield, with nRMSE ranging from 5.7% to 8.3%, nMBE ranging from −2% to −2.7%, and NSE ranging from 91.6% to 97.8%. With respect to total biomass, the nRMSE, nMBE, and NSE varied in the range of 5.5%–6.4%, (−1.8%)–(−3.1%), and 87.5%–93.7%, respectively. The negative signs of nMBE indicate a general overestimation of crop yield and total biomass.

Table 3
The AquaCrop Model Performance Criteria for the Calibration (i.e., 1980–2000) and Validation (i.e., 2001–2010) Data Sets

Process	Crop	Yield			Total Biomass		
		nRMSE (%)[a]	nMBE (%)	NSE (%)	nRMSE (%)	nMBE (%)	NSE (%)
Calibration	Irrigated Wheat	5.9 ± 2.1	−2.7 ± 6.3	91.6 ± 9.1	5.8 ± 1.7	−2.4 ± 6.6	91.1 ± 4.5
	Rainfed Wheat	5.8 ± 2.5	−2.1 ± 7.7	96.2 ± 4.1	5.5 ± 2.2	−2.1 ± 6.8	93.7 ± 5.6
	Irrigated barley	6.1 ± 6.9	−2.2 ± 6.7	94.2 ± 7.4	6.0 ± 1.7	−2.2 ± 6.5	89.9 ± 5.2
	Rainfed barley	5.9 ± 3.1	−2.4 ± 6.6	97.0 ± 3.2	5.7 ± 2.3	−2.2 ± 6.6	92.6 ± 7.1
	Irrigated maize	5.8 ± 1.5	−2.2 ± 5.7	92.6 ± 8.7	6.0 ± 1.8	−1.8 ± 6.7	87.5 ± 7.1
	Rainfed maize	8.3 ± 4.3	−2.5 ± 7.4	97.8 ± 8.0	6.0 ± 1.8	−2.1 ± 7.4	90.7 ± 6.4
	Irrigated rice[a]	5.7 ± 2.2	−2.0 ± 6.4	92.8 ± 9.8	6.4 ± 1.7	−3.1 ± 6.0	93.1 ± 3.5
Validation	Irrigated Wheat	6.0 ± 3.3	−2.1 ± 7.8	98.3 ± 1.7	5.1 ± 3.6	−2.6 ± 7.5	95.2 ± 4.2
	Rainfed Wheat	6.1 ± 3.7	−1.4 ± 6.9	98.3 ± 1.8	6.0 ± 3.3	−2.4 ± 7.9	95 ± 4.8
	Irrigated barley	6.6 ± 3.4	−2.0 ± 8.1	98.0 ± 2.0	5.3 ± 3.0	−2.3 ± 6.8	96.3 ± 3.5
	Rainfed barley	6.5 ± 4.2	−2.1 ± 8.1	98.0 ± 2.0	5.9 ± 4.5	−1.8 ± 9.0	94.3 ± 5.4
	Irrigated maize	5.7 ± 3.5	−2.0 ± 7.5	98.0 ± 2.0	5.4 ± 4.2	−2.0 ± 8.4	92.3 ± 5.6
	Rainfed maize	6.9 ± 4.8	−2.7 ± 7.9	91.8 ± 8.5	5.9 ± 3.1	−2.5 ± 7.6	94.5 ± 4.5
	Irrigated rice	5.4 ± 3.5	−2.4 ± 6.8	98.2 ± 2.4	5.1 ± 3.6	−1.6 ± 7.1	93.8 ± 4.8

Note. The variations show the effects of different regions and years.
[a]The rainfed cropping of rice is not feasible in Iran.

A close match was obtained between the observed and simulated crop yield and total biomass during the validation process, with nRMSE, nMBE, and NSE, respectively, ranging from 5.4% to 6.9%, (−1.4%)–(−2.7%), and 91.8%–98.3% for crop's yield; and ranging from 5.1% to 6%, (−1.6%)–(−2.6%), and 95%–96.3% for total biomass. A similar match between the observed and AquaCrop-simulated yield and total biomass was reported in the other studies (e.g., nRMSE = 6%–12% and 6%–8% for rice yield and total, biomass, respectively, reported by Vahdati et al. (2020); NSE = 85%–98% and 80%–85% for maize yield and total biomass, respectively, reported by Kheir and Hassan (2016); nRMSE = 10.9%–13.9% and NSE = 96% for wheat yield, reported by Alvar-Beltran et al. (2021); and nRMSE = 8.1% for barley yield, reported by Yawson and AduArmah (2020))."

3.2. Cereal Production Under Current Climate and Agricultural Practices

3.2.1. Cereal Production

On average, a total of 14.8 million t yr^{-1} cereal were produced over the period 1980–2010, 73% of which (10.8 million t yr^{-1}) were from irrigated croplands. Total production (14.8 million t yr^{-1}) was built-up as follows: 6.7 million t yr^{-1} of wheat (68% is achieved from the irrigated fields), 1.4 million t yr^{-1} of barley (of which 67% irrigated), 1.8 million t yr^{-1} of rice (100% irrigated) and 0.9 million t yr^{-1} of maize (of which 99.8% irrigated).

Figure 3 shows the 30-year average contributions of different provinces in the national production of the rainfed and irrigated cereals in Iran. About 81.1% was produced in the arid and semi-arid regions, where crop production heavily relied on blue water resources. Humid and dry sub-humid regions contributed 14.4% to nationwide cereal production, of which 54% was irrigated cereal (mostly rice paddy fields).

Provinces with large contributions to the total cereal production are Fars (responsible for 12.5% of national cereal production; arid) Khuzestan (9.7%; arid), Golestan (5.9%; dry sub-humid), East-Azarbaijan (5.3%; arid), and Mazandaran (5.2%; humid; Figure 3). While wheat, barley and maize were produced under both irrigated and rainfed conditions, rice was only produced in irrigated fields. Most rice in Iran was produced in humid regions (74.7% of total rice production), the rest being produced in semi-arid (17.2%), hyper-arid (2.4%) and arid (0.3%) regions.

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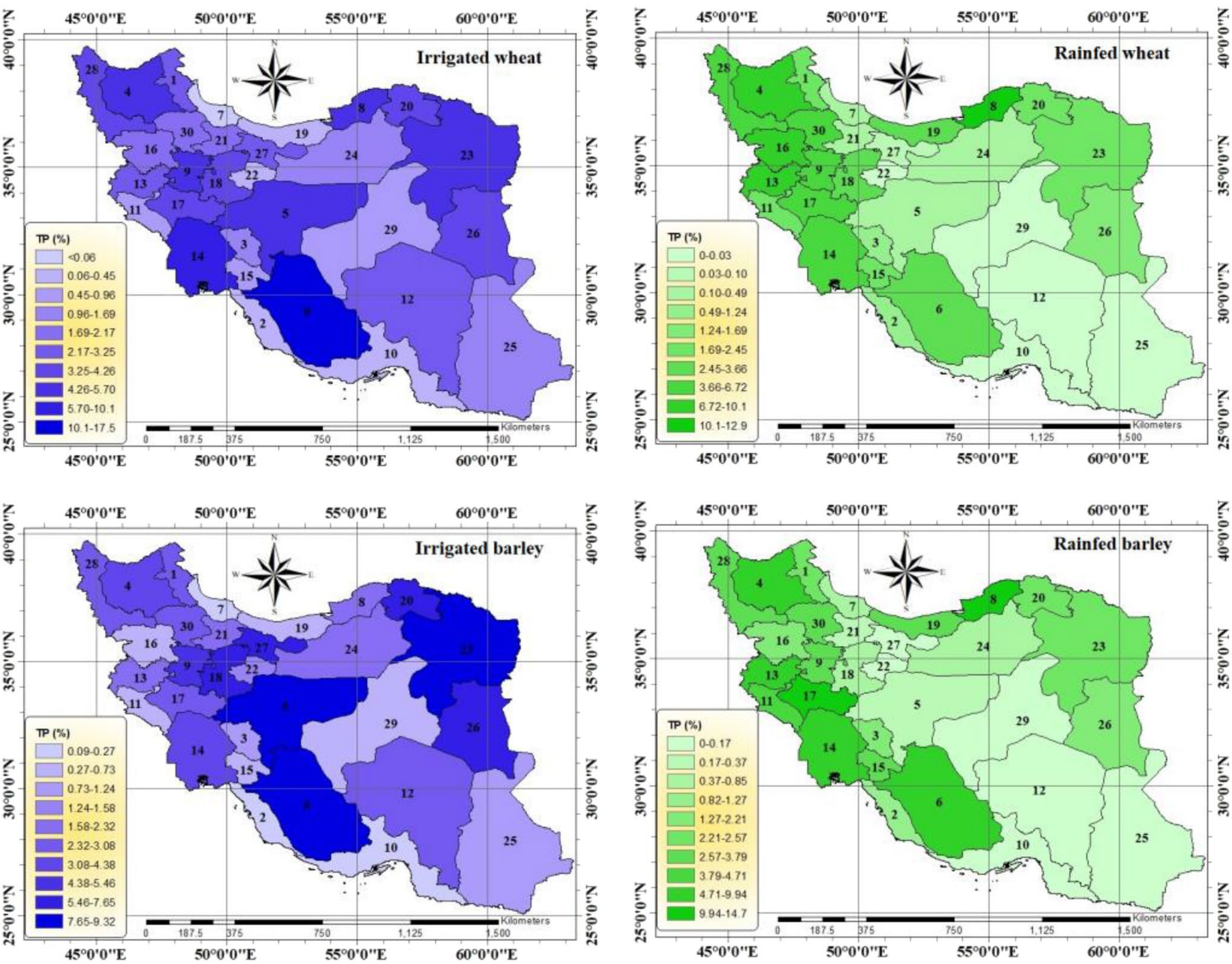

Figure 3. Share of Iran's provinces in total production of each irrigated (left) and rainfed (right) crop. Average for the base period (1980–2010).

