Agricultural adaptation to reconcile food security and water sustainability under climate change: the case of cereals in Iran

Fatemeh Karandish[1*], Hamideh Nouri[2], Joep F. Schyns[1]

[1] Multidisciplinary Water Management, Faculty of Engineering Technology, University of Twente, P.O. Box 217, 7500 AE Enschede, Netherlands
[2] Division of Agronomy, University of Göttingen, Von-Siebold-Strasse 8, 37075, Göttingen, Germany
* Corresponding author, Email: f.karandish@utwente.nl

Abstract

Reconciling food security and water sustainability is a major challenge in water-limited countries like Iran, which are facing rapid population growth, changing diets, and limited arable land besides erratic water availability. The uncertain effects of climate change on the production and associated water use of food crops in these countries often complicates food-water reconciliation challenges. In this study, we simulate the crop yield and water footprint (WF) of major food crops of Iran, wheat, barley, rice, and maize, on irrigated and rainfed croplands for all provinces. We do this for the historical (1980-2010) and the future (2041-2070) climate under three climate change scenarios, RCP2.6, RCP4.5 and RCP8.5. Then, we assess the effects of three agricultural adaptation strategies to climate change in terms of potential blue water savings and the degree to which these savings reduce unsustainable blue water consumption (i.e. in provinces or months where the total blue WF exceeds the maximum sustainable level for that location and month). These three adaptation strategies are (i) off-season cultivation, i.e. replacing irrigated cereal production in the dry part of the year by rainfed production in the wet part of the year, (ii) early planting, and (iii) benchmarking the WF of cereals. 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 y^{-1}, respectively) as a result of increased yields (6.6%-78.7%). Simultaneously, the WF per unit of crop (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 y^{-1}, respectively). This is most noticeable in the arid regions, where consumptive water use increases by roughly 70% under climate change. To alleviate additional pressure on blue water resources, off-season cultivation is the most effective adaptation strategy with blue water savings of 14-15 billion m^3 y^{-1}, depending on the climate change scenario. However, this strategy is accompanied by significant production losses, which – when compensated by increased irrigated area – reduces net blue water savings. Second most effective is WF benchmarking which results in

blue water savings of 1.1-3.5 billion m^3 y^{-1}, depending on the climate change scenario and the definition of the benchmark level. The early planting strategy is less effective, but still leads to blue water savings of 1.7-1.9 billion m^3 y^{-1}, depending on the climate change scenario. In the same order of effectiveness, these three strategies can reduce blue water scarcity and unsustainable blue water use in Iran under current condtions. However, we find that these strategies do not mitigate water scarcity in all provinces per se, nor in all months of the year. Further research is required to find adapation strategies to reconcile food security and sustainable water use throughout the country, with consideration of socio-economic impacts as well.

Keywords: water scarcity; food security; climate change; climate adaptation; water productivity; water footprint

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 (Torero, 2020, Galanakis, 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 (Nouri et al., 2020, Hameed et al., 2019; Nouri et al., 2019; Blatchford et al., 2018). 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 and Hoekstra, 2017; Madani, 2014). Water scarcity and over-abstraction of water for irrigation purposes occur in most provinces (Faramarzi et al., 2010; Karandish and Hoekstra, 2017). A recent study claimed that sacrificing a degree of self-sufficiency is a must to minimize 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 eighty million people. Several studies evaluated the effects of climate change on crop yields (t/ha) and crop water footprints (WF) (m^3/ha and/or m^3/t) and reported different, and sometimes controversial, outcomes, in size and direction of the effects (Tubiello et al., 2000; Bocchiola et al., 2013; Moradi et al., 2013; Zhuo et al., 2016a; Araya et al., 2017; Karandish et al., 2017ab; Shrestha et al., 2017; Masud et al., 2018; Darzi-Naftchali and Karandish, 2019; Arunrat et al., 2020; Zheng et al., 2020). 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 et al., 2017a; Karandish and Mousavi, 2018; Paymard et al., 2019). A net effect of these effects is an increase in the green water deficit - the difference between potential evapotranspiration and precipitation - mostly in the growing seasons of irrigated crops in the semi-arid zone (Karandish and Mousavi 2018), which accounts for a considerable share of Iran's agricultural production (~25%) (Karandish and 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 et al. 2017a). However, the effect of elevated CO_2 levels on simulated yields and adaptation scenarios on WFs were left out of this study. 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 (Yang et al., 2019; Rezaei 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 (Moradi et al., 2013; Karandish et al., 2017b) and Kansas, US (Araya et al., 2017), rice production in Iran (Darzi-Naftchali and Karandish, 2019) and Thailand (Arunrat et al., 2020) and several crops in Italy (Tubiello, 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 (Schyns and Hoekstra, 2014; Nouri et al., 2019a; Karandish and Hoekstra, 2017). 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 (Karandish et al., 2018; Chukala et al., 2017; Zhuo et al., 2016c; Mekonnen and Hoekstra, 2014; Schyns and Hoekstra, 2014; Brauman et al., 2013; Mekonnen and Hoekstra, 2011; 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.

In this study, we assess the effects of the latest IPCC scenarios on crop yields and WFs, complementing earlier studies using previous IPCC scenarios (Karandish et al. 2017ab; Karandish and Mousavi, 2018; Darzi-Naftchali and Karandish, 2019). We select major cereal crops in Iran – wheat, barley, maize, rice (rainfed and irrigated) to generate a more comprehensive understanding of the national food security challenges than the available literature. Previous crop water productivity studies that focused on Iran either a- studied only one crop (Moradi et al., 2013; Darzi-Naftchali and Karandish, 2019; Paymard et al., 2019); b- did not distinguish between individual cereal crops (Karandish et al. 2017a); c- studied only rainfed cereal (Paymard et al., 2019); or d- studied only irrigated crops (Moradi et al., 2013; Karandish et al. 2017ab; Darzi-Naftchali and Karandish, 2019). This study includes the four major food crops of Iran 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 provides an opportunity for water managers 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 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 an annual precipitation of 228 mm y^{-1} and internal renewable freshwater resources of 129×10^{9} m^3 y^{-1} (AQUASTAT, 2020). Over the past 20 years, the per capita water availability has declined from 2194 m^3 cap^{-1} y^{-1} to 1700 m^3 cap^{-1} y^{-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 rainfed. Together, the four crops contribute to about half of the domestic food supply (in calories) of Iran (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 as is illustrated in Fig. 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 (Fig. 1), of which arid and semi-arid are prevailing (Karandish et al., 2017a). 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).

