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Assessing climate change impacts on plant production and irrigation water demand at country level: analysis for Iran

AFSHIN SOLTANI[1,*], SHABNAM POURSHIRAZI[1], BENJAMIN TORABI[1], SAMANEH RAHBAN[1], SEYYEDMAJID ALIMAGHAM[1]

[1]*Agronomy Group, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran*

**Correspondence details: Afshin.Soltani@gmail.com*

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Abstract: Climate change poses a critical challenge to plant production and food security. A comprehensive report on the effects of climate change on the production of all major agricultural crops in the entire country level is currently lacking. We assessed the impact of climate change on 35 key agricultural plant species by analyzing crop yield under irrigated and rainfed conditions, and examining net irrigation water volume (IWV) at the country level for Iran as example case. The entire country was covered using the SSM-iCrop2 crop model. Rainfed or irrigated conditions, climate type, and crop species influenced the results. Results revealed that, except for wheat and rapeseed under rainfed conditions, climate change had either neutral or negative effects on crop yields. Rainfed cool-season pulses and barley showed no benefits from climate change, while under irrigated conditions, crop yields were projected to decline more significantly for plant species and climate zones currently experiencing higher temperatures. Warm-season crops experienced yield reductions of 8-12%, whereas cool-season crops saw smaller declines of around 5%. At the national level, the net impact of climate change on plant production was a 9% decrease under irrigated conditions and a 16% increase under rainfed conditions, largely due to the dominance of wheat and rapeseed as major rainfed crops. However, the 9% decline in irrigated systems is particularly concerning, as 92% of Iran's plant production relies on irrigation. Additionally, while IWV decreased by 7.5% nationwide—primarily due to reduced water use for wheat, barley, and rapeseed—the challenge of adapting Iran's agriculture to water scarcity remains greater than that posed by climate change alone. These findings highlight the need for future research focused on optimizing water and land resource allocation to sustain plant production in a changing climate.

Keywords: Climate change, Food Security, Yield, Simulation, Irrigation, Iran.

Introduction

The production of agricultural plants is the basis of food production, as the production of other products, such as livestock, depends on them. Plant production requires huge amounts of resources, such as water and land, and inputs like fertilizers and pesticides, making it economically and environmentally important. In recent years, increasing plant production and removing restrictions to increase yield has been a critical focus due to its impact on countries' food security (van Ittersum et al., 2013; Silva et al., 2021; Soltani et al., 2020c). Furthermore, the Russia-Ukraine War and the COVID-19 pandemic served to emphasize the necessity for countries to pay more attention to plant production.

Climate change has a profound impact on plant production and poses a critical challenge to food security. Accordingly, it is necessary to estimate the impact of climate change on plant production to assess matters concerning food security. The concentration of greenhouse gases has been heightened due to various human activities, such as the utilization of fossil fuels, land use change, expansion of livestock farming, expansion of production, and the use of nitrogen fertilizers and landfills, resulting global environmental change (IPCC, 2013). This change includes increasing atmospheric CO_2 concentration ([CO_2]), temperature and weather extremes, and a change in the pattern and amount of rainfall, which can seriously impact plant production (Ladrera and Cagasan, 2022; Akram et al., 2022). On one hand, the rise in [CO2] led to an increase in temperature; while on the other hand, it has a positive impact on plant production through its role in photosynthesis (Sonmez et al., 2022). The average global temperature has increased by 0.74 °C in the last century, and it is projected that it will increase by 1.1 to 6 °C by the end of this century (Rajak et al., 2021; Song et al., 2022). Depending on the location, climate change will either increase or decrease rainfall due to changes in precipitation patterns (Kontgis et al., 2019).

The effect of climate change on agricultural crops has been studied widely in different countries, including Iran (e.g. Gohari et al., 2013; Deihimfard et al., 2018; Akbary and Sayad, 2021; Valizadeh et al., 2014). These evaluations have limitations regarding the number of evaluated crop species and/or the numbers of production sites in the country. Moreover, they have prioritized the study of specific field crops focused on one or a few important field crops while neglecting other plant species, such as forages, vegetables and fruit trees that are integral to agricultural systems. There is no comprehensive study that covers all important agricultural plant species in the entire country scale. A comprehensive study covering all significant agricultural plant species can help in designing programs for increasing plant production and improving food security and future research on plant production.

To address this gap, Soltani et al. (2020b) identified 37 crop species (each with an area of cultivation equal to more than 50,000 ha) that occupy more than 94% of agricultural lands in Iran and developed a simple simulation model (SSM-iCrop2) for these species, including forages, vegetables, and fruit trees. The model was parameterized and tested for the purpose of assessing crop yield and water use, and it demonstrated robustness in predicting these variables. Following a bottom-up approach, the model was implemented across the entire country to simulate the growth, yield, and water use of the 37 crop species, providing representative estimates of crop yield and other properties at the provincial level as influenced by climate, soil, management and cultivar. The country-level estimates of crop yields and other variables can be derived from the provincial estimates.

In this study, the framework developed by Soltani et al. (2020b) was utilized to evaluate the impact of future projected climate change on plant production in Iran. The study investigates how the projected climate change will affect crop yield under rainfed and irrigated conditions, along with the irrigation water requirement under irrigated conditions at the country level. It is worth mentioning that the assessment of blue water resources and the occurrence of pests and diseases as affected by climate change are not undertaken, and the potential advantages of adaptation measures are not taken into account due to the large number of evaluated plant species at the country level.

Methods

Model used

SSM-iCrop2, as described and tested by Soltani et al. (2020a), was utilized in this study. In brief, the model considers the effects of environmental factors, solar radiation, CO_2, temperature, water availability, and genotype on phenological development, leaf area development, dry mass accumulation and yield formation. The model uses daily time steps to simulate phenology, leaf development and senescence, dry matter accumulation, yield formation, and soil water balance.

The model includes functions that account for the positive effect of [CO_2] on crop radiation use efficiency (RUE) and transpiration efficiency coefficient (TEC) as well as the effect of extreme temperatures on leaf area senescence (Soltani and Sinclair, 2012a; Soltani et al., 2020a). However, the model does not incorporate extreme temperatures effects on pollination and seed set due to limited quantified information on many plant species. RUE response to [CO_2] is quantified using the following equation (Soltani and Sinclair, 2012):

$$RUE_x = RUE_o\ (1 + b \times \ln (C_x/C_o))$$

where RUE_x is the value of RUE at [CO_2] lower or higher than the reference level, RUE_o is the value of RUE at the reference [CO_2], Co is the reference [CO_2] (330 ppm), and C_x is the target [CO_2]. The coefficient *b* is a constant coefficient. The same function is used to adjust TEC for [CO_2]. Using a value of 0.35 in C4 plants and 0.8 in C3 plants for *b* results in a 14% to 25% increase in RUE in C3 plants and a 7% to 12% increase in C4 plants under elevated [CO_2] (499 to 571 ppm) compared to 385 ppm (mean concentration during 2000-2015). These increases in RUE fall within the range reported for diurnal carbon assimilation in C3 and C4 plants by Ainsworth and Long (2005).