3.2.2. WF_{prod} and $WF_{overall}$ of the Major Cereals

The map of 30-year-average provincial WF_{prod} ($m^3\ t^{-1}$) of major cereal over the period 1980–2010 revealed a noticeable variation of WF_{prod} across the country (Figure 4). The north (humid and dry sub-humid) and the northwest of the country (mostly semi-arid) had the largest green WF_{prod} while the central and southeast (mostly hyper-arid and arid) of Iran had the largest blue WF_{prod}. For the green + blue WF_{prod}, semi-arid regions had the largest and humid regions had the smallest values. The contribution of green WF_{prod} to total WF_{prod} heavily depends on the fraction of rainfed and irrigated production and the availability of green water from precipitation on irrigated lands.

Counterintuitively from a water perspective, provinces in the semi-arid climate with high blue WF_{prod} were in charge of most cereal production in Iran; these results point out that—from a water management perspective—a thoughtful reconsideration of the cereal cultivation pattern in Iran is advised. This finding is in accordance with those suggested by Karandish and Hoekstra (2017). Karandish et al. (2020) reported that relocating the production area of cereals in Iran can lead to a 10% reduction in blue water consumption.

To present the differences of water consumption of cereal production for irrigated and rainfed croplands, we simulate the green, blue and total WF_{prod} (and $WF_{overall}$, $m^3\ yr^{-1}$) of wheat, barley, rice and maize for irrigated and rainfed, separately, and we report the regional-average values per climate zone (Table 4). On average, 24.2 billion m^3 water (green + blue) per annum was consumed by irrigated cereals, 87% of which was consumed in the arid

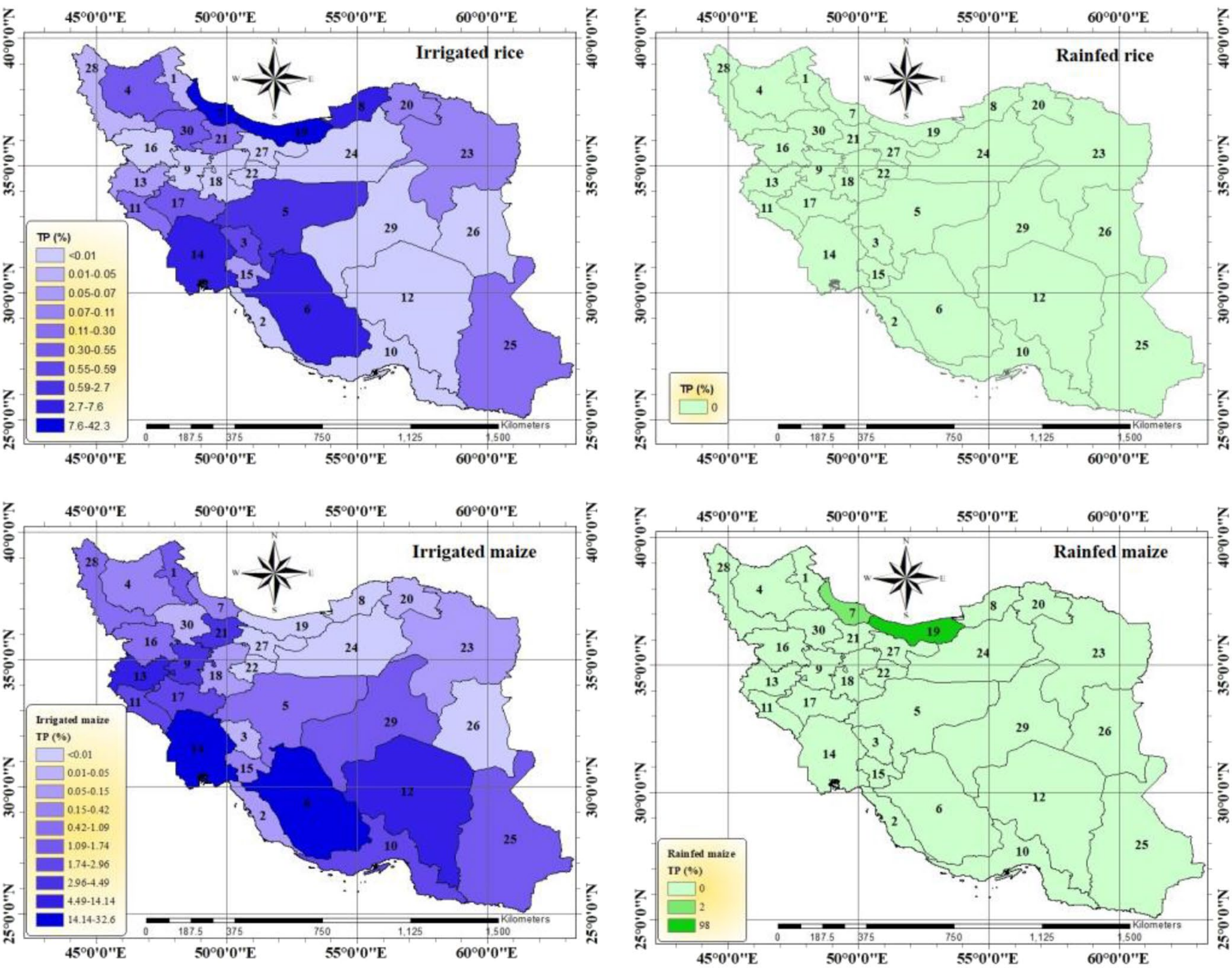

Figure 3. (Continued)

(55%) and semi-arid (32%) regions. For all climatic regions, wheat had the largest contribution to the total water consumption (67.5%–73.8%), except for the humid region, in which rice ranked first (97.2%). Rainfed cereals consumed 18.6 billion m^3 of green water per annum, 95.7% in arid (33.4%) and semi-arid (62.3%) regions. Except for the hyper-arid region, in which barley had the largest contribution to total water consumption (56.4%), wheat had the largest contribution in all other climatic regions.

3.3. Cereal Production Under Future Climate Scenarios and Current Practices

3.3.1. Yield and Total Production

We investigated the spatial variation of relative changes in yield (t ha^{-1}) of cereal production under climate change scenarios (different RCPs) for irrigated and rainfed croplands across Iran's climate zones for the period 2041–2070. The regional-average effects are summarized in Table 5. In case of no limitation in blue water availability for irrigation, there is an overall increase in cereal yield in the irrigated croplands, with the lowest positive projection under RCP8.5 (the most pessimistic scenario) and the highest one under RCP2.6 (the most optimistic one). In irrigated cereal production, climate change projects an increase in the yield in all climate zones; 22%–26.4% in hyper-arid, 25.3%–29.5% in arid, 23.1%–27.3% in semi-arid, and 25.3%–30.3% in dry sub-humid, and 22.7%–26.6% in humid regions as presented in Table 5. In rainfed cereal production, climate change projects a positive change in cereal's yield grown in the rainfed croplands accounted for 6.6%–29.6% in

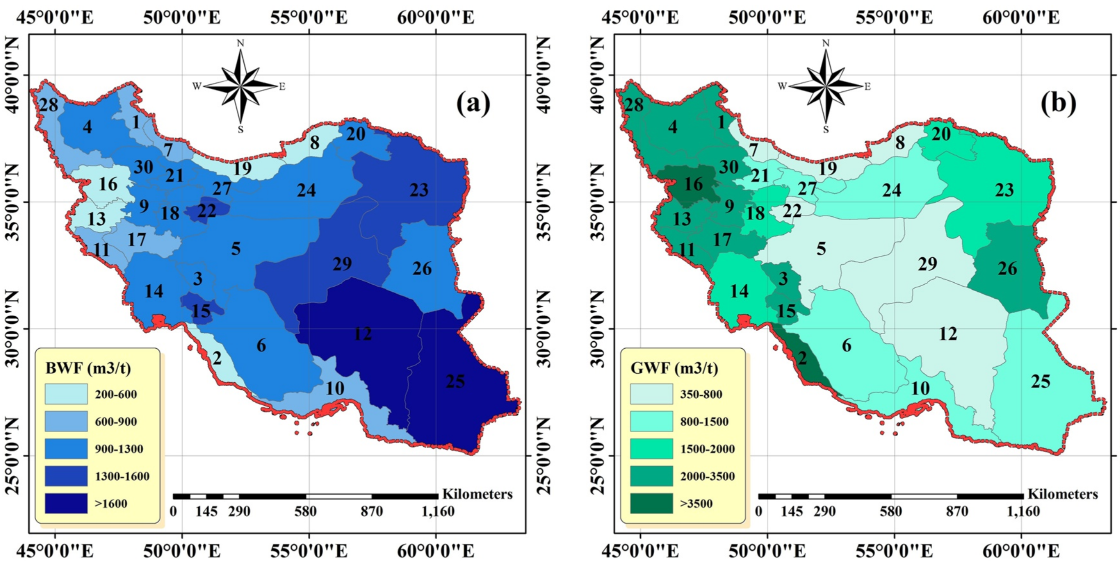

Figure 4. The spatial variation of the 30-year average (1980–2010) blue (a) and green (b) water footprint of cereal production in Iran (average over the four studied crops).

the arid, 55%–78.7% in semi-arid, 20.6%–29.2% in dry sub-humid, and 26%–36% in humid regions. The only exception is the hyper-arid region, in which a 29.5%–46.9% yield reduction is expected.

In general, yield improvement under climate change may occur when elevated CO_2 levels result in photosynthesis improvement, leading to crop growth improvement when the increased crop transpiration demand can be met by precipitation and irrigation (Araya et al., 2017; Leakey et al., 2009). This is known as the CO_2 elevation effect. Fulfilling crop's transpiration demand by irrigation within the irrigated land or by an increased amount of precipitation within the rainfed land may also overcome potential soil water shortage during the cropping cycle, which ends up with yield amelioration under future climate. This is a possible scenario when there is no restriction on water availability.