Insert Fig. 1.

Insert Fig. 2.

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 which is supplied from the surface and/or groundwater resources (Karandish and 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:

$$S_{[t]} = S_{[t-1]} + P_{[t]} + I_{[t]} + CR_{[t]} - ET_{[t]} - RO_{[t]} - DP_{[t]} \qquad (1)$$

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 day^{-1}. Following Karandish and Hoekstra (2017a), 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 assumed to be deeper than one meter below the rooting zone all over Iran. 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 et al. (2016b), green soil water content (S_{green}) and blue soil water content (S_{blue}) were calculated as:

$$S_{¿[t]} = S_{¿[t-1]} + P_{[t]} - RO_{[t]} \times \frac{P_{[t]}}{P_{[t]} + I_{[t]}} - \left(DP_{[t]} + ET_{[t]}\right) \times \frac{S_{¿[t-1]}}{S_{[t-1]}} \tag{2}$$

$$S_{¿[t]} = S_{¿[t-1]} + I_{[t]} - RO_{[t]} \times \frac{I_{[t]}}{P_{[t]} + I_{[t]}} - \left(DP_{[t]} + ET_{[t]}\right) \times \frac{S_{¿[t-1]}}{S_{[t-1]}} \tag{3}$$

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

2.3. 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 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, which are 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 two 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 (Zwart et al., 2010; Mekonnen and Hoekstra, 2011; Brauman et al., 2013; Zhuo et al., 2016b). 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 conditions and managerial factors (Hoekstra, 2014, 2013). 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 and Hoekstra, 2014; Zhuo et al., 2016c). 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). 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.

2.4. 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 do this analysis for the base period only.

Per province, monthly local blue water availability was calculated as the local annual natural runoff minus environmental flow requirements (Hoekstra et al., 2011). Data on monthly natural runoff at the province scale 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 and 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. A month/province with $BWS > 1$ is therefore considered an 'environmental hotspot' and any blue WF there as 'unsustainable'. In such a month/province, 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.

2.5. Data

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 Fig 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 twenty General Circulation Models described in the Coupled Model Intercom-parison Project, Phase 5 (Miao et al., 2014) for three different Representative Concentration Pathways (RCPs): RCP2.6, RCP4.5 and RCP8.5. 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 towards 2100. In RCP8.5, which indicates the most extreme climate-change scenario, the emissions follow a consistently increasing trend throughout the 21st century.

3. Results and Discussion

We assess the cereal production and the associated WFs under current (section 3.1) and future (section 3.2) climate. Subsequently (section 3.3), we assess three agricultural adaptation strategies in response to the estimated climate change impacts on cereal production and WFs.

3.1. Cereal production under current climate and agricultural practices

3.1.1. Cereal production

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

Fig. 2 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) (Fig. 2). 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.

3.1.2. 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 (Fig. 3). 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.

Insert Fig. 3.

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 $WF_{overall}$, $m^3\ y^{-1}$) of wheat, barley, rice and maize for irrigated and rainfed, separately, and we report the regional-average values per climate zone (Table 1). 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 (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.

Insert Table 1

3.2. Cereal production under future climate scenarios and current practices

3.2.1. 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 2. 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 2. 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 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.

Insert Table 2

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 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 et al., 2017b), which consequently lead to shortening the available time to capture solar radiation and assimilate CO_2 (Rezaei et al., 2015; Bassu et al., 2014; Chmielewski et al., 2004). 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 2 also shows the absolute change in annual cereal production (thousand t y^{-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 y-^{1}) and arid (1497-1746 thousand tonnes y-^{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.

3.2.2. Precipitation and evapotranspiration

To have a better picture of climate change projections, we estimated the regional average of relative changes in precipitation, $ET_{green+blue}$ and ET_{blue} (all in mm y^{-1}) of irrigated and rainfed cereal croplands in different climate zones of Iran. Table 3 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 (Darzi-Naftchali and Karandish, 2019; Araya et al., 2017; 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 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 which consequently leads to a higher transpiration rate (Karandish et al., 2017ab; 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.

Insert Table 3.

3.2.3. Cereal's water footprint

We estimate climate change effects on green/blue/total WF_{prod} (m^3 t^{-1}), and $WF_{overall}$ (m^3 y^{-1}) of the major cereals in the different climatic regions (Table 4). 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.

Insert Table 4

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 y^{-1} of irrigated cereal, and 4.0 million t y^{-1} of rainfed cereal, see Table 1), 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 billion m^3 y^{-1} and 0.26-0.30 billion m^3 y^{-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, and27.5-29.4 billion m^3 y^{-1} and 22.1-24 billion m^3 y^{-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 billion m^3 y^{-1} and 3.5-5.4 billion m^3 y^{-1} higher than water consumption within the irrigated and rainfed cereal croplands in the base period (Table 4). 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 y^{-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.

3.3. 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.

3.3.1. Offseason/rainfed cultivation

While climate change more likely reduces WF_{prod} over the period 2041-2071 (Table 4), it may have an adverse impact on blue water availability in the irrigation season (Karandish and 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 and Hoekstra, 2016). To reduce the risk of limited water availability constraining irrigation demand (or irrigation water withdrawals tapping into environmental flows), 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 (Fig. 4).

Insert Fig. 4

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 5.

If only irrigated wheat is replaced with rainfed wheat, 9.2 billion m^3 y^{-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 y^{-1} production loss (65 kg cap^{-1} y^{-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 y^{-1} blue water saving at the cost of an overall production loss of 1.9 million t y^{-1} (25 kg cap^{-1} y^{-1}).

Table 5

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 for by producing 100 kg cap^{-1} y^{-1} of potato, which has 85% less blue WF compared to the irrigated cereal (Karandish and Hoekstra, 2017). This would require 21 m^3 cap^{-1} y^{-1} of blue water (compared to 39 m^3 cap^{-1} y^{-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 y^{-1} extra blue water, which could be supplied by the 13 billion m^3 y^{-1} of blue water saved under this adaptation strategy in the baseline 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 6). If only irrigated wheat is replaced with rainfed wheat, 9.1 (under RCP2.6) to 10 (under RCP8.5) billion m^3 y^{-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 cost of a production loss up to 6.3 million t y^{-1} (84 kg cap^{-1} y^{-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 y^{-1} extra blue water saving at the cost of an overall production loss of up to 3.5 million t y^{-1} (46 kg cap^{-1} y^{-1}). More production loss in the future scenarios compared to the baseline period is attributed to improved irrigated yields under climate change.