The model testing results confirmed its reliability in simulating the crop yield and water use of more than 30 agricultural plant species in Iran (Soltani et al., 2020a). To accomplish this, data on plant phenology, dry mass accumulation, yield, and evapotranspiration/irrigation were collected from a wide range of environmental and growth conditions in the primary producing areas of each plant across Iran. Over 300 published papers and numerous local research reports from across the country were extensively used to parameterize and test the crop model. Normalized Root Mean Square of Error (nRMSE) for yield was 18% for grain field crops, 14% for non-grain crops and vegetables, and 28% for fruit trees. The correlation coefficient (*r*) between simulated and observed yields was 0.95 for both grain and non-grain field crops, 0.85 for vegetables, and 0.98 for fruit trees, all significant at $P \leq 0.01$. For net irrigation water (under irrigated conditions) or evapotranspiration (under rainfed conditions), nRMSE was 14% in grain crops, 8% in non-grain crops, and 22% in both vegetables and fruit trees. For the same variables, *r* was 0.93 in grain crops, 0.85 in non-grain crops, 0.79 in vegetables, and 0.72 in fruit trees. The statistics of the model testing fall within the common range of nRMSE and *r* in many other model testing research. The present study uses the tested model for the same crops/cultivars over the same regions. The model can be downloaded from ‘https://sites.google.com/view/ssm-crop-models’.

Modeling framework used

Simulation of plant growth and yield under future climates of Iran was conducted using the SSM-iCrop2 model setup for Iran across all agricultural lands, as described by Soltani et al. (2020b). In brief, the SSM-iCrop2 model was established to simulate all important crop species across the country. This was achieved by utilizing local information as input for the model to estimate crop production, which was then scaled-up to the regional and national levels using a spatial framework (www.yieldgap.org; van Ittersum et al., 2013; van Wart et al., 2013; van Bussel et al., 2015; Grassini et al., 2015).

The modeling setup allows for the generation of representative estimates of crop yield and other variables, such as net applied irrigation water, at the provincial level under potential and water-limited conditions as influenced by climate, soil, management, and genetics (cultivar). The estimates are subsequently used to calculate crop variables of crop species at the national level under potential and water-limited conditions. Under potential production conditions, crop growth and yield are assumed to be not limited by the availability of water and nutrients or crop pests, diseases, and weeds. Crop yield under such a condition is called potential yield (Y_p). Water-limited production conditions are similar to those of potential production conditions, but water availability through rainfall or irrigation may limit crop growth and yield. Crop yield under this production condition is called water-limited potential yield (Y_w). To gain insights into the model setup, it is recommended to refer to the study conducted by Soltani et al (2020b). Soltani et al. (2020c) employed the model setup and simulated the growth, yield, and water use of the main agricultural plants across the entire of Iran under 2000-2015 climate for irrigated and rainfed conditions.

Future climates

Two climate change scenarios were simulated to reflect the projected future climate conditions with one scenario representing moderate (RCP4.5, [CO_2] = 499 ppm) and the other scenario representing relatively high emissions (RCP8.5, [CO_2] = 571 ppm) for the middle of the 21st century (2041-2060). Two global circulation models (GCM) including HadGEM2-ES and IPSL-CM5A-MR were used to obtain the projections. Normally future climate is projected using several GCM (usually 3 to 5) to cover uncertainty with climate variability. Here, two GCMs were used, but they were selected based on a previous study (Maddah, 2015) that demonstrated their superior performance for Iran conditions among the 16 evaluated GCMs.

The future weather data was obtained from the Fifth Coupled Model Intercomparison Project (CMIP5). The Delta Method (Ruane et al., 2015) was employed to adjust the historical weather data in order to represent projected alterations in average temperatures and precipitation, as well as changes in the standard deviation of daily temperatures and the frequency of rainy days. We used the CMIP5 climate projections because the newer CMIP6 scenarios released just after completion of this research. However, using CMIP5 scenarios has the advantage that it facilitates the comparison of climate change impacts with previous studies including our previous study of plant production and water use in Iran under 2000-2015 climates using the same crop species and weather stations (Soltani et al., 2020b). In general, the CMIP6 and CMIP5 projections largely overlap, with the difference between models being larger than the difference between CMIPs (Martre et al., 2023).

Plant simulations

The SSM-iCrop2 setup employed historical and future weather data from 128 weather stations across the country to simulate the growth, yield, and water use of 35 crop species in both irrigated and rainfed conditions. Figure 2 of Soltani et al. (2020b) illustrates the spatial distribution of irrigated and rainfed areas, as well as the location of weather stations utilized in this study. The Supplementary Information (SI) provides maps illustrating the spatial distribution of each crop. The evaluated crop species, along with the area under cultivation for each species under both irrigated and rainfed conditions can be found in Table 1. Fig. 1 presents climate zones across the country

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according to the GYGA-ED zonation method (van Wart et al., 2013). It is evident from Fig. 1 that warm and hot climates are predominantly located in the southern part of the country.

Table 1. The area under cultivation of each of 35 important agricultural crops of Iran (data from Ministry of Agriculture) under irrigated and rainfed conditions along with estimated country potential yield (Yp), net irrigation water volume (IWV) and water-limited potential yield (Yw) under historical climate (2000-2015) simulated using SSM-iCrop2 model.