On the other hand, yield reduction in rainfed cereal production in the hyper-arid region implies that the negative impact of increased temperature (and short term dry spells, despite the overall increase in growing season total precipitation; Section 3.2.2) on crop yield can counteract the positive CO_2 fertilisation effect. *t*. Crop's maturity period is shortened when they are exposed to high temperature (Karandish, Kalanaki, & Saberali, 2017), which consequently lead to shortening the available time to capture solar radiation and assimilate CO_2 (Bassu

Table 4
Consumptive Water Footprint per Tonne of Crop (WF_{prod}, $m^3\ t^{-1}$) and as a Total ($WF_{overall}$, Million $m^3\ yr^{-1}$), the Share of Blue Water in the Consumptive Water Footprint (for Irrigated Crops) and Cereal Production per Climatic Region and for Irrigated and Rainfed Cereals, Separately

	Irrigated crop				Rainfed crops		
Climatic region	Total WF_{prod} ($m^3\ t^{-1}$)	Total $WF_{overall}$ (million $m^3\ yr^{-1}$)[a]	% of blue	Total production (million t yr^{-1})[a]	Green WF_{prod} ($m^3\ t^{-1}$)	Green $WF_{overall}$ (million $m^3\ yr^{-1}$)[a]	Total production (million t yr^{-1})[a]
Hyper-arid	2779	1.49 (6.1)	78.2	0.54 (5.3)	2860	0.01 (0.1)	0 (0)
Arid	2232	13.21 (54.6)	61.2	5.92 (58.4)	5728	6.22 (33.4)	1.09 (27)
Semi-arid	2700	7.83 (32.3)	58.8	2.9 (28.6)	5072	11.61 (62.2)	2.29 (56.7)
Dry sub-humid	1271	0.5 (2.1)	36.1	0.39 (3.8)	929	0.46 (2.5)	0.5 (12.4)
Humid	1117	1.18 (4.9)	57.7	0.39 (3.9)	2018	0.33 (1.8)	0.16 (3.9)

Note. Averages over the period 1980–2010 and the four studied crops.
[a]Values in brackets indicate the % contribution to the total.

Table 5
Relative Changes in Cereal's Yield Under Climate Change Scenarios Assuming Unconstrained Water Availability for Irrigation (2041–2070) Compared to the Base Period (1980–2010)

Scenario	Climatic region	Relative change in irrigated cereal yield (%)	Absolute change in total production (1000 t yr^{-1})	Relative change in rainfed cereal yield (%)	Absolute change in total production (1000 t yr^{-1})
RCP2.6	Hyper-arid	26.4	141.5	−29.5	−0.8
	Arid	29.5	1745.9	26.6	288.2
	Semi-arid	27.3	791.4	78.7	1801.0
	Dry sub-humid	30.3	118.5	29.2	145.7
	Humid	26.6	280.9	36	58.5
RCP4.5	Hyper-arid	23.4	125.4	−51.9	−1.5
	Arid	25.3	1497.3	3	32.5
	Semi-arid	27.1	785.6	47.5	1087.0
	Dry sub-humid	30.2	118.1	25.8	128.7
	Humid	26.6	280.9	28.7	46.6
RCP8.5	Hyper-arid	22	117.9	−46.9	−1.3
	Arid	25.3	1497.3	6.6	71.5
	Semi-arid	23.1	669.6	55	1258.6
	Dry sub-humid	25.3	99.0	20.6	102.8
	Humid	22.7	239.7	26	42.2

et al., 2014; Chmielewski et al., 2004; Rezaei et al., 2015). Aggregation of these impacts generally results in yield reduction in water-scarce regions (Lobel et al., 2012), which we also observe in the rainfed croplands of the hyper-arid region of Iran.

Table 5 also shows the absolute change in annual cereal production (thousand t yr^{-1}) under future climate within different climatic regions, assuming unconstrained water availability for irrigation. Compared to the base period (i.e., 1980–2010), climate change may result in an annual increase in the total production of irrigated cereal in different climate zones, with the lowest and the highest increase in the dry sub-humid (99–118 thousand tonnes yr^{-1}) and arid (1497–1746 thousand tonnes yr^{-1}) regions, respectively. Except for the hyper-arid region, climate change projects an annual increase in rainfed cereal production, with the highest increase in the semi-arid zone.

3.3.2. Precipitation and Evapotranspiration

To better picture climate change projections, we estimated the regional average of relative changes in precipitation, $ET_{green+blue}$ and ET_{blue} (all in mm yr^{-1}) of irrigated and rainfed cereal croplands in different climate zones of Iran. Table 6 summarizes the results. Climate change projections show both positive (increases) and negative (decrease) changes in these variables. Such projections relate either to the selected RCP or to the type of cereal and the climate-zone of the cereal field. In general, RCP2.6 and RCP8.5 show the least and most severe impacts, respectively, which is consistent with the available literature (Araya et al., 2017; Darzi-Naftchali & Karandish, 2019; Ruane et al., 2013).

Compared to the base period of 1980–2010, growing season total precipitation increases in all cases, except for irrigated croplands in the semi-arid zone in the RCP4.5 scenario. In the future scenarios, irrigated cereals in the

Table 6
Relative Changes in Growing Season Total Precipitation, Blue (ET_{blue}; Only for Irrigated Cereal), Green (ET_{green}), and Total ($ET_{green+blue}$) Evapotranspiration Under Climate Change Scenarios (2041–2070) Compared to the Base Period (1980–2010)

		Relative changes for irrigated cereal			Relative changes for rainfed cereal	
Scenario	Climatic region	Precipitation (%)	ET_{blue} (%)	$ET_{green+blue}$ (%)	Precipitation (%)	ET_{green} (%)
RCP2.6	Hyper-arid	12.6	5.6	7.1	16.5	16.5
	Arid	6.5	2.3	3.9	14.1	14.1
	Semi-arid	2.4	−9.7	−4.7	5.8	5.8
	Dry sub-humid	5.4	2.4	4.3	8.9	8.9
	Humid	1	−4	−1.9	18.4	18.4
RCP4.5	Hyper-arid	12.1	6.6	7.8	13.8	13.8
	Arid	3.4	5.9	4.9	7.2	7.2
	Semi-arid	−1.2	−7	−4.6	0.4	0.4
	Dry sub-humid	3.8	4.3	4	4.4	4.4
	Humid	0.2	0.3	0.3	7.5	7.5
RCP8.5	Hyper-arid	13.3	25	22.5	17.3	17.3
	Arid	7.1	14.1	11.4	11.6	11.6
	Semi-arid	3.3	−4.8	−1.5	5.1	5.1
	Dry sub-humid	8.5	9.6	8.9	8.6	8.6
	Humid	5.7	−0.3	2.2	11.3	11.3

Table 7
Relative Changes in Cereal's Water Footprint per Unit of the Crop (WF_{prod}, $m^3\ t^{-1}$) Under Climate Change Scenarios (2041–2070) Compared to the Base Period (1980–2010)

		Relative changes for irrigated crops			Relative changes for rainfed crops
Scenario	Zone	Green WF_{prod} (%)	Blue WF_{prod} (%)	Green + blue WF_{prod} (%)	Green WF_{prod} (%)
RCP2.6	Hyper-arid	−10.9	−16.5	−15.3	65.2
	Arid	−17.8	−21.0	−19.7	−9.7
	Semi-arid	−19.6	−29.1	−25.2	−40.8
	Dry sub-humid	−19.1	−21.4	−19.9	−15.7
	Humid	−20.2	−24.2	−22.5	−12.9
RCP4.5	Hyper-arid	−9.2	−13.6	−12.6	136.6
	Arid	−17.5	−15.5	−16.3	4.2
	Semi-arid	−22.3	−26.8	−25.0	−31.9
	Dry sub-humid	−20.3	−19.9	−20.1	−17.0
	humid	−20.9	−20.8	−20.8	−16.5
RCP8.5	Hyper-arid	−7.1	2.5	0.4	120.9
	Arid	−14.5	−8.9	−11.1	4.9
	Semi-arid	−16.1	−22.7	−20.0	−32.2
	Dry sub-humid	−13.4	−12.5	−13.1	−10.0
	Humid	−13.9	−18.7	−16.7	−11.7

Note. For rainfed cereal, WF is all in green since there is no irrigation during the crop's growing period.

hyper-arid, arid, and dry sub-humid zone require more water (green + blue) during their cropping cycles (7.1%–22.5%, 3.9%–11.4% and 4.3%–8.9%, respectively), while those grown in arid and humid regions will require less water (1.5%–4.7% and 1.9%, respectively). ET_{blue} projections follow a similar pattern. In the rainfed croplands, cereals show constant positive projections regarding (green) water demand of 16.5%–17.3%, 7.2%–14.1%, 0.4%–5.8%, 4.4%–8.9%, and 7.5%–18.4% in the hyper-arid, arid, semi-arid, dry sub-humid and humid regions, respectively.

Increased ET_{blue} under climate change implies that the increase in crop's $ET_{green+blue}$ is comparably higher than the increase in precipitation during the cropping cycle under future climate. Earlier researchers, who confirmed ET_{blue} increases under climate change, claimed that when crops in optimal water condition are projected to a higher temperature, the canopy-cooling requirement will increase, leading to a higher transpiration rate (Karandish,Kalanaki, & Saberali, 2017; Karandish,Mousavi, &Tabari, 2017; Leakey et al., 2009). However, reduced $ET_{green+blue}$ of irrigated cereal in the north-west and some parts of north-east and south-east of the country imply that the compensating effect of increased temperature on reducing the time needed for the crop to reach maturity (more/faster accumulation of growing degree days) is stronger than its impact on increasing crop transpiration during the shortened growing period.

3.3.3. Cereal's Water Footprint

We estimate climate change effects on green/blue/total WF_{prod} ($m^3\ t^{-1}$) and $WF_{overall}$ ($m^3\ yr^{-1}$) of the major cereals in the different climatic regions (Table 7). Our results show that green + blue WF_{prod} may decrease for irrigated cereals in different climate zones: hyper-arid (12.6%–15.3%), arid (11.1%–19.7%), semi-arid (20.0%–25.2%), dry sub-humid (13.1%–20.1%), and humid (16.7%–22.5%). In these regions, the blue WF_{prod} of cereals will reduce by 8.9%–29.1%. For rainfed cereal, the WF_{prod} (green) will increase in the hyper-arid (65.2%–120.9%) and arid (4.2%–4.9%) regions, while it may decrease in the semi-arid (31.9%–40.8%), dry sub-humid (10.0%–15.7%), and humid (11.7%–16.5%) regions. WF_{prod} reduction indicates that yield improvement is greater than the increase in crop's $ET_{green+blue}$ under climate change. The CO_2 fertilisation effect on crop yield compensates the negative impacts of the projected temperature increase on increasing crop's $ET_{green+blue}$ in the future.