Insert Table 6

3.3.2. Early planting

Our results indicate that early planting may improve cereal's yield by 1.4-9.1% under climate change (Table 7). Farmers mainly adjust the agricultural calendar to climate variabilities by changing the land preparation and sowing/planting dates (Yegbemey et al. 2014; Karandish et al., 2017b). 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 et al., 2017b). Completing either a specific phenological phase or the whole cropping cycle requires a specific range of temperatures, and extremely low or high temperature causes noticeable impacts on crop's growth and yield at the end (Yegbemey et al., 2014; Kelkar and Bhadwal 2007; Commuri and Jones, 2001). 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 7 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 y^{-1} decrease at the national scale. This practice thus can partially alleviate pressure on blue water resources in the future. Besides, efficient use of green water resources can be achieved by reduction of the total (green+blue) WF_{prod}; accounted for 0.63-0.82 billion m^3 y^{-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 y^{-1}) by 0.7-3.2%.

Insert Table 7.

3.3.3. Benchmarking

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 8). 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 y^{-1} in wheat, 0.88 billion m^3 y^{-1} in barley, 0.3 billion m^3 y^{-1} in rice, and 0.22 billion m^3 y^{-1} in maize. Under this benchmarking option, we expect considerable savings in blue water within the arid (2.36 billion m^3 y^{-1}) and semi-arid (1.28 billion m^3 y^{-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 y^{-1}, 3.26 billion m^3 y^{-1}, and 3.52 billion m^3 y^{-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; Zhuo et al., 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., 2016 and 2014; Zwart et al., 2010). Besides, the maximum attainable yield, which also strongly affects crop's consumptive WF (Tuninetti et al., 2015; Mekonnen and Hoekstra, 2011), is an agroclimatic variable that varies between the different climatic zones.

Insert Table 8

WF benchmarking: option 2

While the given environmental conditions affect the crop's consumptive WF, it is also determined by managerial factors. 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 9 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 y^{-1} in wheat, 0.3 billion m^3 y^{-1} in barley, 0.17 billion m^3 y^{-1} in rice, and 0.084 billion m^3 y^{-1} in maize. The total of 0.47 billion m^3 y^{-1} of the overall blue water saving (0.55 billion m^3 y^{-1}) will occur within the arid and semi-arid regions (0.3 billion m^3 y^{-1} and 0.17 billion m^3 y^{-1}, respectively).

Insert Table 9

Yield improvement is possible through improving field management practices such as precision irrigation (no water stress), soil management practices or precision fertilization (Karandish and 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 pattern, 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).

Benchmarking could also be done from the consumption perspective (e.g. food loss control, dietary change or food trade modification) or virtual water trade, which are left out of this study.

3.4. 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 Fig. 5. According to the annual assessment, 21.5 billion m^3 y^{-1} unsustainable blue water was consumed to produce the major crops in Iran, 45% (9.7 billion m^3 y^{-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 for all climatic regions, the summer period (June-August) consistently had the highest contribution in the regional unsustainable blue water consumption. 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 to 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.

Insert Fig. 5

The investigated agricultural adaptation practices (section 3.3) can reduce unsustainable blue water consumption in the study area (Fig. 5). 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 reduce 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; and 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 as 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 y^{-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 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 y^{-1}; which consequently leads to 1-8% reduction in annual provincial BWS values. This means a 5% reduction in the annual national BWS. 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.

The general overview of projected changes in regional BWS values and the number of hotspot provinces/months is presented in Table 10. 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, and it is particularly the case in the hyper-arid and dry sub-humid regions. In the hyper-arid region, nuts production contributes largely to blue water consumption (Karandish and Hoekstra, 2017). In a similar situation in the dry sub-humid region, irrigated rice has a noticeable contribution (29%) to the total blue water consumption of cereal. While the substitution of irrigated rice with rainfed rice is not feasible, a reassessment is needed to evaluate the suitability of irrigated rice production in this climate zone.

Insert Table 10

4. Conclusion

We evaluated the impacts of climate change on cereals' production and water consumption for Iran's case and assessed alternative agricultural strategies to adapt to climate change. Overall, we found that cereal yields increase under climate change, which reduces the consumptive water use per unit of product. However, the annual consumptive water use (m^3 y^{-1}) will increase if the current cropland area remains the same, or expands to produce more food for the growing population. Hence, agricultural adaptation strategies are needed to alleviate additional pressure on already scarce water resources while preventing loss of agricultural productivity. We assessed blue water saving possibilities through three climate change adaptation strategies in cereal production: (i) off-season cultivation, i.e. replacing irrigated cereal production in dry seasons by rainfed production in wet seasons, (ii) early planting, (iii) and WF benchmarking. All strategies had positive impacts on blue water savings nationwide, which are substantial, considering the extra blue water demand to nourish 29 million extra population in 2055 is estimated to be around 4.4-5 billion m^3 y^{-1}. Off-season cultivation is the most effective with blue water savings of 14-15 billion m^3 y^{-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 irrigated area (of substitutable crops) instead of food import (or reduced consumption). Second most effective is WF benchmarking which results in blue water savings of 1.1-3.5 billion m^3 y^{-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 up of 1.7-1.9 billion m^3 y^{-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 in 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, assessing both effective and feasible climate change adaptation strategies to reconcile food security and sustainable water use throughout the country, remains a topic of further research.

Acknowledgement

Data for this research are not publicly available due to privacy and ethical concerns. Datasets for this research are included in these papers (and their supplementary information files): Karandish et al. (2017) [Karandish, F., Hoekstra A.Y. 2017. Informing national food and water security policy through water footprint assessment: The Case of Iran. Water (Switzerland). 10.3390/w9110831]; Karandish et al. (2018) [Karandish, F., Hoekstra A.Y., Hogeboom R.J. 2018. Groundwater saving and quality improvement by reducing water footprints of crops to benchmarks levels. Advances in Water Resources. 10.1016/j.advwatres.2018.09.011]; and Karandish (2019) [Karandish, F. 2019. Applying grey water footprint assessment to achieve environmental sustainability within a nation under intensive agriculture: a high-resolution assessment for common agrochemicals and crops. Environmental Earth Sciences. 10.1007/s12665-019-8199-y].

References

Abid, M., Schneider, U.A., Scheffran, J., 2016. Adaptation to climate change and its impacts on food productivity and crop income: perspectives of farmers in rural Pakistan. J. Rural Stud. Part A 47, 254–266.

Allen RG, Pereira LS, Raes D, Smith M 1998. Crop evapotranspiration: guideline for computing crop water requirements. FAO No. 56. Rome: FAO.