	IRRIGATED			RAINFED	
PLANT	Area (ha)	Yp (t ha^{-1})	IWV (m^3 ha^{-1})	Area (ha)	Yw (t ha^{-1})
Wheat	2213416	8.48	3165	3695187	2.32
Rice	565519	7.93	9340	0	-
Chickpea	10603	2.86	1790	484680	1.31
Lentil	7149	2.97	2994	132176	1.51
Bean	113260	4.42	4771	1651	2.44
Potato	156063	69.57	6938	600	32.50
Canola	54395	5.35	1771	19682	3.41
Cotton	75262	5.91	7129	1381	2.70
Sesame	39340	2.59	5102	5649	0.48
Soybean	50955	4.40	3543	6571	3.57
Sunflower	48295	4.65	5851	11379	1.25
Olive	80064	4.34	7045	6513	2.22
Sugar beet	109518	111.47	11196	0	-
Sugarcane	89050	129.33	15128	4	78.03
Almond	105331	5.18	6883	90058	0.98
Apple	237457	54.31	7825	590	17.36
Apricot	64523	43.60	6981	0	0.00
Grape	224301	52.89	10172	73791	11.55
Peach1	59740	35.83	6511	412	29.84
Pistachio	419216	3.49	5866	0	-
Pomegranate	84538	30.07	8995	1065	17.58
Walnut	139292	7.53	8929	8127	2.80
Date	218847	11.40	24804	19975	6.93
Fig	7186	19.30	9512	48704	1.42
Oranges	140018	52.42	8704	31018	32.28
Cucumber	71704	34.89	2605	542	26.47
Melon	91334	46.61	3822	1682	17.12
Onion	57765	71.22	5019	297	26.59
Tomato	152509	106.38	6854	823	39.69
Water melon	145442	62.90	5810	31285	18.32
Barley	695441	6.86	2568	973299	2.64
Grain maize	203066	15.99	9995	18	9.83
Silage maize	198819	93.15	8050	1485	60.62
Alfalfa	587453	30.11	10950	55627	8.35
Clover	40364	31.67	9089	18225	20.32

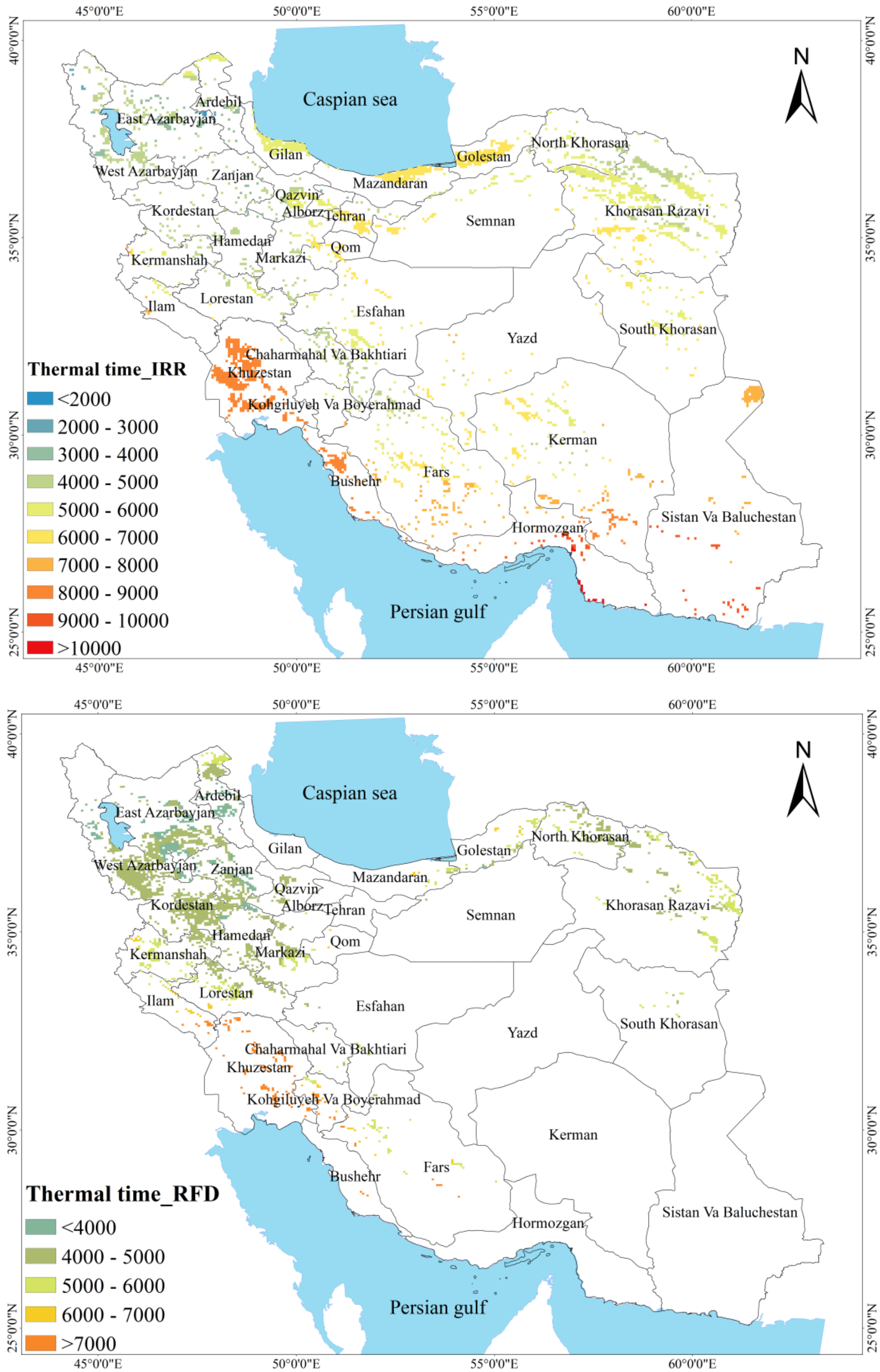

Figure 1: Climate zones as quantified by annual thermal time zones using a base temperature of 0 °C (www.yieldgap.org) in irrigated (IRR; above) and rainfed (RFD; below) of Iran

Simulations were done for the historical and the future projected climates. For the future projected climate conditions (2041-2060), four combinations (two GCMs × two RCPs) simulated weather series were employed as input to the crop model. The period 2041-2060 was chosen to obtain estimates of climate change on Y_p and Y_w in 2050 which is a reference year in many previous

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food security studies. The atmospheric CO_2 concentration for the baseline was set to 385 ppm for the historical climate (2000-2015), and this value was raised to 499 and 571 ppm for the future climates under RCP4.5 and RCP8.5, respectively.

The study did not consider the potential implications of different adaptation methods for climate change adaptation. Thus, the same sowing date and cultivars were used for both the historical and future climate conditions. The main purpose of this approach was to avoid potential disruptions in cropping systems and cultivation resulting from changes in practices, such as altering the sowing date and cultivar as adaptation measures. For example, altering the sowing dates or cultivars of wheat would have an effect on the subsequent sowing of soybean in a double cropping system. Consequently, separate and careful studies are required to evaluate adaptation measures. Furthermore, including adaptation measures would hinder the assessment of pure climate change impact due to the mixing of impact and adaptation effects. However, for fruit trees and permanent forages (such as alfalfa), increased temperatures under future climates will accelerate bud burst or the beginning of spring re-growth, and this is simulated by the crop model.