For the period 2041–2070, if we assume crop production amounts do not change with respect to the base period (i.e., 10.8 million t yr^{-1} of irrigated cereal, and 4.0 million t yr^{-1} of rainfed cereal, see Table 4), total $WF_{overall}$ reduction takes place in all regions for both irrigated and rainfed cereals, because the harvested area is reduced under this assumption (since yields increase). The only exception is for the rainfed farms located within the hyper-arid and arid regions, where total $WF_{overall}$ increases under this assumption of constant production with respect to the base period (by 0.005–0.011 and 0.26–0.30 billion $m^3\ yr^{-1}$, respectively).

A plausible alternative to the assumption of constant production is the assumption of a constant harvested area with respect to the base period. Under this assumption, total cereal production may increase through yield improvement, and 27.5–29.4 and 22.1–24 billion $m^3\ yr^{-1}$ of water will, respectively, be consumed within the irrigated and rainfed croplands of cereal under future climatic scenarios. These values are, respectively, 3.3–5.2 and 3.5–5.4 billion $m^3\ yr^{-1}$ higher than water consumption within the irrigated and rainfed cereal croplands in the base period (Table 7). In this regard, the hyper-arid and arid regions will be the most vulnerable parts of the country, in which the highest total $WF_{overall}$ increase will be induced. In most cases, the increase in the yield under climate change explains higher water consumption (in $m^3\ yr^{-1}$) despite lower WFs per unit of crop production.

Population growth is the other major concern that should be considered; with the anticipated population rise of 39% in Iran, residents increase from 74 million in 2010 to about 103 million in 2055 (UN, 2019). It means that producing the same amount of cereal as the base period does not fulfill the country's food demand to nourish the increased population. Consequently, the government may plan to increase cereal production, which leads to a significant increase in the related $WF_{overall}$ and consequently, extra pressure on limited water resources. A rough estimation shows that for 2041–2070 per capita blue $WF_{overall}$ of cereal will be in the range of 152–173 m^3 cap^{-1}, depending on the RCP. It means that 4.4–5 billion m^3 more of blue water resources will be required to feed 29 million extra population in 2055.

3.4. Cereal Production Under Future Climate Scenarios and Agricultural Adaptation Strategies

We evaluated the effects of three climate change-adapted agricultural practices, including offseason cultivation, early planting and benchmarking water productivity, on the green and blue WF of cereal production under three climate change scenarios.

3.4.1. Offseason/Rainfed Cultivation

While climate change more likely reduces WF_{prod} over the period 2041–2071 (Table 7), it may have an adverse impact on blue water availability in the irrigation season (Karandish & Mousavi, 2018). Uncertain blue water availability hampers cereal production on currently irrigated croplands and reduces possibilities to increase the irrigated area to meet future cereal's water demand.

Blue water availability typically varies within a year (Mekonnen & Hoekstra, 2016). To reduce the risk of limited water availability constraining irrigation demand (or irrigation water withdrawals tapping into environmental flows), the cultivation of irrigated cereal should ideally take place in months with the highest rate of water availability. However, our monthly analysis shows that the highest water consumption of major crops in Iran occurs during summer, June-August, when blue water availability is at its lowest (Figure 5).

A potential strategy to reduce consumptive irrigation water use during blue water-scarce months in Iran could be to replace irrigated cereal production with rainfed production on the same land but in a different part of the year; the precipitation season. We assessed the effects of this strategy on crop production and WFs, as summarized in Table 8.

If only irrigated wheat is replaced with rainfed wheat, 9.2 billion m^3 yr^{-1} blue water will be saved, with 99% of this saving occurring in the hyper-arid, arid and semi-arid regions. However, this blue water saving will be at the cost of a 4.9 million t yr^{-1} production loss (65 kg cap^{-1} yr^{-1}), because yields in rainfed systems are lower than in irrigated systems. Replacing irrigated barley and maize by their counterparts may result in 3.84 billion m^3 yr^{-1} blue water saving at the cost of an overall production loss of 1.9 million t yr^{-1} (25 kg cap^{-1} yr^{-1}).

To assess the expected nutrition loss under this strategy, we considered the data reported by FAOSTAT (2013) on per capita nutrition supplied through domestically producing a unit of wheat, barley, maize and rice in terms of energy, protein and fat. Based on these data, production loss through replacing irrigated cereal with rainfed results in less supply of energy, protein, and fat within the country. Considering the population of 2010, these losses translate into 205 kcal cap^{-1} d^{-1} loss of energy, 6.17 g cap^{-1} d^{-1} loss of protein, and 1.21 g cap^{-1} d^{-1} loss of fat.

While such supply losses could be compensated by importing these crops from abroad, supplying them with domestically produced crops with the same nutrition value and less blue WF_{prod} could be a proper alternative. For instance, nutrition losses could be compensated by producing 100 kg cap^{-1} yr^{-1} of potato, which has a blue WF (m^3 t^{-1}) that is only 15% of that of irrigated cereals (Karandish & Hoekstra, 2017). This would require 21 m^3 cap^{-1} yr^{-1} of blue water (compared to 39 m^3 cap^{-1} yr^{-1} when the same nutritional value would be derived from cereals). Hence, nourishing the projected 103 million people in 2050 (UN, 2019) by producing extra potatoes may require 2.2 billion m^3 yr^{-1} extra blue water, which could be supplied by the 13 billion m^3 yr^{-1} of blue water saved under this adaptation strategy in the base period.

Also, in the future scenarios, replacing irrigated cereal production with rainfed production leads to blue water savings on the one hand, but production losses on the other hand (Table 9). If only irrigated wheat is replaced with rainfed wheat, 9.1 (under RCP2.6) to 10 (under RCP8.5) billion m^3 yr^{-1} blue water will be saved, with 99% of this saving again occurred in the hyper-arid, arid and semi-arid regions. Such blue water saving will be at the

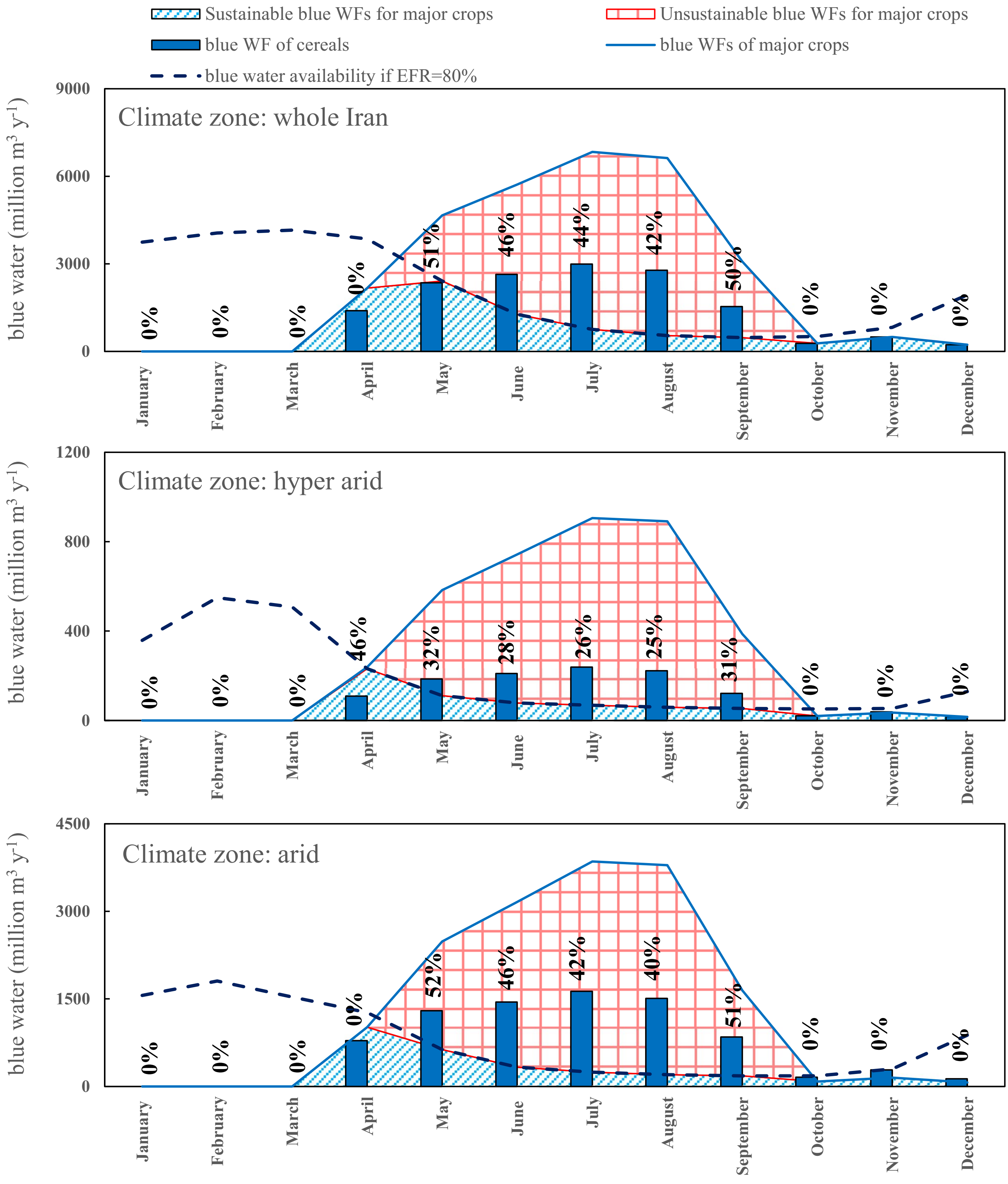

Figure 5. Monthly blue water availability along with blue WFs of 26 major crops in Iran, and blue WFs of irrigated (major) cereal. The numbers on the columns refer to the contribution of cereal in total unsustainable blue WFs. The assessment is for the climate status in the base period (1980–2010).