Altieri, M.A., Nicholls, C.I. 2017. The adaptation and mitigation potential of traditional agriculture in a changing climate. Climatic Change, 140, 33-45.

AQUASTAT, 2020. Food and Agriculture Organization. http://www.fao.org/nr/water/aquastat/main/index.stm

Araya, A., Kisekka, I., Lin, X., Vara, P.V., Gowda, P.H., Rice, C., Andales, A. 2017. Evaluating the impact of future climate change on irrigated maize production in Kansas. Climate Risk Management. 17, 139-154.

Bassu, S., N. Brisson, J.-L. Durand, K. Boote, J. Lizaso, J.W. Jones, C. Rosenzweig, A.C. Ruane, M. Adam, C. Baron, B. Basso, C. Biernath, H. Boogaard, S. Conijn, M. Corbeels, D. Deryng, G. De Sanctis, S. Gayler, P. Grassini, J. Hatfield, S. Hoek, C. Izaurralde, R. Jongschaap, A.R. Kemanian, K.C. Kersebaum, S.H. Kim, N.S. Kumar, D. Makowski, C. Müller, C. Nendel, E. Priesack, M.V. Pravia, F. Sau, I. Shcherbak, F. Tao, E. Teixeira, D. Timlin, and K. Waha, 2014: How do various maize crop models vary in their responses to climate change factors? Glob. Change Biol., 20, no. 7, 2301-2320, doi:10.1111/gcb.12520

Bastakoti, R.C., Gupta, J., Babel, M., vanDijk, M.P. 2014. Climate risks and adaptation strategies in the Lower Mekong River basin. Regional Environmental Change. 14, 207-219.

Batjes, N.H. 2012. ISRIC-WISE Global Data Set of Derived Soil Properties on a 5 by 5 Arc-Minutes Grid (Version 1.2); Report 2012/01; ISRIC World Soil Information: Wageningen, The Netherlands.

Bocchiola, D., Nana, E., Soncini, A. 2013. Impact of climate change scenarios on crop yield and water footprint of maize in the Po valley of Italy. Agricultural Water Management. 116, 50-61.

Brauman, K.A. , Siebert, S. , Foley, J.A. , 2013. Improvements in crop water productivity increase water sustainability and food security: a global analysis. Environ. Res. Lett. 8 024030, 2013

Bryan, E., Ringler, C., Okoba, B., Roncoli, C., Silvestri, S., Herrero, M. 2013. Adapting agriculture to climate change in Kenya: Household strategies and determinants. Journal of Environmental Management. 114, 26-35.

Chmielewski, F.M., Müller, A., Bruns, E. 2004. Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961–2000. Agriculture and Forest Meteorology. 121(1-2), 69-78.

Chukalla, A.D., Krol, M.S. and Hoekstra, A.Y. 2015. Green and blue water footprint reduction in irrigated agriculture: Effect of irrigation techniques, irrigation strategies and mulching, Hydrology and Earth System Sciences, 19(12): 4877–4891

Commuri, P.D., Jones, R.D. 2001. High temperatures during endosperm cell division in maize: a genotypic comparison under in vitro and field conditions. Crop Sci. 41,1122–1130.

Darzi-Naftchali, A., Karandish, F. 2019. Adapting rice production to climate change for sustainable blue water consumption: an economic and virtual water analysis. Theoretical and Applied Climatology. 135, 1-12.

De Martonne, E. 1926, 'Une nouvelle fonction climatologique: L'indice d'aridité', La Meteorologie, 2, 449–58.

FAO, 2013. FAOSTAT. Food and Agriculture Organization, Rome, Italy.

Hameed, M., Ahmadalipour, A., Moradkhani, H. 2020. Drought and food security in the middle east: An analytical framework. *Agricultural and Forest Meteorology, 281*, 107816. doi:https://doi.org/10.1016/j.agrformet.2019.107816

Hoekstra, A.Y. , 2013. The Water Footprint of Modern Consumer Society. Routledge, Lon- don, UK

Hoekstra, A.Y. , 2014. Sustainable, efficient, and equitable water use: the three pillars under wise freshwater allocation. Wiley Interdiscip. Rev. 1, 31–40

Hoekstra, A.Y. , Chapagain, A.K. , Aldaya, M.M. , Mekonnen, M.M. , 2011. The Water Foot- print Assessment Manual: Setting the Global Standard. Earthscan, London, UK

Hoekstra, A.Y., Mekonnen, M.M., Chapagain, A., Mathews, R., Ritcher, B.D. 2012. Global Monthly Water Scarcity: Blue Water Footprints versus Blue Water Availability. PLOS ONE, 7(2), 1-9.

IMAJ. 2019. Iran's Ministry of Agriculture Jihad. http://www.maj.ir

IRIMO, 2016. Iran Meteorological Organization, Tehran, Iran. http://www.irimo.ir/far

Karandish, F. , Hoekstra, A.Y. , 2017. Informing national food and water security policy through water footprint assessment: The case of Iran. Water 9 (11), 831

Karandish, F. , Mousavi, S.S. , 2018. Climate change uncertainty and risk assessment in Iran during twenty-first century: evapotranspiration and green water deficit analysis. Theoretical and Applied Climatology, 131(1-2), 771-791.

Karandish, F., and Mousavi, S. S., Tabari, H. 2017a. Climate change impact on precipitation and cardinal temperatures in different climatic zones in Iran: analyzing the probable effects on cereal water-use efficiency. Stoch Environ Res Risk Assess, 31(8) 2121-2146.

Karandish, F., Hoekstra, A.Y., Hogeboom, R.J. 2018. Groundwater saving and quality improvement by reducing water footprints of crops to benchmarks levels. Advances in Water Resources. 121, 480-491.

Karandish, F., Hoekstra, A.Y., Hogeboom, R.J. 2020. Reducing food waste and changing cropping patterns to reduce water consumption and pollution in cereal production in Iran. Journal of Hydrology, 586,124881

Karandish, F., Kalanaki, M., Saberali, SF. 2017b. Projected impacts of global warming on cropping calendar and water requirement of maize in a humid climate. Archive of Agronomy and Soil Sciences. 63(1), pp. 1-13

Karandish, F., Šimůnek, J. 2018. An application of the water footprint assessment to optimize production of crops irrigated with saline water: A scenario assessment with HYDRUS. Agricultural Water Management, 208, 67-82

Kelkar, U., Bhadwal, S. 2007. South Asian regional study on climate change impacts and adaptation: implications for human development [report]. Sri Lanka: Human Development Report Office.