Country estimates of crop yield under potential (irrigated) conditions (Y_p), water-limited conditions (Y_w), and net irrigation water volume (IWV; simulated for potential conditions) were obtained from simulations for both the historical and future climate conditions. To streamline the presentation and interpretation of results, only percentage changes in Y_p, Y_w, and IWV were presented.

Results and Discussion

Future climates

The temperature increase projection varies depending on the GCM and the selected RCP. In general, a temperature increase between 2.5 and 4.0 ^{o}C was observed in most stations (Fig. S1). However, the projected precipitation exhibits variations in both direction and magnitude based on location, GCM, and RCP, which suggests a greater level of variability and uncertainty in comparison to the temperature (Fig. S2). It is projected that there will be an increase in rainfall of approximately 8% across all scenarios and locations. Nearly half of the stations observed an increase in rainfall, whereas the remaining half witnessed a decrease. For IPSL, most weather stations that witness increased rainfall are located in the southern half of the country, and vice versa. However, no such pattern was found for HadGEM. However, it is important to mention that none of the changes in rainfall amounts were statistically significant. This is due to the high variability of rainfall under the baseline climate, coupled with a significant increase in variability under the future climate scenarios. Therefore, with rising temperatures, drier climate conditions are anticipated.

Country estimates of Y_p, Y_w and IWV under baseline historical climate

Table 1 presents the country estimates of Y_p, Y_w, and IWV for all evaluated plant species under the historical climate conditions. Examining relative changes of Y_p, Y_w, and IWV under future climates showed that plant species can be classified into groups, as presented in Table 2. However, results for wheat and rice are shown separately as they are leading crops in the country. Average changes of Y_p, Y_w, and IWV across future climates throughout the country are presented in Fig. 2 and Table S1 in Supplementary Information. The quantified effects are the average of the predicted changes under future climate conditions based on two general circulation models, HadGEM and IPSL, and two greenhouse gas emission scenarios of RCP 4.5 and RCP 8.5. Additionally, the estimates in Fig. 2 are country-weighted averages, calculated based on the cultivated area of each plant in different provinces (see Supplementary Information for crops area distribution maps) and the current cropping pattern. As an example, Fig. 3 illustrates the percentage changes in Y_p and IWV of irrigated wheat under four future climates in 31 weather stations throughout the country; the weighted-country-average change for these variables under irrigated wheat is -6% for Y_p and -32% for IWV, as presented in Fig. 2 and Table S1 in Supplementary Information.

Table 2. List of crops and perennials based on their similarity and their response to future climates.

Plant/plant group	Components
Wheat	
Rice	
Cool-season pulses	Chickpea, Lentil
Warm-season pulses	Beans
Potato	
Cool-season oil-crops	Rapeseed
Warm-season oil-crops	Cotton, sesame, soybean, sunflower, olive
Sugar-beet	
Sugar cane	
Cool-season fruit trees	Almond, Apple, Apricot, Grape, Peach, Pomegranate, Walnut
Warm-season fruit trees	Date, Fig, Orange
Vegetables*	Cucumber, Melon, Onion, Tomato, Water-melon
Barley	
Grain maize	
Silage maize	
Alfalfa and clover	

**Mainly (90%) are summer-sown*

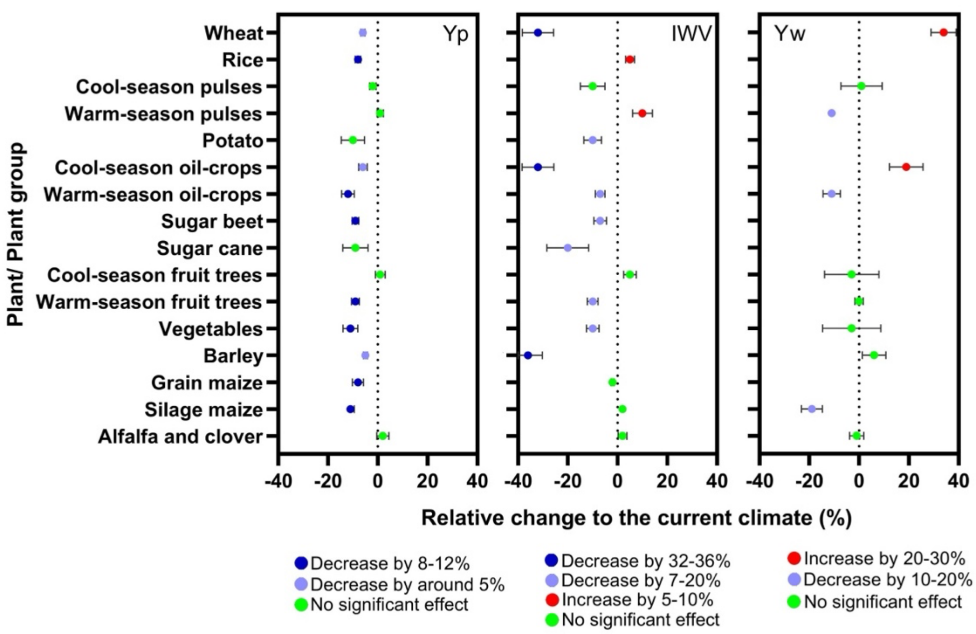

Figure 2: Impact of climate change on country potential yield (Y_p), water-limited potential yield (Y_w), and net applied irrigation water (IWV) of important crop species in Iran. The symbols are the average percentage change relative to the historical climate. Bars indicate standard errors (not confidence intervals). It should be noted that vegetables are mainly (>90%) summer-sown.