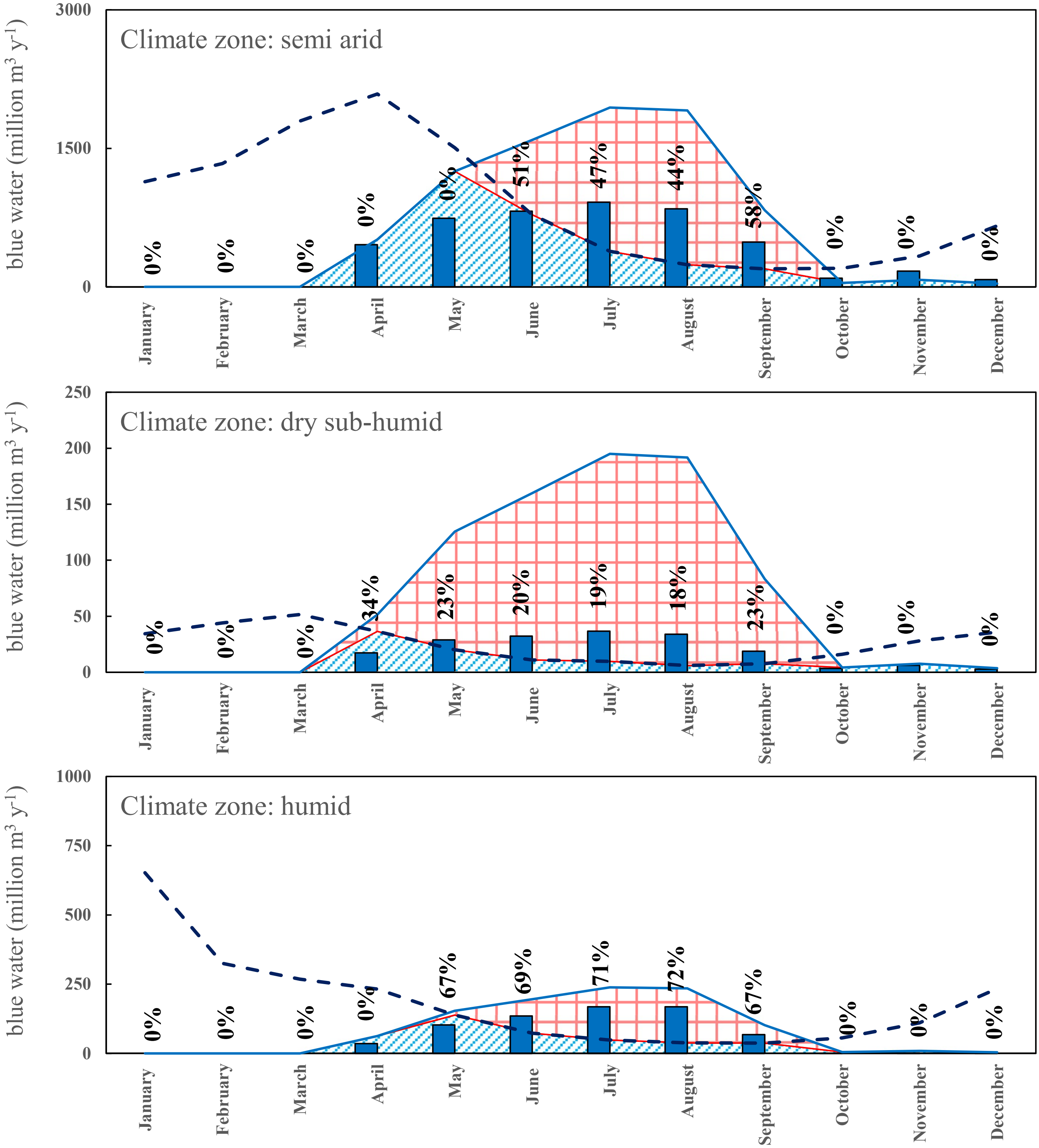

Figure 5. (Continued)

cost of a production loss up to 6.3 million t yr^{-1} (84 kg cap^{-1} yr^{-1}). Replacing irrigated barley and maize by their counterparts may add 4.6 (under RCP2.6) to 5.0 (under RCP8.5) billion m^3 yr^{-1} extra blue water saving at the cost of an overall production loss of up to 3.5 million t yr^{-1} (46 kg cap^{-1} yr^{-1}). More production loss in the future scenarios compared to the base period is attributed to improved irrigated yields under climate change.

Table 8
Absolute Changes in Annual Production, Green, Blue and Total (Green + Blue) $WF_{overall}$ of Wheat, Barley and Maize Under the Off-Season Cultivation (Rainfed-Cropping Substitution) Adaptation Strategy

Item	Climatic zone	Wheat	Barley	Maize	All three cereals[a]
Total production (1000 t yr^{-1})	Hyper-arid	−254	−51	−52	−356
	Arid	−3159	−862	−441	−4462
	Semi-arid	−1405	−336	−155	−1895
	Dry Sub-Humid	−97	−7	−5	−109
	Humid	−3	−2	−1	−5
	Iran	−4917	−1257	−654	−6828
Blue $WF_{overall}$ (billion m^3 yr^{-1})	Hyper-arid	−0.85	−0.23	−0.07	−1.15
	Arid	−5.19	−1.83	−0.54	−7.56
	Semi-arid	−3.09	−0.93	−0.22	−4.24
	Dry Sub-Humid	−0.07	−0.01	−0.01	−0.09
	Humid	0.00	0.00	0.00	0.00
	Iran	−9.20	−3.00	−0.84	−13.05
Green $WF_{overall}$ (billion m^3 yr^{-1})	Hyper-arid	0.07	0.04	0.02	0.14
	Arid	0.75	0.35	−0.06	1.04
	Semi-arid	0.77	0.23	0.14	1.13
	Dry Sub-Humid	−0.12	−0.01	0.01	−0.12
	Humid	0.00	0.00	0.00	0.00
	Iran	1.48	0.60	0.11	2.19
Total $WF_{overall}$ (billion m^3 yr^{-1})	Hyper-arid	−0.78	−0.19	−0.05	−1.01
	Arid	−4.44	−1.49	−0.60	−6.52
	Semi-arid	−2.33	−0.70	−0.08	−3.11
	Dry Sub-Humid	−0.19	−0.02	0.00	−0.21
	Humid	0.00	0.00	0.00	0.00
	Iran	−7.73	−2.40	−0.73	−10.85

Note. Period: 1980–2010.
[a]Rice is excluded here since its rainfed cropping is not feasible in Iran.

3.4.2. Early Planting

Our results indicate that early planting may improve cereal's yield by 1.4%–9.1% under climate change (Table 10). Farmers mainly adjust the agricultural calendar to climate variabilities by changing the land preparation and sowing/planting dates (Karandish, Kalanaki, & Saberali, 2017; Yegbemey et al., 2013). The sowing/planting date is considered the most important date during the cropping cycle since it determines the date of the other agricultural practices (Karandish, Kalanaki, & Saberali, 2017). Completing either a specific phenological phase or the whole cropping cycle requires a particular range of temperatures, and extremely low or high temperature causes noticeable impacts on crop's growth and yield at the end (Commuri & Jones, 2001; Kelkar & Bhadwal, 2007; Yegbemey et al., 2013). Hence, significant resources' loss could be expected if an improper sowing/planting date is selected.

Early planting will also end up with a 0.3%–17.9% decrease in crop's ET_{blue} under climate change. Such reduction is first due to avoiding extremely high temperature during the cropping cycle; and second, due to a considerable increase in the contribution of ET_{green} in total. Table 10 shows that early planting exposes a 5.6%–22.1% increase in crop's ET_{green} over the period 2041–2070.

Less ET_{blue} and $ET_{green+blue,}$ together with yield improvement, leads to a lower blue WF_{prod}, which accounted for 1.72–1.88 billion m^3 yr^{-1} decrease at the national scale. This practice thus can partially alleviate pressure on blue

Table 9
Absolute Changes in Annual Green and Blue $WF_{overall}$ of Wheat, Barley and Maize Under the Off-Season Cultivation (Rainfed-Cropping Substitution) Adaptation Strategy

Scenario	Item	Climatic zone	Wheat	Barley	Maize	All three cereals*
RCP2.6	Blue $WF_{overall}$ (billion m^3 yr^{-1})	Hyper-arid	−0.90	−0.02	−0.24	−1.16
		Arid	−5.31	−0.53	−1.88	−7.72
		Semi-arid	−2.79	−0.33	−0.84	−3.96
		Dry Sub-Humid	−0.07	−0.10	−0.01	−0.17
		Humid	0.00	−0.65	0.00	−0.65
		Iran	−9.07	−1.62	−2.97	−13.66
	Green $WF_{overall}$ (billion m^3 yr^{-1})	Hyper-arid	0.10	0.00	0.05	0.14
		Arid	1.14	−0.04	0.49	1.59
		Semi-arid	0.90	−0.05	0.26	1.11
		Dry Sub-Humid	−0.12	−0.02	−0.01	−0.15
		Humid	0.00	−0.47	0.00	−0.47
		Iran	2.02	−0.59	0.80	2.23
RCP4.5	Blue $WF_{overall}$ (billion m^3 yr^{-1})	Hyper-arid	−0.91	−0.02	−0.25	−1.17
		Arid	−5.50	−0.55	−1.94	−7.99
		Semi-arid	−2.88	−0.34	−0.86	−4.08
		Dry Sub-Humid	−0.07	−0.10	−0.01	−0.18
		Humid	0.00	−0.68	0.00	−0.68
		Iran	−9.35	−1.68	−3.06	−14.09
	Green $WF_{overall}$ (billion m^3 yr^{-1})	Hyper-arid	0.09	0.00	0.05	0.13
		Arid	0.95	−0.04	0.42	1.33
		Semi-arid	0.81	−0.05	0.24	1.00
		Dry Sub-Humid	−0.12	−0.02	−0.01	−0.15
		Humid	0.00	−0.47	0.00	−0.47
		Iran	1.73	−0.58	0.70	1.84
RCP8.5	Blue $WF_{overall}$ (billion m^3 yr^{-1})	Hyper-arid	−1.06	−0.02	−0.29	−1.37
		Arid	−5.92	−0.59	−2.09	−8.61
		Semi-arid	−2.95	−0.34	−0.88	−4.17
		Dry Sub-Humid	−0.07	−0.10	−0.01	−0.19
		Humid	0.00	−0.67	0.00	−0.68
		Iran	−10.00	−1.73	−3.27	−15.01
	Green $WF_{overall}$ (billion m^3 yr^{-1})	Hyper-arid	0.10	0.00	0.05	0.15
		Arid	1.01	−0.04	0.45	1.41
		Semi-arid	0.85	−0.05	0.25	1.05
		Dry Sub-Humid	−0.13	−0.02	−0.01	−0.16
		Humid	0.00	−0.50	0.00	−0.49
		Iran	1.83	−0.61	0.74	1.95

Note. Period: 2041–2070.

water resources in the future. Besides, efficient use of green water resources can be achieved by reducing the total (green + blue) WF_{prod}; accounted for 0.63–0.82 billion m^3 yr^{-1} decrease at the national scale. Such a result is also expected at the regional scale; the only exception is in the dry sub-humid region, where early planting reduces green water footprint (m^3 yr^{-1}) by 0.7%–3.2%.