Leakey, A.A.B., Ainsworth, E.A., Bernacchi, C.J., Rogers, A., Long, S.P., Ort, D.R. 2009. Elevated CO_2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. Journal of Experimental Botany. 60(10), 2859-2876.

Lobel., B.D., Sibley, A., Ortiz-Monasterio, I.J. 2012. Extreme heat effects on wheat senescence in India. Nature Climate Change. 2, 186-189.

Madani, K. , 2014. Water management in Iran: what is causing the looming crisis? J. Env- iron. Stud. Sci. 4 (4), 315–328

Masud, M.B., McAllister, T., Cordeiro, M.R.C., Faramarzi, M. 2018. Modeling future water footprint of barley production in Alberta, Canada: Implications for water use and yields to 2064. Science of Total Environment. 616-617, 208-222.

Matthee, R. 2020. Patterns of Food Consumption in Early Modern Iran. Oxford University Press. 26p. DOI: 10.1093/oxfordhb/9780199935369.013.13.

Mekonnen, M. M., Hoekstra, A. Y. 2016. Four billion people facing severe water scarcity. Science Advances, 2(2), e1500323. doi:10.1126/sciadv.1500323

Mekonnen, M.M. , Hoekstra, A.Y. , 2011. The green, blue and grey water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci. 15 (5), 1577–1600

Mekonnen, M.M. , Hoekstra, A.Y. , 2014. Water footprint benchmarks for crop production: a first global assessment. Ecol. Indic. 46, 214–223

Mesgaran, M.B., Madani, K., Hashemi, H., Azadi, P. 2017. Iran's land suitability for agriculture. Scientific Report, 7: 7670 | DOI:10.1038/s41598-017-08066-y.

Meza, I., Siebert, S., Döll, P., Kusche, J., Herbert, C., Eyshi Rezaei, E., Nouri, H., Gerdener, H., Popat, E., Frischen, J., Naumann, G., Vogt, J.V., Walz, Y., Sebesvari, Z., Hagenlocher, M. 2020. Global-scale drought risk assessment for agricultural systems. *Nat. Hazards Earth Syst. Sci., 20*(2), 695-712. doi:10.5194/nhess-20-695-2020.

Moradi R, Koocheki A, Nassiri Mahallati M, Mansoori H. 2013. Adaptation strategies for maize cultivation under climate change in Iran: Irrigation and planting date management. Mitigation and Adaptation Strategies for Global Change, 18, 265–284.

Blatchford, M. L., Karimi, P., Bastiaanssen, W. G. M., Nouri, H. 2018. From Global Goals to Local Gains—A Framework for Crop Water Productivity. ISPRS International Journal of Geo-Information, 7(11), 414.

Nouri, H., Stokvis, B., Galindo, A., Hoekstra, A.Y. 2019a. Water scarcity alleviation through water footprint reduction in agriculture: The effect of soil mulching and drip irrigation, Science of the Total Environments. 653, 241-252.

Nouri, H., Chavoshi S., Hoekstra, A.Y. 2019b. The blue water footprint of urban green spaces: An example for Adelaide, Australia, Landscape and Urban Planning, 190-103690.

Nouri, H., Stokvis, B., Chavoshi Borujeni, S., Galindo, A., Brugnach, M., Blatchford, M. L., Hoekstra, A. Y. 2020. Reduce blue water scarcity and increase nutritional and economic water productivity through changing the cropping pattern in a catchment. *Journal of Hydrology, 588*, 125086. doi:https://doi.org/10.1016/j.jhydrol.2020.125086

Rezaei, E.E., Lashkari, A. 2019. The consequences of change in management practices on maize yield under climate warming in Iran. *Theor Appl Climatol* **137,** 1001–1013.

Rezaei, E.E., Siebert, S., Wert, F. 2015. Intensity of heat stress in winter wheat—phenology compensates for the adverse effect of global warming. Environmental Research Letter. 10(2), 1-8.

Ruane, A.C., L.D. Cecil, R.M. Horton, R. Gordón, R. McCollum, D. Brown, B. Killough, R. Goldberg, A.P. Greeley, Rosenzweig, C. 2013. Climate change impact uncertainties for maize in Panama: Farm information, climate projections, and yield sensitivities. Agric. Forest Meteorol. 170, 132-145, doi:10.1016/j.agrformet.2011.10.015.

Schyns, J.F. and Hoekstra, A.Y. (2014) The Added Value of Water Footprint Assessment for National Water Policy: A Case Study for Morocco. PLoS ONE 9(6). doi.org/10.1371/journal.pone.0099705.

Shahsavari, F., Karandish, F., Haghighatjou. 2019. Potentials for expanding dry-land agriculture under global warming in water-stressed regions: a quantitative assessment based on drought indices. Theoretical and applied climatology. 137, 1555–1567.

Shrestha, S., Chapagain, R., Babel, M.S. 2017. Quantifying the impact of climate change on crop yield and water footprint of rice in the Nam Oon Irrigation Project, Thailand. Science of Total Environment. 599-600, 689-699.

Steduto, P., Raes, D., Hsiao, T.C., Fereres, E., 2012. AquaCrop: concepts, rationale and operation. In: Steduto, P., Hsiao, T. C., Fereres, E., Raes, D., Crop Yield Response to Water, FAO Irrigation and Drainage, Paper No. 66. Food and Agriculture Organization of the United Nations, Rome, Italy. pp. 17-49.

Tubiello, F.N., Donatelli, M., Resenzweig, C., Stockle, C.O. 2000. Effects of climate change and elevated CO2 on cropping systems: Model predictions at two Italian locations. European Journal of Agronomy. 13, 178-189.

Tuninetti, M., Tamea, S., D'Odorico, P., Laio, F., and Ridolfi, L. 2015. Global sensitivity of high resolution estimates of crop water footprint, Water Resources Research, 51, 8257-8272.

UN. 2019. United Nations: World Population Prospects. https://population.un.org/wpp/Graphs

WFP. 2016. Food and Nutrition Security in Iran. A summary report of WFP Iran office, 37p.

World Bank. 2020. https://data.worldbank.org/indicator/SP.POP.GROW?locations=IR

Yang, C., Fraga, H., van Ieperen, W., Trindade, H., Santos, A. 2019. Effects of climate change and adaptation options on winter wheat yield under rainfed Mediterranean conditions in southern Portugal. *Climatic Change* **154,** 159–178.