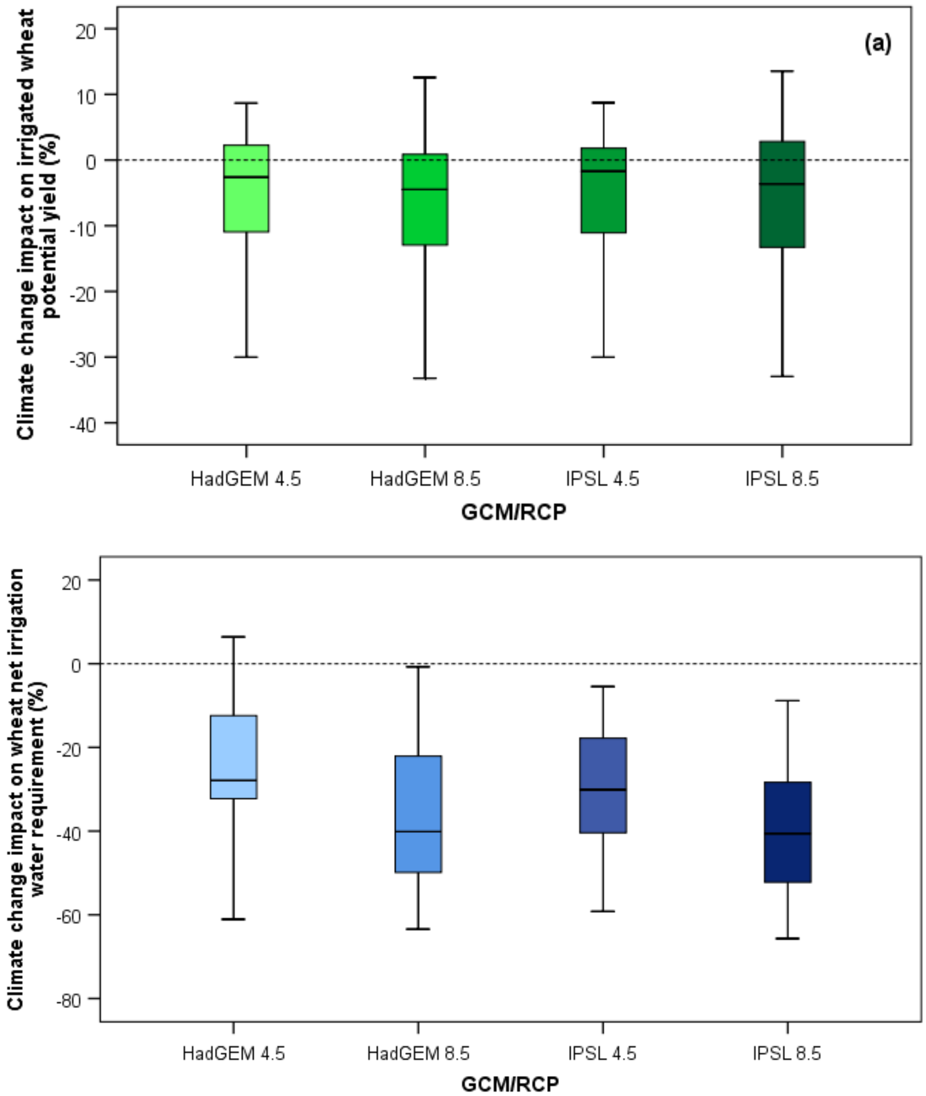

Figure 3: Percentage change in irrigated wheat yield (Y_p) and net applied irrigation water (IWV) in 31 provinces (weather stations) over the country under future climates resulted from HadGEM and IPSL general circulation models (GCM) and representative concentration pathways (RCP) of 4.5 and 8.5.

Impact of climate change on Y_p

The evaluated plant species, simulated under irrigated conditions, can be divided into three categories based on the impact of climate change on Y_p including:

(i) The first category includes rice, warm-season oil-crops, sugar beets, warm-season fruit trees, vegetables, and grain and silage maize, showing a significant decline in Y_p of ca. 10% (between 8 and 12%).

(ii) The second category includes wheat, cool-season oil-crops (rapeseed), and barley. A statistically significant decrease of ca. 5% in Y_p was observed for this category.

(iii) The third category comprises warm-season pulses, potato, cool-season fruit trees, sugarcane, and alfalfa, wherein the reduction in Y_p was not statistically significant.

Under irrigated conditions, the final impact of climate change on yield is largely the result of the relative importance of four major mechanisms (Fig. 4a): (1) the negative effect on crop growth and yield via shortening the duration of the growing season due to increased temperatures, (2) the negative or (3) positive impact of increased temperatures on crop photosynthesis and growth, which depends on the current temperature regime of the location of interest (Hatfield et al., 2011), and (4) the positive effect of increasing [CO_2] on crop photosynthesis, growth, and hence yield (Ahmed and Ahmad, 2019).

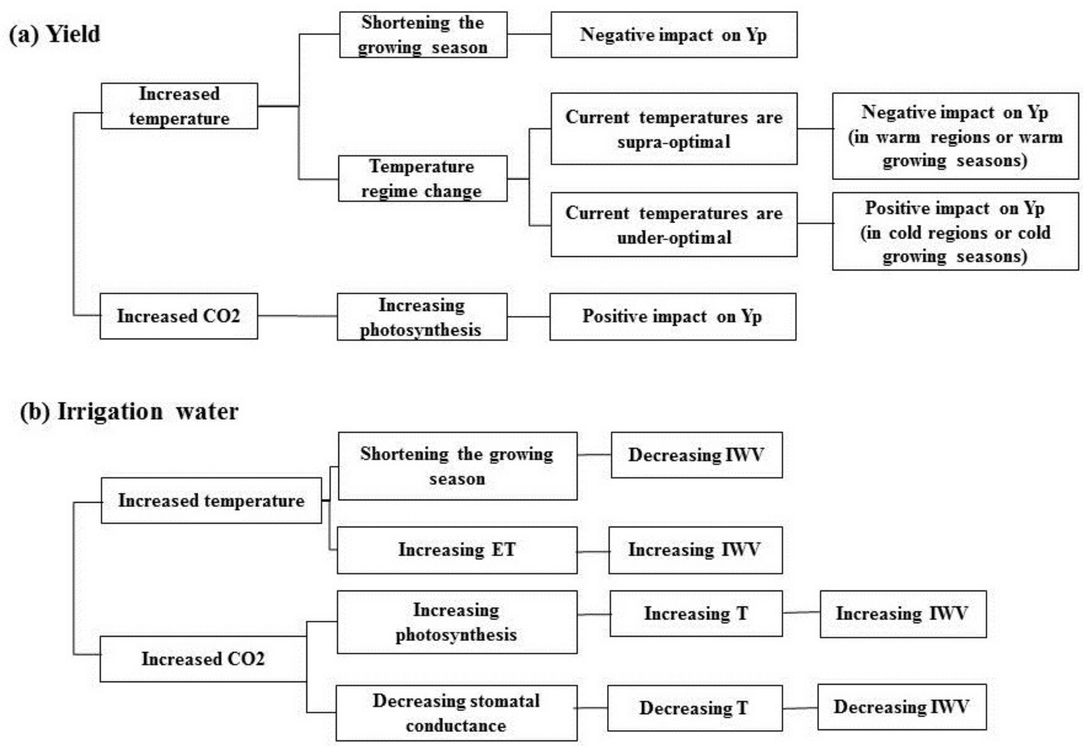

Figure 4. Major mechanisms captured in SSM-iCrop2 through which increased temperature and [CO2] under climate change result in a decreased or increased (a) crop yield or (b) net applied irrigation water (IWV) under irrigated conditions.

