



Stanford Iran 2040 Project

An Academic Platform for Research on Iran's Long-Term Sustainable Development

A National Adaptation Plan for Water Scarcity in Iran

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About the Stanford Iran 2040 Project

The Stanford Iran 2040 Project is an academic initiative that serves as a hub for researchers all around the world—particularly scholars of the Iranian diaspora—to conduct research on economic and technical matters related to the long-term development of Iran and to evaluate their possible implications in a global context.

The project encourages quantitative and forward-looking research on a broad array of areas relating to Iran's economic development. It seeks to envision the future of the country under plausible scenarios. The sectors that will be covered within the first phase of the project include the economy, energy, water, environment, food and agriculture, and transportation. The project has been co-sponsored by the Hamid and Christina Moghadam Program in Iranian Studies and the Freeman Spogli Institute for International Studies at Stanford.

Stanford Iran 2040 Project

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Executive Summary

Iran's water crisis is entering a new paradigm where its impacts are becoming visible in the daily lives of millions of people. Today, the average annual water consumption in Iran is estimated to be around 96 billion cubic meters (BCM)—a figure that is about 8% higher than Iran's total renewable water resources (89 BCM) or about 80% higher than the scarcity threshold level of the country (about 53 BCM). The practical solutions that can potentially help Iran address its formidable water crisis can be grouped into those that seek to (i) improve water productivity (e.g., modernization of irrigation, expansion of greenhouses, and optimization of crop pattern), and (ii) selectively terminate some water-intensive activities. Herein, we argue that—given the massive imbalance between sustainable supply and demand for water—the ultimate potential reductions in water use by the solutions targeting productivity will not be sufficient to change the calculus in Iran. Although modern irrigation systems can significantly save water at the farm level, their overall effectiveness in reducing water use at the basin level is modest. Furthermore, no more than half the irrigated lands (i.e., a quarter of total farmlands) in Iran are deemed suitable for such a transformation. Therefore, the amounts of water that can be saved in Iran through irrigation modernization would be too small (about 7 BCM) compared to the copious amounts of water that should be saved to sufficiently mitigate the ongoing crisis (about 44 BCM). We then demonstrate that the annual costs of adaptation to water scarcity in Iran through reduction in farming will hover around \$25 billion or a maximum of 5.5% of Iran's projected GDP in the future. Based on the presented analysis in this paper, we suggest the following:

- Agricultural production should be reduced substantially. Even in the absence of intended reduction in farming, it is likely that shortage of water and deterioration of soil will lead to an inadvertent and uncontrolled reduction in the output from the agriculture sector in the long run. To compensate for the reduced amounts of homegrown food, in rough terms, Iran will need to spend an additional \$300 per person per year to import food;
- Policymakers should renounce the rhetoric of glorifying food self-sufficiency which, considering Iran's limited natural resources and access to technology, only comes as a huge burden on the environment and future generations. Instead, the focus should be on ensuring the food security of the nation with no concern as to whence food originates. Furthermore, pronatalist population policies seeking to increase the total fertility rate (which is currently close to the replacement level) should be abandoned;
- Experts should devote their efforts to developing an effective water governance framework that encompasses a detailed spatial account of water availability and a set of fair and economically viable rules for water distribution among various stakeholders. Experts should also clearly and truthfully explain the realities of the matter to the public and policymakers and avoid populist statements (e.g., “saving both agriculture and water is possible”) or contentless arguments (e.g., “water crisis” vs. “water bankruptcy”).

A National Adaptation Plan for Water Scarcity in Iran

Over the past few decades, due to the sheer amount of water used for farming, water consumption in Iran has consistently exceeded its initial water stress threshold (i.e., a quarter of total renewable water) by approximately fourfold. As a result of this massive gap between the demand and sustainable supply of water, Iran is heading for a full-fledged socio-environmental crisis with a decisive impact on the wellbeing of current and future generations. Besides the visible signs of Iran's water crisis in its shrinking lakes, drying rivers, and over-drafted aquifers, the downward trends in the country's water availability are evident in escalation of inter-regional and inter-sectoral conflicts over water. The longer the current situation persists, the more damage will be done to the environment and the less likely it will be that the environment can be restored to its normal state.

The underlying solution to address Iran's water problem is obvious: consumption should be regulated and reduced, water productivity should be improved, and wastewater should be treated and reused in the system. However, managing the economic and social costs associated with these potential remedies is not a trivial undertaking. In each hydrological year, the available water is distributed among four major sectors: municipal, industry, agriculture, and the environment. The demands for water differ significantly among these sectors in terms of quantity, quality, and shadow prices (i.e., willingness to pay for a marginal unit of water input). Considering the vital role of water in people's daily lives and health, it is generally accepted that the shadow value of water for direct human use (municipal water) is the highest among these sectors. Also, given the substantially higher marginal benefits of water for industrial applications compared to the agriculture sector, industry would typically gain allocation priority should there be a local competition between the two sectors for water. In addition to their relatively higher allocation priorities warranted by the fundamentals, municipal and industrial water consumption in Iran constitutes just about one tenth of the total water use and thus inherently lacks the capacity to affect the water crisis on the grand scheme of things. Therefore, reducing water use by agriculture remains the only viable option to address Iran's ongoing water crisis. This goal may be achieved through a combination of the strategies outlined above: regulating and selectively reducing of irrigated farming, enhancing productivity (e.g., expansion of high-tech irrigation and greenhouses, and smart crop patterns), and reusing treated wastewater. However, reduction in agricultural activities will be associated with important consequences for the provision of food for the nation and employment for some four million farmers—the majority of whom being over the age of fifty and lacking other professional skills and, as such, unemployable in other sectors.