Yegbemey, R.N., Yabi, J.A., Tovignan, S.D., Gantoli, G., Kokoye, S.E.H. 2013. Farmers' decisions to adapt to climate change under various property rights: acase study of maize farming in Northern Benin (West Africa). Land Use Policy. 34, 168–175.

Zhang, P., Zhang, J., Chen, M. 2017. Economic impacts of climate change on agriculture: The importance of additional climatic variables other than temperature and precipitation. Journal of Environmental Economics and Managements. 83, 8-31.

Zheng, J., Wang, W., Ding, Y., Liu, G., Xing, W., Cao, X., Chen, D. 2020. Assessment of climate change impact on the water footprint in rice production: Historical simulation and future projections at two representative rice cropping sites of China. Science of the Total Environment. 709, 136190. doi.org/10.1016/j.scitotenv.2019.136190

Zhuo, L., Mekonnen, M.M. and Hoekstra, A.Y. 2014. Sensitivity and uncertainty in crop water footprint accounting: a case study for the Yellow River basin. HESS, 18(6): 2219-2234.

Zhuo, L. , Mekonnen, M.M. , Hoekstra, A.Y. , 2016a. Consumptive water footprint and virtual water trade scenarios for China – with focus on crop production, consumption and trade. Environment International. 94, 211-223.

Zhuo, L. , Mekonnen, M.M. , Hoekstra, A.Y. , Wada, Y. , 2016b. Inter- and intra-annual vari- ation of water footprint of crops and blue water scarcity in the Yellow River Basin (1961–2009). Adv. Water Resour. 87, 21–4

Zhuo, L., Mekonnen, M.M. and Hoekstra, A.Y. 2016c. Benchmark levels for the consumptive water footprint of crop production for different environmental conditions: A case study for winter wheat in China, Hydrology and Earth System Sciences, 20(11): 4547–4559.

Zwart, S.J. , Bastiaanssen, W.G.M. , de Fraiture, C. , Molden, D.J. , 2010. A global benchmark map of water productivity for rainfed and irrigated wheat. Agric. Water Manage. 97, 1617–1627

Table 1. Consumptive water footprint per ton of crop (WF_{prod}, m^3 t^{-1}) and as a total ($WF_{overall}$, million m^3 y^{-}), 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. Averages over the period 1980-2010 and the four studied crops.

Climatic region	Irrigated crops				Rainfed crops		
	total WF_{prod} (m^3 t^{-1})	total $WF_{overall}$ (million m^3 y^{-1})*	% of blue	total production (million t y^{-1})*	green WF_{prod} (m^3 t^{-1})	green $WF_{overall}$ (million m^3 y^{-1})*	total production (million t y^{-1})*
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)

* Values in brackets indicate the % contribution to the total.

Table 2. Relative changes in cereal's yield under climate change scenarios assuming unconstrained water availability for irrigation (2041-2070) compared to the baseline period (1980-2010).

Scenario	Climatic region	Relative change in irrigated cereal yield (%)	Absolute change in total production (1000 t y-1)	Relative change in rainfed cereal yield (%)	Absolute change in total production (1000 t y-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

Table 3. 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 baseline period (1980-2010).

Scenario	Climatic region	Relative changes for irrigated cereal			Relative changes for rainfed cereal	
		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 4. 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 baseline period (1980-2010). i.e., for rainfed cereal, WF is all in green since there is no irrigation during the crop's growing period.

Scenario	Zone	Relative changes for irrigated crops			Relative changes for rainfed crops
		Green WF_{prod} (%)	Blue WF_{prod} (%)	Green+blue WF_{prod} (%)	Green WF_{prod} (%)
RCP 2.6	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
RCP 4.5	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
RCP 8.5	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

Table 5. 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. Period: 1980-2010.

Item	Climatic zone	Wheat	Barley	Maize	All three cereals*
Total production (1000 t y^{-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 y^{-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 y^{-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 y^{-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

* Rice is excluded here since its rainfed cropping is not feasible in Iran

Table 6. Absolute changes in annual green and blue $WF_{overall}$ of wheat, barley and maize under the off-season cultivation (rainfed-cropping substitution) adaptation strategy. Period: 2041-2070.

Scenario	Item	Climatic zone	Wheat	Barley	Maize	All three cereals*
RCP2.6	Blue $WF_{overall}$ (billion m^3 y^{-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 y^{-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 y^{-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 y^{-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 y^{-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 y^{-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

Table 7. 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*	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 y^{-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 y^{-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 y^{-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

* Negative signs denote decrease and positive signs denotes increase in the considered parameter

Table 8. Absolute changes in green, blue and total water consumption ($WF_{overall}$, billion m^3 y^{-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 baseline period (1980-2010) and different RCPs across mid-21th century (2041-2070).

Item	Scenario	Hyper-arid	Arid	Semi-arid	Dry sub-humid	Humid	Iran
Green $WF_{overall}$ (billion m^3 y^{-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 y^{-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 y^{-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 9. Absolute changes in annual blue water footprint (WF), green WF and total WF of cereal production (billion m^3 y^{-1}) when water footprints are reduced to benchmarks values according to option 2 (10% yield improvement compared to baseline) for the baseline period (1980-2010) and different RCPs across mid-21[th] century (2041-2070).

Item	Scenario	Hyper-arid	Arid	Semi-arid	Dry sub-humid	Humid	Iran
Green $WF_{overall}$ (billion m^3 y^{-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 y^{-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 y^{-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

Table 10. 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 baselineperiod. HA=hyper-arid; A=arid; SA=semi-arid; DSH=dry sub-humid; H=humid.

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

* 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

Fig 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.