Fig. 5 illustrates the effect of temperature on development rate and RUE (which determines the rate of dry matter production) in cool- and warm-season crops, as used in many crop models (e.g., Soltani and Sinclair, 2012a). It indicates how increased temperatures may positively or negatively impact crop development and dry mass growth. If current temperatures experienced by crops are sub-optimal, an increase in temperature can boost crop development and dry mass production. Increased temperatures within the optimal range have no effect on development rate and dry mass production. However, increased temperatures would have a negative impact if the current temperature regime is close to the upper-optimal temperature or falls within super-optimal temperatures. Nevertheless, compared to the development rate, the RUE has a wider optimal temperature range; hence, development rate is more responsive to temperature changes in the sub-optimal range. For instance, an increase in temperature from 12 to 25 ºC does not affect RUE but increases development rate in cool-season crops. Similarly, a temperature rise from 20 to 30 ºC hastens the development rate in warm-season crops but does not affect the RUE of the crops.

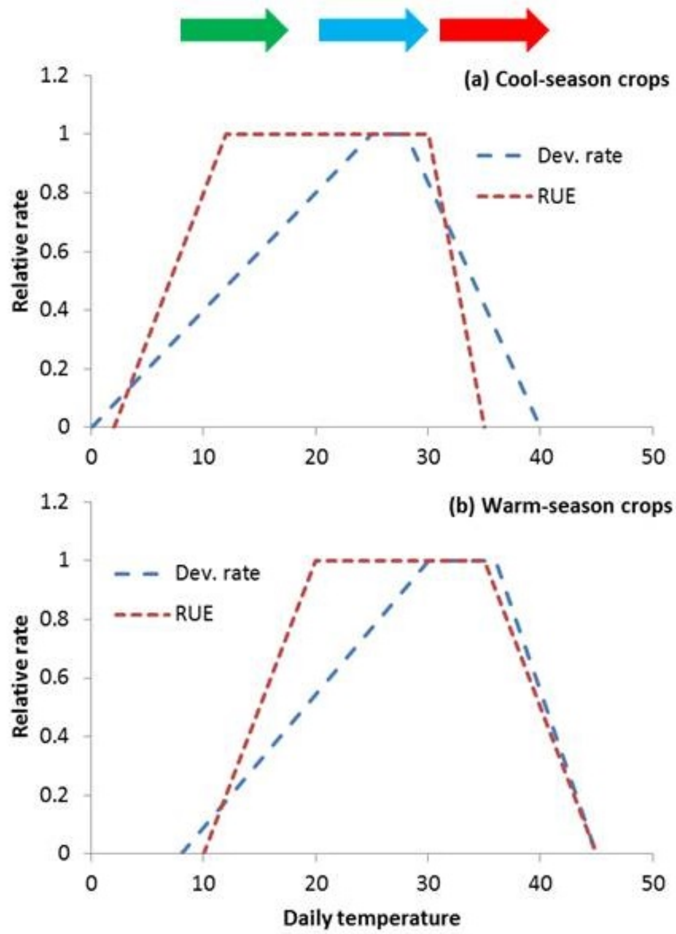

Figure 5. Effect of daily temperature on crop development rate and radiation use efficiency (RUE) in cool-season (a) and warm-season (b) crops as included in SSM-iCrop2 (and many other crop models). An increase in temperature may increase crop development and RUE if current temperatures are within sub-optimal range (first arrow in green), may have no effect if current temperatures are within optimal range (second arrow in blue) and may decrease crop development rate and RUE if current temperatures are within supra-optimal range (third arrow in red).

The reduced rate of development under supra-optimal temperatures is unlikely to lead to an increase in crop yield, given that crop growth is concurrently inhibited by these temperatures (Fig. 5). For example, it was observed that climate change led to a longer growing season for grain maize in the southern part of the country. Nevertheless, crop yield decreased as temperatures rise to and within the supra-optimal range (data not shown). In fruit trees, increased temperature due to climate change hastens bud burst time, which may lead to a lengthening of the growing season. However, increased temperature over the growing season cancels out most of the advantage. Across the country, days to harvest decreased by 3% in cool-season fruit trees and increased by 3% in warm-season fruit trees (data not shown).

Considering the mentioned mechanisms (Fig. 4a), the responses of Y_p to climate change in Fig. 2 are justifiable. Both warm-season species (i.e., rice, warm-season oil-crops like soybean, warm-season fruit trees, summer vegetables, and grain and silage maize) and sugar beet are projected to show a significant decrease in Y_p in 2050 as a result of climate change. Although sugar beet is a cool-season crop, it is mainly sown in spring and has a long growing season throughout the summer. Therefore, the net impact of climate change was negative for plant species that are currently experiencing higher temperatures, which means mechanism #2 (negative impact of increased temperatures on crop photosynthesis and growth) had a more negative effect in these cases. While sugarcane and alfalfa are categorized as warm-season crops, the impact of climate change on these crops was negligible. The reason behind this is the continuous growth of these crops throughout the year, with increased growth during cooler months compensating for any decrease in growth during warmer months. Other plant species, which are marginally affected by climate change and show a smaller decrease in yield, are mainly cool-season plant species that are cultivated in currently cold areas, or if they are cultivated in currently warm areas (like wheat), their growing season takes place in autumn, winter, and early spring when current temperatures are still sub-optimal or optimal.

Impact of climate change on Y_w

Under rainfed conditions, the mechanisms of climate change impact via increased temperature and [CO_2] are similar to those of irrigated conditions (Fig. 4a), with one difference: while the shortening of the growing season due to increased temperature results in decreased crop yield under irrigated conditions, it does not necessarily harm crop yield under rainfed conditions. Instead, it can even have a positive effect on crop yield (Fig. 6). The reason is that under rainfed conditions, reducing the growing season (earliness) may help the crop escape from terminal droughts (which is dominant in Iran), and consequently crop yield may increase (Fig. 6b). Soltani et al. (2012b) found that chickpea benefits from earliness under rainfed conditions of Iran under both current and future climates. Van Ittersum et al. (2003) reported that in the case of terminal drought, earlier flowering of wheat due to higher temperatures moves the grain filling period to a cooler, wetter part of the season, which can increase grain yield. Asseng et al. (2004) showed that in the Mediterranean environment of Western Australia, the impact of elevated CO_2 and increased temperature on grain yield of wheat was on average positive but varied with seasonal rainfall distribution.