Table 10
Relative Changes in Crop Yield, Consumptive Green Water Use (ET_{green}), Consumptive Irrigation Water Use (ET_{blue}), Green, Blue and Total (Green + Blue) Water Footprint per Unit of the Crop (WF_{prod}) Under the Early Planting Adaptation Strategy Compared to Normal Planting in Period 2041–2070

Item[a]	Scenario	Hyper-arid	Arid	Semi-arid	Dry sub-humid	Humid	Iran
Yield (%)	RCP2.6	3.6	3.1	1.8	9.1	4.7	3.1
	RCP4.5	3.6	2.7	2.3	1.4	4.4	2.8
	RCP8.5	3.3	2.6	2.3	6.6	5.0	2.9
ET_{green} (%)	RCP2.6	7.9	14.9	22.1	5.6	7.9	15.6
	RCP4.5	7.3	14.1	15.3	−1.5	6.0	12.4
	RCP8.5	7.7	13.9	14.7	5.9	6.0	12.6
ET_{blue} (%)	RCP2.6	−2.1	−3.9	−4.2	−17.9	−2.3	−4.0
	RCP4.5	−2.6	−4.0	−4.1	−5.0	−0.9	−3.7
	RCP8.5	−2.8	−4.6	−4.0	−17.7	−0.3	−4.3
Green WF_{prod} (billion m^3 yr^{-1})	RCP2.6	0.02	0.58	0.64	−0.01	0.01	1.25
	RCP4.5	0.02	0.56	0.40	−0.01	0.01	0.99
	RCP8.5	0.02	0.56	0.39	0.00	0.00	0.98
Blue WF_{prod} (billion m^3 yr^{-1})	RCP2.6	−0.08	−1.06	−0.65	−0.04	−0.04	−1.88
	RCP4.5	−0.09	−1.03	−0.57	0.01	−0.03	−1.72
	RCP8.5	−0.09	−1.06	−0.56	−0.04	−0.03	−1.79
Total (green + blue) WF_{prod}(billion m^3 yr^{-1})	RCP2.6	−0.06	−0.48	−0.01	−0.05	−0.03	−0.63
	RCP4.5	−0.07	−0.47	−0.17	0.00	−0.02	−0.73
	RCP8.5	−0.07	−0.50	−0.17	−0.04	−0.03	−0.81

[a]Negative signs denote decrease and positive signs denotes increase in the considered parameter.

3.4.3. Benchmarking

3.4.3.1. WF Benchmarking: Option 1

The influence of WF benchmarking based on spatial differences in achieved WFs on the potential green, blue and total (green + blue) water saving in different climatic zones of the study area has been investigated (Table 11).

Table 11
Absolute Changes in Green, Blue and Total Water Consumption ($WF_{overall}$, Billion m^3 yr^{-1}) When Water Footprints Are Reduced to Benchmarks Values According to Option 1 (Benchmark Set by Top-25% Most Efficient Producers per Climate Zone) for the Base Period (1980–2010) and Different RCPs Across Mid-21st Century (2041–2070)

Item	Scenario	Hyper-arid	Arid	Semi-arid	Dry sub-humid	Humid	Iran
Green $WF_{overall}$ (billion m^3 yr^{-1})	Base	−0.08	−0.38	−0.12	−0.04	−0.01	−0.63
	RCP2.6	−0.07	−0.33	−0.14	−0.03	−0.01	−0.59
	RCP4.5	−0.08	−0.30	−0.11	−0.03	−0.01	−0.53
	RCP8.5	−0.08	−0.29	−0.13	−0.03	−0.01	−0.54
Blue $WF_{overall}$ (billion m^3 yr^{-1})	Base	−0.28	−2.36	−1.28	−0.02	−0.10	−4.04
	RCP2.6	−0.23	−1.86	−0.91	−0.02	−0.08	−3.09
	RCP4.5	−0.24	−1.99	−0.94	−0.02	−0.08	−3.26
	RCP8.5	−0.28	−2.15	−0.99	−0.02	−0.08	−3.52
Total $WF_{overall}$ (billion m^3 yr^{-1})	Base	−0.36	−2.73	−1.40	−0.06	−0.11	−4.66
	RCP2.6	−0.31	−2.19	−1.05	−0.05	−0.09	−3.68
	RCP4.5	−0.32	−2.29	−1.05	−0.05	−0.09	−3.79
	RCP8.5	−0.36	−2.43	−1.12	−0.05	−0.09	−4.06

Table 12
Absolute Changes in Annual Blue Water Footprint (WF), Green WF and Total WF of Cereal Production (Billion m^3 yr^{-1}) When Water Footprints Are Reduced to Benchmarks Values According to Option 2 (10% Yield Improvement Compared to Baseline) for the Base Period (1980–2010) and Different RCPs Across Mid-21st Century (2041–2070)

Item	Scenario	Hyper-arid	Arid	Semi-arid	Dry sub-humid	Humid	Iran
Green $WF_{overall}$ (billion m^3 yr^{-1})	Base	−0.06	−0.08	−0.10	−0.07	−0.04	−0.35
	RCP2.6	−0.12	−0.22	−0.30	−0.22	−0.13	−0.98
	RCP4.5	−0.11	−0.22	−0.33	−0.22	−0.13	−1.00
	RCP8.5	−0.09	−0.19	−0.26	−0.17	−0.10	−0.83
Blue $WF_{overall}$ (billion m^3 yr^{-1})	Base	−0.20	−0.12	−0.14	−0.04	−0.06	−0.57
	RCP2.6	−0.52	−0.39	−0.56	−0.13	−0.20	−1.80
	RCP4.5	−0.47	−0.32	−0.53	−0.13	−0.18	−1.62
	RCP8.5	−0.15	−0.24	−0.47	−0.09	−0.17	−1.12
Total $WF_{overall}$ (billion m^3 yr^{-1})	Base	−0.25	−0.20	−0.25	−0.12	−0.10	−0.92
	RCP2.6	−0.64	−0.60	−0.86	−0.35	−0.33	−2.78
	RCP4.5	−0.57	−0.53	−0.86	−0.35	−0.31	−2.62
	RCP8.5	−0.24	−0.43	−0.74	−0.27	−0.27	−1.94

We learned, during the base period, reducing irrigated cereal's WF_{prod} to their 25th percentile benchmark levels saves blue water in cereal production, in particular, 2.63 billion m^3 yr^{-1} in wheat, 0.88 billion m^3 yr^{-1} in barley, 0.3 billion m^3 yr^{-1} in rice, and 0.22 billion m^3 yr^{-1} in maize. Under this benchmarking option, we expect considerable savings in blue water within the arid (2.36 billion m^3 yr^{-1}) and semi-arid (1.28 billion m^3 yr^{-1}) regions, for the base period.

Over the period 2041–2070, benchmarking option 1 can save blue water at the national scale by 3.09 billion m^3 yr^{-1}, 3.26 billion m^3 yr^{-1}, and 3.52 billion m^3 yr^{-1} under RCP2.6, RCP4.5 and RCP8.5. The greatest blue water saving will occur for irrigated wheat within the arid and semi-arid regions.

These results show that achieving the benchmark levels can help overcome the societal challenge of meeting food demands in the future, particularly where water scarcity is amongst the main obstacles. However, it is essential to differentiate between the benchmark levels for different climatic zones since the environmental condition is reported to highly affect the minimum attainable WFs per unit of crop production (Karandish et al., 2018; Vanham & Mekonnen, 2021; Zhuo, Mekonnen, Hoekstra, & Wada, 2016). The WF is determined by the crop's yield and ET, both of which are partly controlled by the given climatic condition. The drier and the warmer the weather is, the higher the potential ET and the crop water demand are. The positive correlation between potential ET and crop's WF is also reported by earlier researchers (Zhuo et al., 2014; Zhuo, Mekonnen, Hoekstra, & Wada, 2016; Zwart et al., 2010). Besides, the maximum attainable yield, which also strongly affects the crop's consumptive WF (Mekonnen & Hoekstra, 2011; Tuninetti et al., 2015), is an agroclimatic variable that varies between the different climatic zones.

3.4.3.2. WF Benchmarking: Option 2

While the given environmental conditions affect the crop's consumptive WF, managerial factors also determine it. A crop's yield affects a crop's $WF_{prod,}$ and therefore, yield improvement could be considered as a managerial solution to achieve the benchmark levels of crop WF_{prod}. Cereal's yield in Iran is much below global-average yields for the same crops. For instance, the national average of wheat's yield in Iran is about 2.9 t ha^{-1} (IMAJ, 2019), while the global average is 3.27 t ha^{-1} (FAO, 2013) –, which indicates the potential for yield improvement by adopting better technologies and field practices similar to those adopted by countries with comparable environmental and climatic conditions. We assume that a 10% increase in cereal yield in Iran is possible and evaluated the effects of this on green and blue water savings under current and future climate. Table 12 demonstrates the impact of 10% yield improvement on annual blue water footprint (WF), green WF and total WF of cereal production.

The impact of yield improvement on blue water saving is more noticeable in irrigated cereal production, in particular, 0.92 billion $m^3 yr^{-1}$ in wheat, 0.3 billion $m^3 yr^{-1}$ in barley, 0.17 billion $m^3 yr^{-1}$ in rice, and 0.084 billion $m^3 yr^{-1}$ in maize. The total of 0.47 billion $m^3 yr^{-1}$ of the overall blue water saving (0.55 billion $m^3 yr^{-1}$) will occur within the arid and semi-arid regions (0.3 billion $m^3 yr^{-1}$ and 0.17 billion $m^3 yr^{-1}$, respectively).