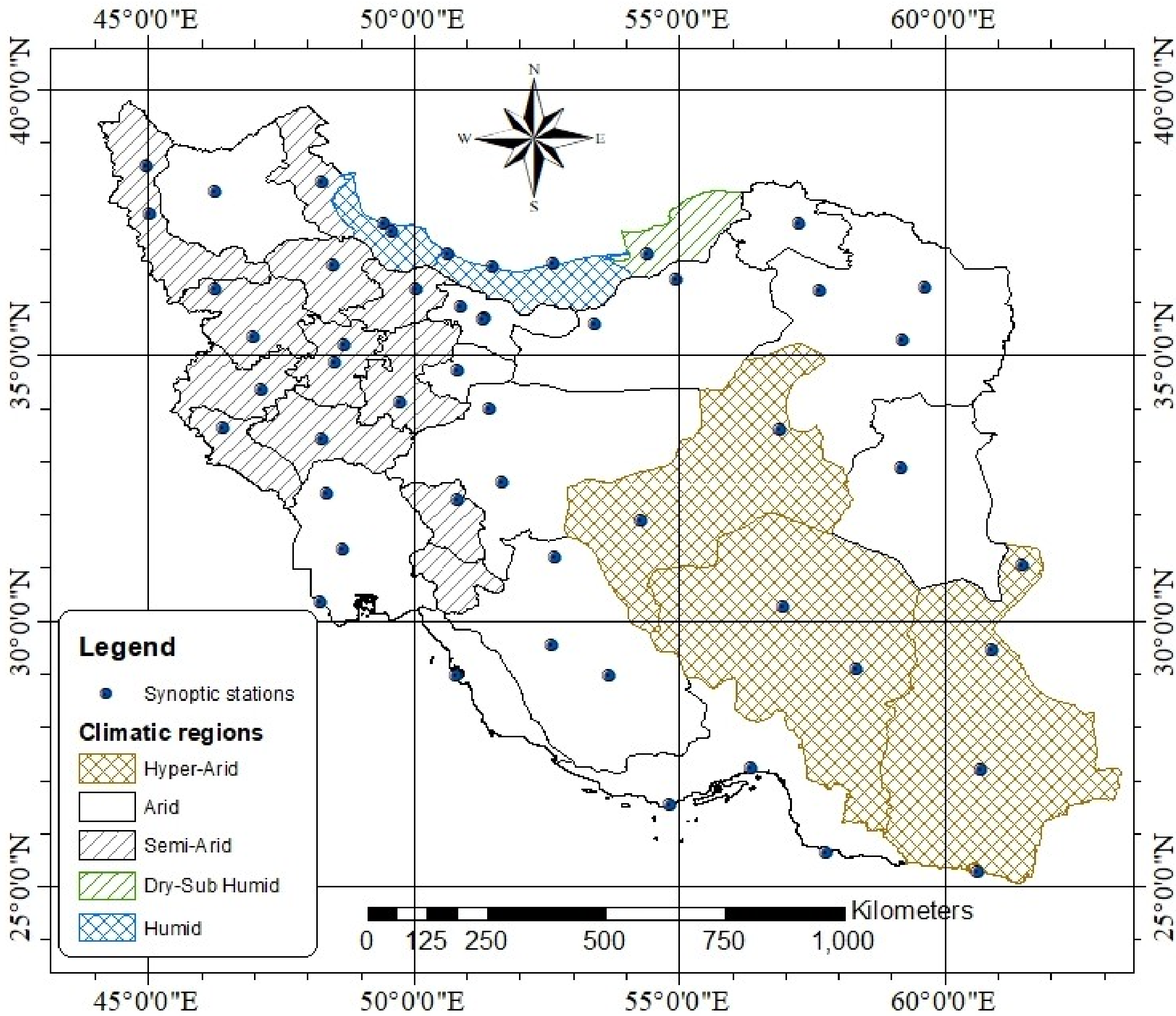

Fig 2. Share of Iran's provinces in total production of each irrigated (left) and rainfed (right) crop. Average for the baseline period (1980-2010).

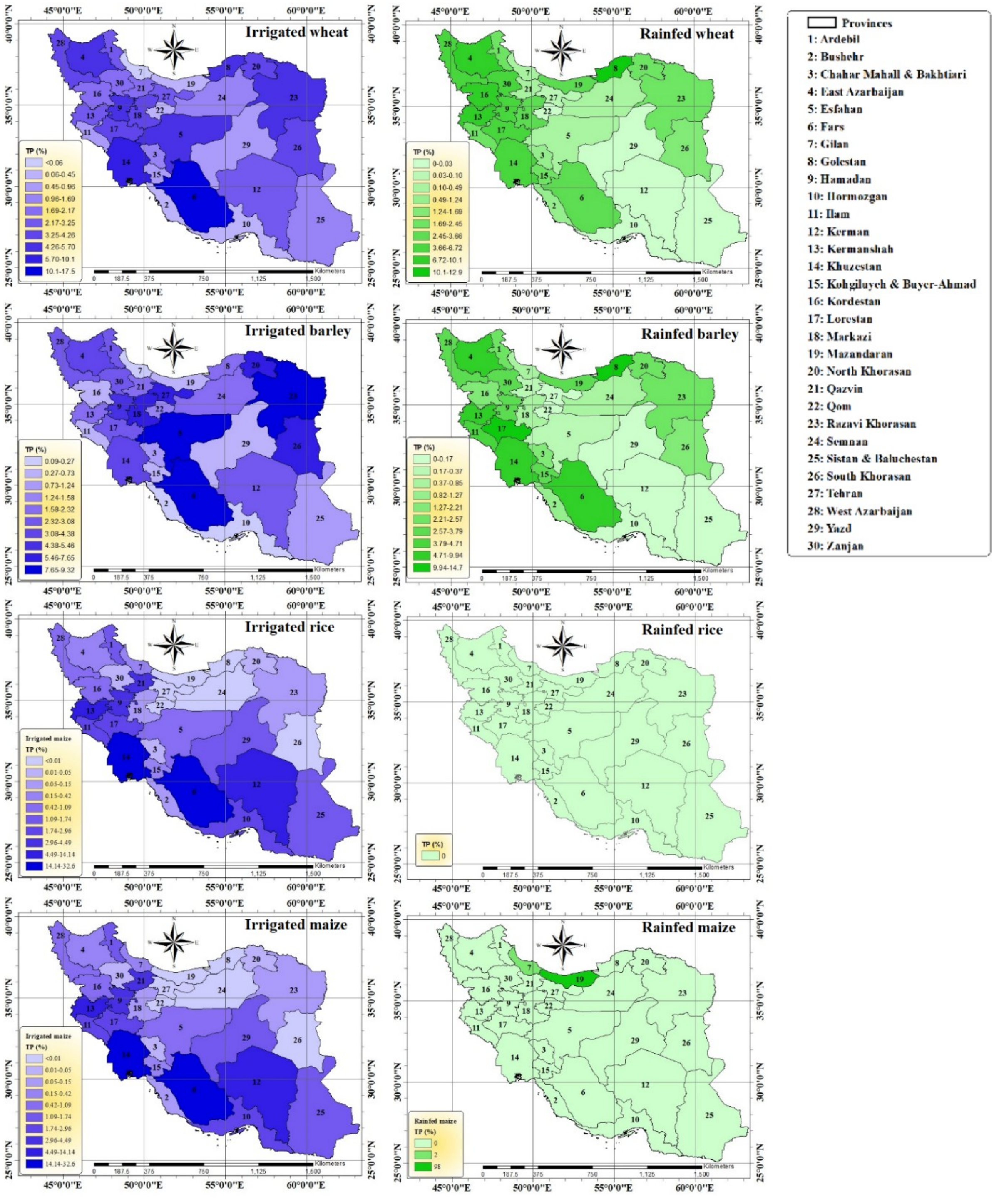

Fig 3. The spatial variation of the 30-year average (1980-2010) blue (a) and green (b) water footprint of cereal production in Iran (average over the four studied crops).