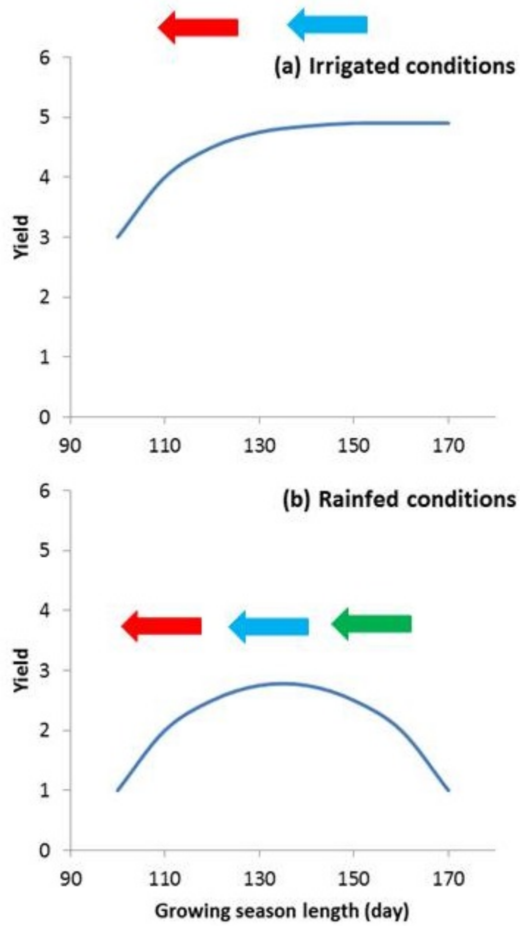

Figure 6: A sample relationship between crop yield and growing season length under irrigated (a) and rainfed (b) conditions in field crops as captured by SSM-iCrop2; shortening growing season may increase (arrow on the right in green) or decrease (arrow in the left in red) crop yield under rainfed conditions depending on the current growing season length.

Under rainfed conditions, it is projected that the yield of wheat and cool-season oil-crops (rapeseed) will increase between 20 and 30%. However, this increase is less and not statistically significant for barley and cool-season pulses. This can be attributed to the fact that, when compared to wheat, barley occupies a smaller crop area in the country's cool climates (please refer to the crop area maps provided in the Supplementary Information). Furthermore, the predominant cultivation period for cool-season pulses like chickpea and lentil is spring rather than autumn. For warm-season pulses (such as common bean) and warm-season oil-crops (such as cotton and soybean), a significant decrease in yield is predicted by ca. 11%. This reduction is higher (about 20%) for silage maize. It should be noted that the area under rainfed production of warm-season crops is negligible (Table 2) due to very limited summer rainfall in the country. Rainfed production of these crops is limited to the humid coastal region near the Caspian Sea in the north of Iran. For other plant species, climate change impacts under rainfed conditions were not significant (Fig. 2).

Impact of climate change on the IWV

The effect of climate change, via increased temperature and [CO_2], on crop evapotranspiration (ET) and the need for irrigation depends on the following mechanisms and their relative importance (Fig. 4b): (1) reduction in IWV due to the shortening of the growing season as a result of increased temperatures, (2) increase in ET and hence IWV due to increased temperature, (3) increase in IWV due to the positive effect of increased [CO_2] and temperature on crop photosynthesis and growth, which requires more water in transpiration due to the linkage between transpiration and photosynthesis (Tanner and Sinclair, 1983), and (4) reduction in IWV due to the reduction of stomatal conductivity and hence transpiration due to an increase in [CO_2] (Hatfield et al., 2011). Rainfall is a determinant impacting IWV, yet it is worth mentioning that Iran has a dry climate, thus requiring a substantial portion of crop water requirements to be met through irrigation (Soltani et al., 2020b).

For wheat, barley, and cool-season oil-crops (rapeseed), a 32 to 36% reduction in IWV is projected, which was statistically significant (Fig. 2). Taking into account the fact that the growing season of these crops presently falls in the cold months of the year, it leads to a low vapor pressure deficit. Accordingly, the increase in IWV resulting from mechanisms #2 (temperature-induced increase in IWV) and #3 (increase in IWV due to growth and transpiration) is diminished. The decrease in IWV is attributed to the effects of mechanisms #1 and #4. Mechanism #1 is characterized by a shorter growing season, resulting in a decrease in IWV. Mechanism #4 involves a reduction in IWV due to decreased stomatal conductivity and transpiration (Fig. 4b). In potato, warm-season oil-crops, sugar beet, sugarcane, warm-season fruit trees, and summer vegetables, the net impact of the mechanisms caused a significant reduction of 7 to 20% in IWV. The reduction in IWV for grain maize was statistically significant, despite being only 2%. Projections indicate a significant rise in IWV of 5% for rice and 10% for warm-season pulses.

Other considerations

Assuming that blue water resources for irrigated plant production will remain constant in the future, the impact of climate change on the country's potential plant production is projected to result in a 6% decrease. This decrease is attributed to a 9% decline in irrigated conditions and a 16% increase in rainfed conditions (Fig. 7). The volume of net irrigation water needed for irrigated potential production decreased by 7.5% under the future climate conditions (Fig. 8). It's worth noting that Iran's primary crop production system is irrigated, and 92% of plant production is derived from these systems (Soltani et al., 2020bc). Therefore, even the small decrease of approximately 9% in irrigated systems as a result of climate change impacts can significantly affect Iran's overall agricultural production and cannot be ignored.

A major concern in irrigated plant production in Iran is that over 50% of current blue water withdrawals for irrigated agriculture are over-withdrawal and must be reduced promptly due to its devastating effect on natural ecosystems, the environment, and agriculture itself (Soltani et al., 2020c). To create a balance, about 40 to 60% of current irrigated lands must be abandoned, resulting in approximately a 50% decrease in plant production under irrigated conditions. Therefore, the challenge of adapting Iran's agriculture to water scarcity is greater than the challenge of climate change.