Yield improvement is possible through improving field management practices such as precision irrigation (no water stress), soil management practices or precision fertilization (Karandish & Hoekstra, 2017). In addition, a proactive institutional attempt is required to inform local farmers of the short and long-term effects of climate change and train and support them to employ up-to-date knowledge and technology and facilitate their preparations through climate change adaptation and mitigation strategies. Abid et al. (2016) demonstrated that farmers might adapt better to climate change if they have more farming experience, education and more land under cultivation. Whereas, low educated farmers, those who have a higher dependency of their household on agriculture, have more difficulties in adapting to climate change (Bastakoti et al., 2014; Bryan et al., 2013).

Besides yield improvement, some other managerial activities can help achieve the WFs benchmark levels by improving crop's water productivity. These managerial activities include modifying cropping patterns, improving field practices (i.e., mulching, improving soil fertility, weed control, protecting crops from diseases and pests, etc.) and/or applying more efficient irrigation strategies (i.e., deficit irrigation, partial root-zone drying, or pressurized irrigation).

3.5. The Effects of Agricultural Adaptation Strategies on Provincial Blue Water Scarcity

Monthly variations of local blue water availability, blue water scarcity, and sustainable/unsustainable blue water consumption of Iran's major cereals have been assessed. The spatial distribution of provincial BWS values under the different adaptation strategies are presented in Figure 6. According to the annual assessment, 21.5 billion $m^3 yr^{-1}$ unsustainable blue water was consumed to produce the major crops in Iran, 45% (9.7 billion $m^3 yr^{-1}$) of which was related to irrigated cereals. Wheat is the major contributor (63%) to the cereal's total unsustainable blue water consumption. The contribution of irrigated cereals in the unsustainable blue water consumption in different climate zones varies from largest in arid and semi-arid regions (62% and 23%, respectively) to smallest in hyper-arid, humid and dry sub-humid regions (9%, 4%1%, respectively).

Monthly assessment reveals that the summer period (June-August) consistently had the highest contribution in the regional unsustainable blue water consumption for all climatic regions. On a national scale, May-September months are labelled as hotspot months due to a BWS > 1. The annual provincial BWS values vary in the range of 0.2–6 in the country, with 20 out of 30 provinces with a BWS > 1. The national average BWS of 1.22 denotes a moderate blue water scarcity under current agricultural practices in Iran. Detailed results show that six provinces experience moderate, five provinces experience significant, and nine provinces experience severe blue water scarcity.

The investigated agricultural adaptation practices (Section 3.3) can reduce unsustainable blue water consumption in the study area (Figure 6). In the case of off-season cultivation, in which irrigated cereal is substituted by rainfed cereal, the blue component of the cereal's WF will be fully eliminated, which results in a 43% reduction in annual unsustainable blue water consumption through crop production in Iran. This will reduce provincial BWS values to 0.1–3.7. The national annual BWS will decrease by 50% to 0.63, indicating no blue water scarcity at this coarse aggregation scale. In addition, the number of hotspot provinces with BWS > 1 will reduce from 20 to 12 provinces; particularly, the number of provinces with severe and significant scarcity will reduce from 9 and 5 to 1 and 3, respectively. On the monthly scale, reduced unsustainable blue water consumption in May will reduce its BWS by 50% to 0.9, which makes this month no longer a hotspot. Nevertheless, June to September will remain hotspot months, although experiencing a considerable reduction of 42%–50% in their BWS values.

Under early planting, unsustainable blue water consumption of cereal will reduce by 8% to 8.9 billion $m^3 yr^{-1}$. While such reduction results in a 0.7%–5.7% reduction in the annual provincial BWS values, it does not change either number of hotspots with BWS > 1 or the scarcity classes of these hotspots. Besides, May-September will still experience significant blue water scarcity in the study area.

WF benchmarking option 1 ranked second in terms of its considerable effect on reducing the blue water scarcity in the study area. Such benchmarking reduces cereal's annual unsustainable blue water consumption by

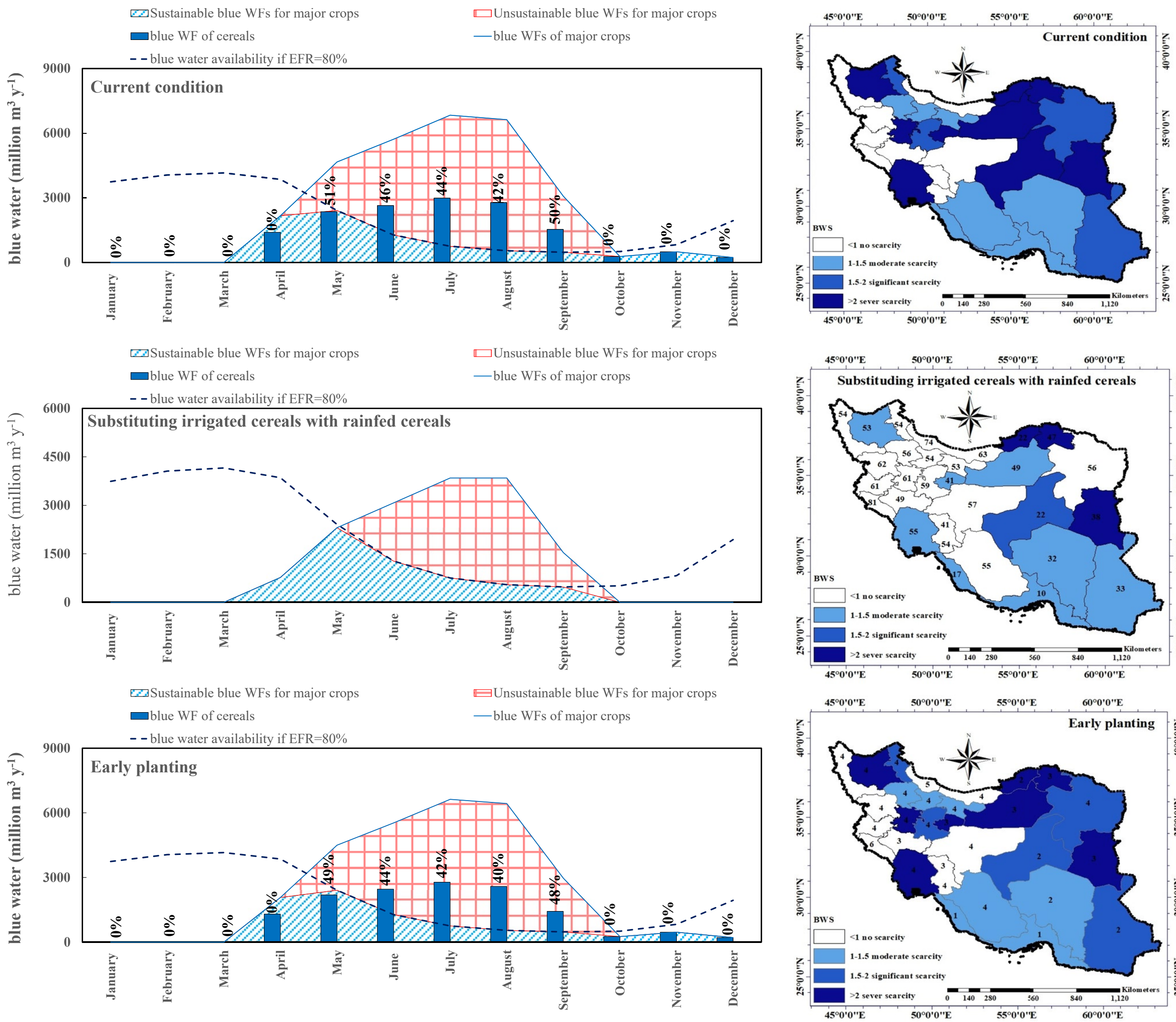

Figure 6. Monthly blue water availability, along with blue WFs of 26 major crops grown in Iran, and blue WFs of irrigated cereal (left), and provincial blue water scarcity (BWS) (right), under current agricultural practice and the adapted practices reducing blue water consumption. The numbers on the columns refer to the contribution of cereal in total unsustainable blue WFs, and the numbers in the BWS maps refer to the relative reduction in provincial BWS values under different scenarios. The assessment is for the climate status in the base period (1980–2010).

30%, which results in an 11%–28% reduction in monthly national BWS values, and a 2%–23% reduction in annual provincial BWS values. While one province (Qazvin in the SA region) will be excluded from hotspots, the number of hotspot months do not change. However, the country as a whole will remain as a moderate blue water-scarce region (BWS = 1.06) with a slight reduction of 13% in its BWS.

WF benchmarking option 2 (yield improvement) results in an 11% reduction in unsustainable blue water consumption of cereal and changes it to 8.6 billion m^3 yr^{-1}; which consequently leads to 1%–8% reduction in annual provincial BWS values. This means a 5% reduction in the annual national BWS (i.e., the ration of annual total blue WF to total water availability). However, this strategy is not strong enough to change the scarcity classes of hotspot provinces or months. Besides, the whole country will remain a moderately water-scarce country with an annual national BWS of 1.17.