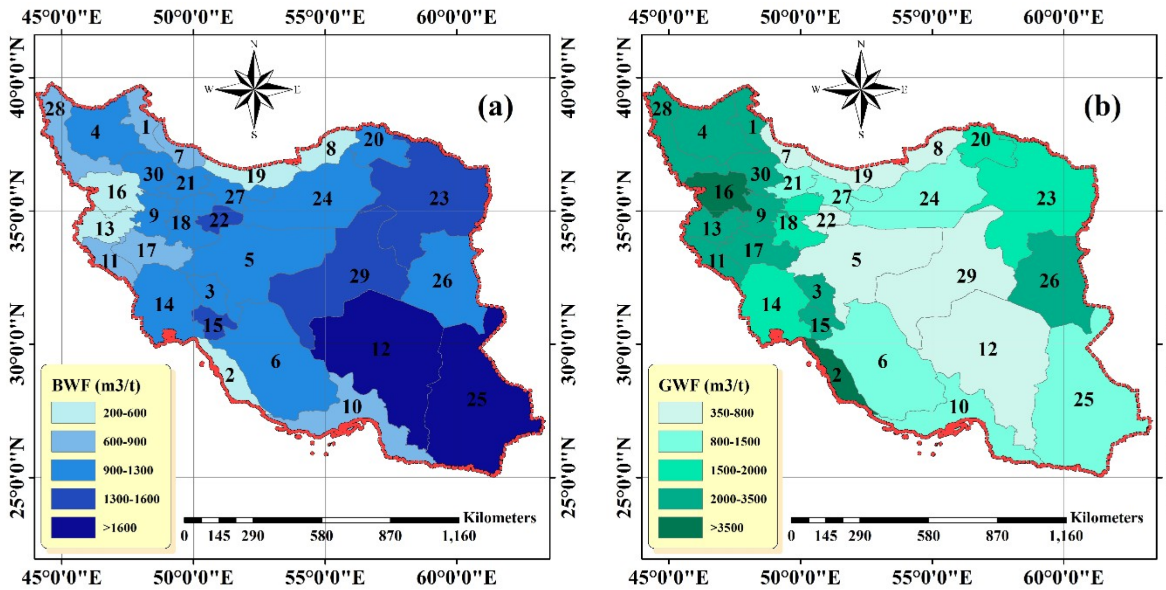

Fig 4. Monthly blue water availability along with blue WFs of 26 major crops in Iran, and blue WFs of irrigated (major) cereal. The numbers on the columns refer to the contribution of cereal in total unsustainable blue WFs.

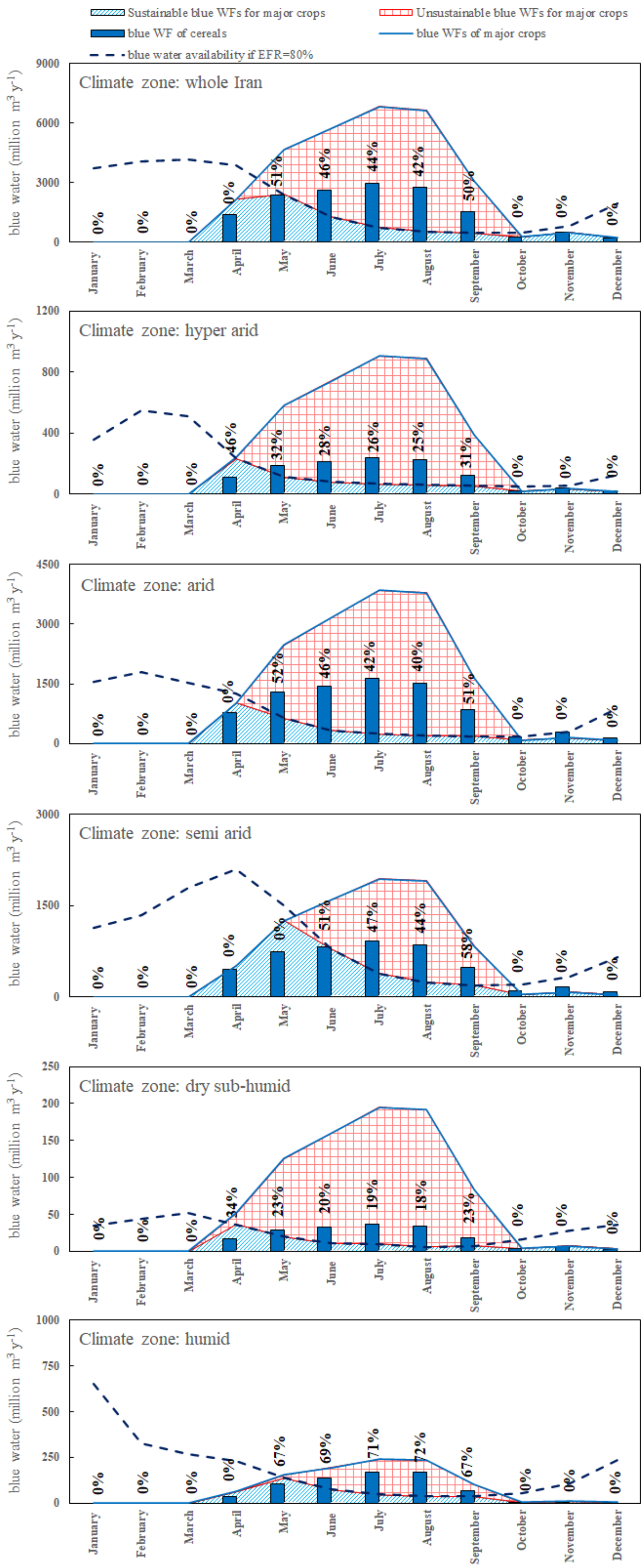

Fig. 5. Monthly blue water availability, along with blue WFs of 26 major crops grown in Iran, and blue WFs of irrigated cereal (left), and provincial blue water scarcity (BWS) (right), under current agricultural practice and the adapted practices reducing blue water consumption for the base period (1980-2010). 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.