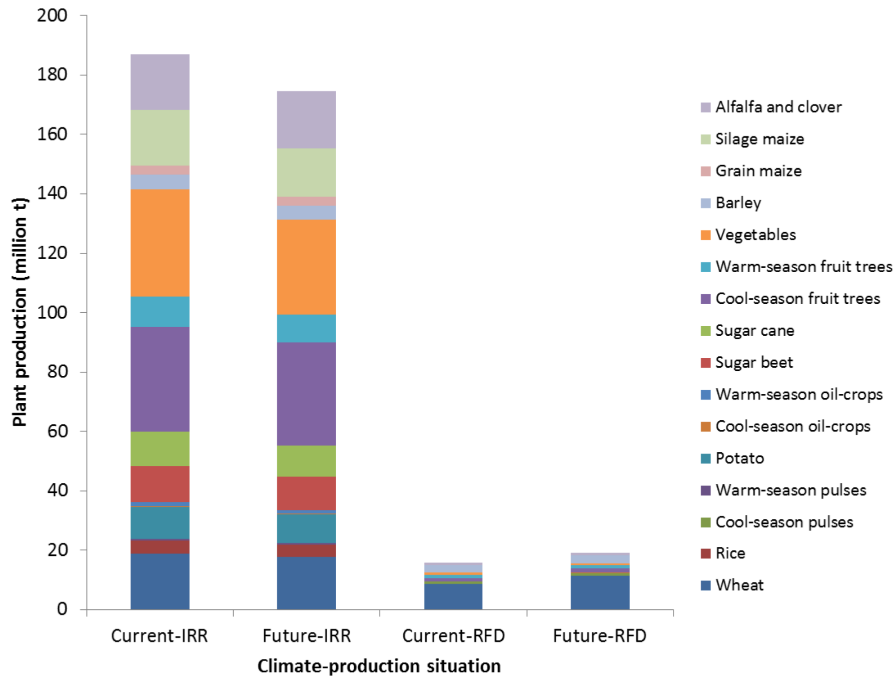

Figure 7: Impact of climate change on Iran's potential plant production under irrigated (IRR) and rainfed (RFD) conditions assuming no change is occurred in crop areas and blue water resources.

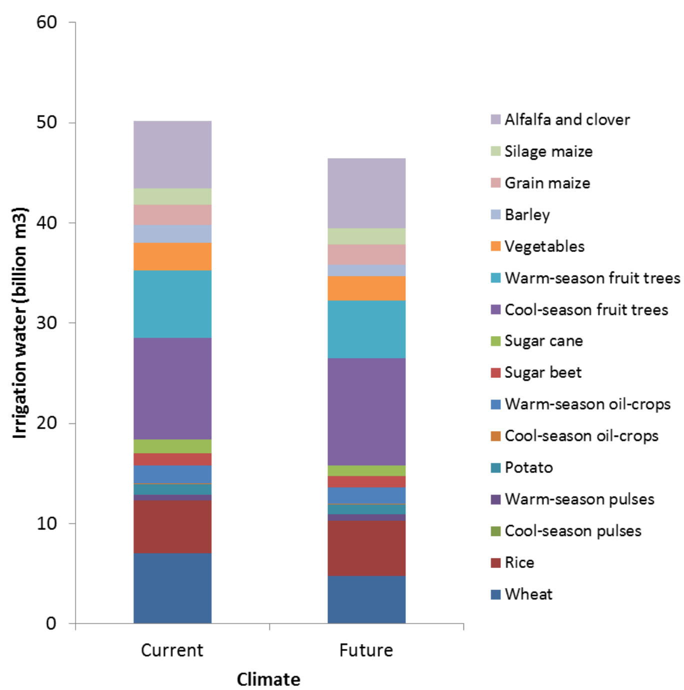

Figure 8: Impact of climate change on required net irrigation water to support potential yields in Iran's plant production assuming no change is occurred in crop areas and blue water resources.

The increasing occurrence of extreme weather due to climate change is very detrimental to plant production (Skendžić et al., 2021), especially for pollination and fertilization of fruit trees (Haokip et al., 2020). However, most crop models, including SSM-iCrop2, are not well-equipped to deal with the effects of extremes (Moriondo et al., 2011; Feng et al., 2018). Improving crop models in this aspect is an important task and is necessary for the precise assessment of climate change's impact on plant production. Fortunately, many attempts have already been initiated to obtain the required functions and information on the effects of extremes on crop processes (Peng et al., 2020). While SSM-iCrop2 includes the effect of low and high temperatures (cool, cold, and heat) on leaf area, it does not include the effect of such temperatures on pollen production, fertilization, and seed-set due to limited information on the subject. The current study needs to be repeated when such information becomes available.

In this study, we conducted a comprehensive assessment of the exclusive effects of climate change on the entirety of agricultural crops in the country. However, in order to obtain a holistic view of the consequences of climate change on plant production and agriculture in the country, it is necessary to study the effects of climate change in conjunction with other factors including the impact of climate change on blue water resources for agriculture and the occurrence of pests, diseases, and weeds (Hatfield et al., 2011; Lu et al., 2019; Naeem-Ullah et al., 2020). Climate change may also affect nutrient management in plant production (Hatfield et al., 2011; Ebrahimi et al., 2016). In addition, it is necessary to study adaptation measures to climate change and assess the positive effects resulting from these measures (Hernandez-Ochoa et al., 2018; Ahmad et al., 2020). Using alternative cultivars, such as cultivars with longer or shorter duration (depending on the crop and location and cropping system) or cultivars that are tolerant to high temperatures, may mitigate the negative effects of climate change (Semenov and Shewry, 2011). Furthermore, crop management can play a crucial role. It has been reported that changing the planting date, especially accelerating the planting date, plays a role in compensating for the negative effects of climate change (Vermeulen et al., 2012). Modifying the intensity of cropping systems (e.g., moving from single to double cropping) and altering the cropping pattern are other management options that can be employed to tackle climate change challenges (Kogo et al., 2021).

Conclusion

For the first time, a comprehensive assessment was conducted on the effects of climate change on agricultural crops, encompassing forages, vegetables, and fruit trees across the entire country. On one hand, climate change had a predominantly negative impact on crop yield under irrigated conditions where more than 90% of the country production comes from. On the other hand, it also caused a decrease in irrigation water volume, which is considered beneficial considering the country's dry climate. Under the rainfed condition, a considerable increase in crop yield was found for wheat and rapeseed, and no significant effect was observed for other important rainfed crops of Iran that currently experience warmer growing seasons, i.e. barley and cool-season pulses. As 92% of plant production in Iran takes place under irrigated conditions, the decline in irrigated plant production due to climate change should be studied further with more details and for possible adaptation measures. However, the challenge of climate change should be studied within the bigger challenge, i.e. the challenge of, adapting Iran’s agriculture to water scarcity. Improving the ability of crop models to account for the effects of extreme weather is crucial in conducting accurate climate change impact assessments on plant production. The study's findings can be implemented in the development of future research aimed at improving the allocation of water and land resources for plant production under changing climates. To do this, simulations as a function of cropping pattern, resource limitation and allocation, and progress in plant and water management would be needed.

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Data/Code availability

The datasets and codes generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author Contribution

Conceptualization, A.S; Methodology, A.S., S.P., B.T. and S.A.; Investigation, A.S., S.P., B.T., S.R. and S.A.; Writing – Original Draft, A.S. and S.P; Writing –Review & Editing, A.S., S.P. and S.A; Funding Acquisition, A.S.; Resources, A.S. and B.T.; Supervision, A.S.

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