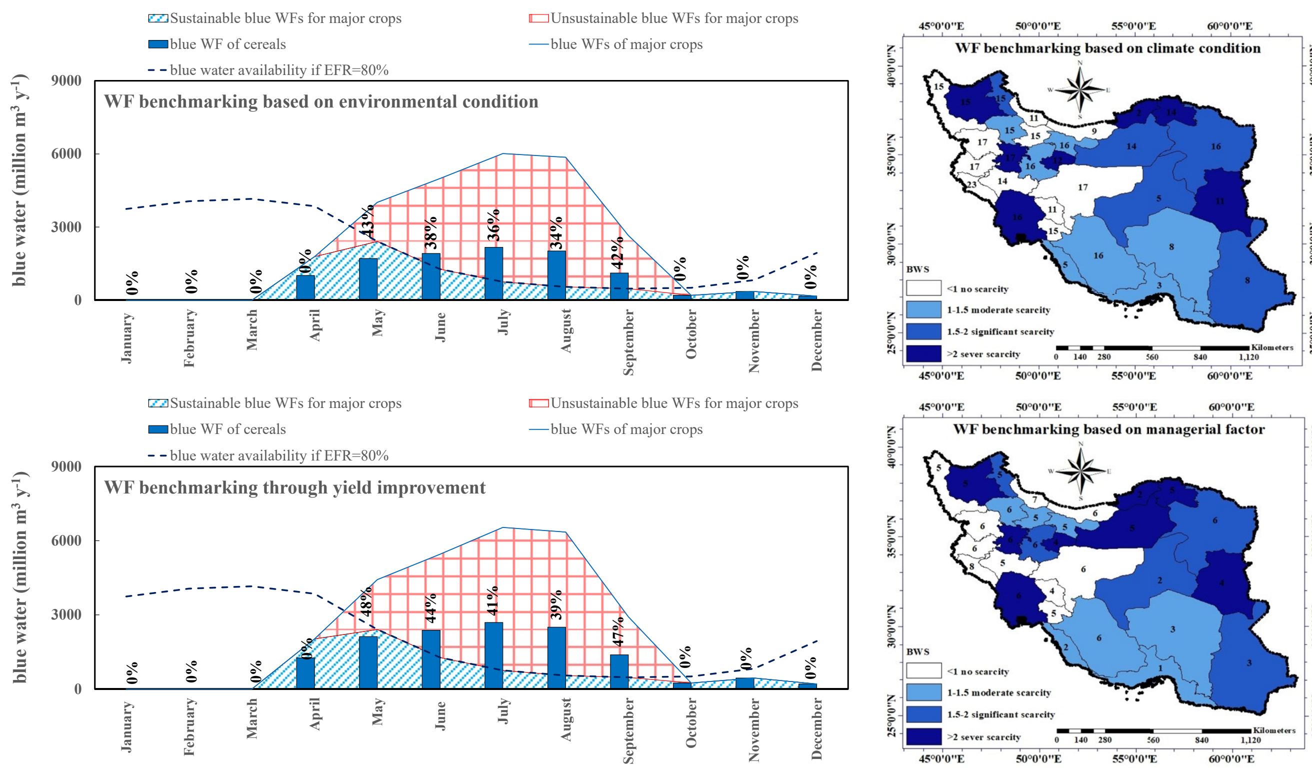

Figure 6. (Continued)

The general overview of projected changes in regional BWS values and the number of hotspot provinces/months is presented in Table 13. It shows that substituting irrigated cereals by their rainfed counterparts (off-season cultivation) has the largest effect on reducing BWS and the number of hotspots (provinces/months). However, even this solution may still hold considerable unsustainable blue water consumption in different regions, particularly during the dry months of June-August. This is mainly caused by irrigating other crops rather than cereal, particularly in the hyper-arid and dry sub-humid regions. In the hyper-arid region, nuts production contributes largely to blue water consumption (Karandish & Hoekstra, 2017). In a similar situation in the dry sub-humid region, irrigated rice has a noticeable contribution (29%) to cereal's total blue water consumption. While substituting

Table 13

Projected Changes in the Annual Blue Water Scarcity (BWS) Values and the Number of Hotspots (Provinces/Months in Which BWS > 1) Per Climatic Region Under Different Adaptation Strategies for the Base Period

Scenario	Relative change to annual BWS (%)					Absoulute change to the number of hotspots *					
						hotspot provinces					hotspot months
	HA	A	SA	DSH	H	HA	A	SA	DSH	H	
Substituding irrigated cereals with rainfed	-31	-50	-56	-22	-68	0	3	4	0	-	1
Off-season cultivation	-2	-3	-4	-2	-5	0	0	0	0	-	0
WF benchmarking option 1	-7	-15	-16	-2	-10	0	0	0	0	-	0
WF benchmarking option 2	-3	-5	-6	-2	-7	0	0	1	0	-	0

* hotspots denotes either provinces ot months with BWS>1

Legend

Relative reduction to BWS (%)		Absolue reduction to hotspots	
0	0%	0	0
	0-10%		1
	11-30%		2
	31-50%		3
	>50%		4

Note. HA = Hyper-arid; A = Arid; SA = Semi-Arid; DSH = Dry Sub-Humid; H = Humid.

irrigated rice with rainfed rice is not feasible, a reassessment is needed to evaluate the suitability of irrigated rice production in this climate zone.

3.6. Challenges and Opportunities for Adaptation Strategies in Iran

Rainfed cropping is possible in most provinces of Iran, particularly those located in the north, north-west and west of the country. Based on the aridity and green water deficit indices, the northern provinces remain the most suitable places for dry-farming under future climate as well (Shahsavari et al., 2019). Nevertheless, most of these lands are currently irrigated (Karandish & Hoekstra, 2017). Irrigated rice-farming, the dominant local activity in northern Iran, is the main contributor to the large blue water demand and severe blue water scarcity there, although the province has benefited from the highest contribution of national annual precipitation (Karandish, 2021). However, Haghnazari et al. (2020) demonstrated that addressing waterlogging issues in northern Iran during wet seasons can provide opportunities for rainfed cropping, which prosper farmers' livelihood. For another instance, lack of rainwater harvesting activities resulted in rapid development of irrigated fruit-trees cultivation on steep lands instead of rainfed-wheat, which intensified soil erosion in the western provinces (Mesgaran et al., 2017). These examples demonstrate that crop cultivation under rainfed or supplementally irrigated conditions can be a viable alternative to fully irrigated crops that currently put severe pressure on Iran's blue water resources, but long-terms plans are needed to support farmers in such a transitions. These long-term plans may include but are not restricted to, modifying agricultural practices (i.e., cultivating drought-tolerant seeds, modifying the rate, type and timing of fertilizer and pesticide application, proper land preparations, etc.), and developing water harvesting activities for supplemental irrigation in these lands (Karandish et al., 2021).

Achieving benchmark levels could be another part of the solution to save blue water. This requires a substantial change in current farming and water management practices in the study area. In this regard, yield gap closure is one of the most important opportunities (Rosa et al., 2018). Karandish et al. (2020) reported up to 8.3 t ha^{-1} gap between cereal's yield in different provinces and their climate-specific attainable levels in Iran. While such a gap could be filled through expanding irrigated lands, it is not advised since it entails extra blue water consumption. However, technology and agricultural practices improvement, and crop traits modification, are among methods that address yield gaps without increasing irrigation water needs. For instance, transitioning toward pressurized irrigation, modifying cropping calendar and tillage practices, cultivating new traits or genetics, improving farming practices like fertilizations and pest and weed control have considerable potentials to fill this yield gap (Chukalla et al., 2015; Darzi-Naftchali & Karandish, 2019; Karandish,2021; Mueller et al., 2012; Sinclair & Rufty, 2012). Knowledge gap and lack of financial means are among the main reasons for not exploiting these potentials. Hence, Iran could invest in training farmers on how to be climate-resilient and find new opportunities for resource mobilizations to implement such strategies.

While the adaptation strategies can achieve blue water savings, the risk of the rebound effect is present when saved water is applied for expanding irrigated croplands. Therefore, regulations are required to avoid temporary beneficial implementations with long-term non-reversible damages. Each of these individual possibilities or a combination of them can alleviate the blue water scarcity and increase the success chance of adaptation strategies. However, further studies are required to assess the feasibility and the impact of combined strategies.

3.7. Limitations and Shortcoming

The impacts of agricultural adaptation strategies on provincial BWS have only been assessed for the base period due to the unavailability of data on future BWA. Our results thus indicate the extent to which different adaptations can reduce BWS across Iran, but future research can give more detailed insight by estimating the effects under future climate scenarios as well. Indeed, water stress might be intensified if climate change projects a significant reduction in BWA during the dry periods, but the opposite might occur as well. Such an assessment requires that future BWA is simulated with hydrological models forced by the weather variables of future climate projections.

Our study lacks disaggregation of BWS by water sources due to data limitations. While closely linked with surface water, groundwater acts considerably different from the other hydrological components in its flux, storage, and residence time (Aeschbach-Hertig & Gleeson, 2012). Hence, Vanham et al. (2018) recommend to separately address the degree of groundwater scarcity in addition to addressing BWS considering the sum of water use from renewable surface and groundwater resources, as done in the current study. While our estimated BWS shows how the sum of surface and groundwater footprints compares to total runoff (incl. the baseflow of groundwater to rivers), it masks that BWS can be larger for certain groundwater stocks, particularly those with limited interactions with surface waters. Therefore, future research could address BWS for groundwater bodies separately to get a more detailed picture of water scarcity in Iran.

4. Conclusion

We evaluated the impacts of climate change on cereals' production and water consumption for Iran and assessed alternative agricultural strategies to adapt to climate change. We found that although cereal yields increase under climate change, the annual consumptive water use ($m^3\ yr^{-1}$) will increase if the current cropland area remains the same or expands to produce more food for the growing population. This explains why agricultural adaptation strategies are needed to alleviate additional pressure on already scarce water resources. We assessed blue water saving possibilities through three climate change adaptation strategies in cereal production: (i) off-season cultivation, that is, replacing irrigated cereal production in dry seasons by rainfed production in wet seasons, (ii) early planting, (iii) and WF benchmarking. All strategies had substantial positive impacts on blue water savings nationwide 5. Off-season cultivation is the most effective, with blue water savings of 14–15 billion $m^3\ yr^{-1}$, depending on the climate change scenario. However, these blue water savings are accompanied by production losses (due to the lower productivity in rainfed compared to irrigated systems), such that the net effects of this strategy are smaller, when these losses are compensated by increases in the irrigated area (of substitutable crops) instead of food import (or reduced consumption). The second most effective is WF benchmarking, which results in blue water savings of 1.1–3.5 billion $m^3\ yr^{-1}$, depending on the climate change scenario and the definition of the benchmark. The early planting approach is less effective but still leads to blue water savings of 1.7–1.9 billion $m^3\ yr^{-1}$, depending on the climate change scenario. In the same order of effectiveness, these three strategies can reduce current blue water scarcity and unsustainable blue water use in Iran. However, we find that these strategies do not mitigate water scarcity in all provinces per se, nor all months of the year. Besides, the magnitude of challenges in terms of applicability and feasibility of the adaptation strategies have not been assessed in this study (e.g., availability of fertile soil, competition between water users, farmer willingness to change practices, etc.). Thus, introducing effective and feasible climate change adaptation strategies to reconcile food security and sustainable water use throughout the country remains a topic of further research.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data supporting this work is available from Zenodo Digital Repository; DOI to this data repository is "https://doi.org/10.5281/zenodo.5572767".

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