Thus far, the solutions implemented by the government to balance the supply and demand of water have almost entirely avoided any form of direct interventions leading to a reduction in the existing quotas. Instead, attempts have been focused on closing the gap by increasing the supply

(construction of more dams, exploitation of more groundwater) and, to a lesser extent, incentivizing modern irrigation techniques to improve water use efficiency. However, the construction of more dams to capture surface water and the development of water wells for exploitation of groundwater that were once considered to be part of the solution are now perceived to be part of the problem. The trends in Iran's water withdrawal and dams in service over the past three decades are depicted in **Figure 1**.

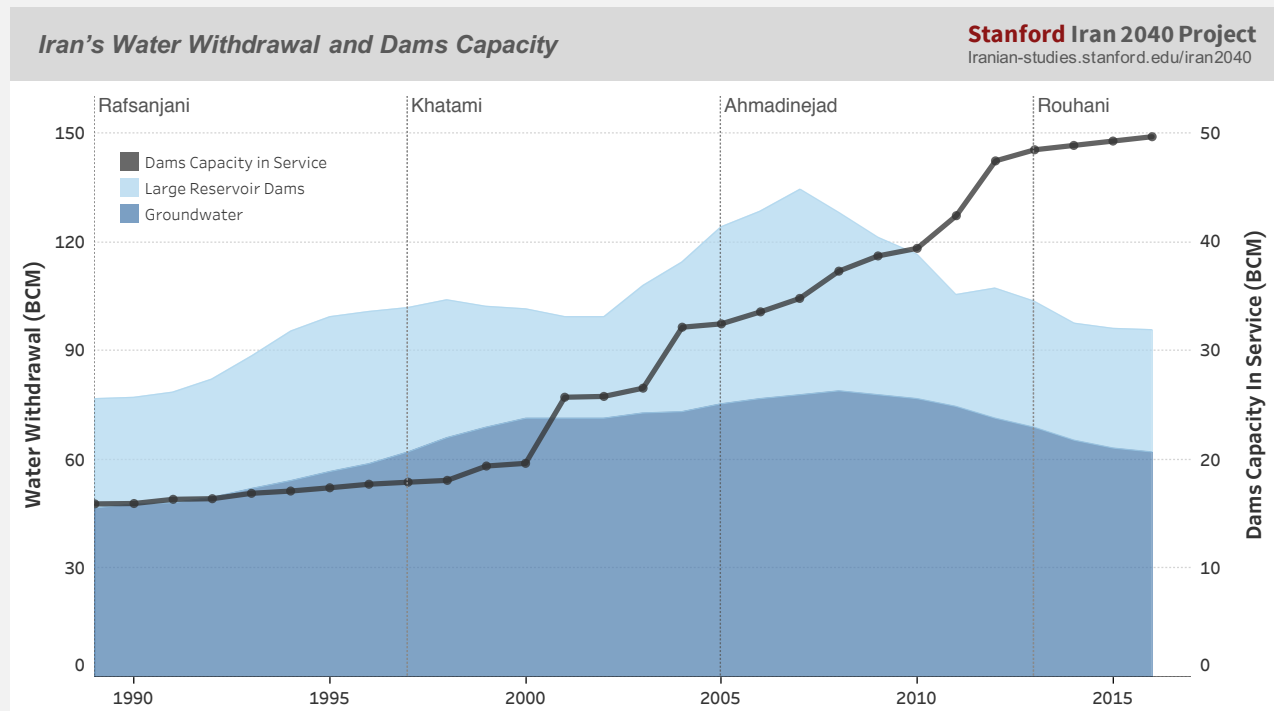


Figure 1. Iran's water withdrawal (surface water and groundwater) and its total capacity of dams in service [1,2]. Sources of groundwater withdrawal include wells, qanats, and springs.

Besides the provision of food and employment by the agriculture sector, strategic policies rooted in the ideologies of past decades have consistently advocated and incentivized farming to reach the state of food self-sufficiency. Food self-sufficiency, defined as the ratio of domestic production to total agricultural requirements, has long been a major goal for the agriculture sector in Iran. Historically, about 85% of the food consumed in Iran has been produced domestically. But food self-sufficiency does not necessarily translate into food security. The Food and Agriculture Organization of the United Nations (FAO) defines food security as “a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life.” Food security therefore makes no a priori assumptions as to where the food originates but rather focuses on an equitable and stable availability of food to people. By focusing on the origin of food or the capacity to produce it internally, a productionist approach only addresses the availability (supply) component of food security. As a result, a self-sufficient or even food exporter country may still contain a large number of undernourished people whose

low incomes are not sufficient to purchase food (e.g., Pakistan) [3]. Meanwhile, some non-self-sufficient countries such as the United Kingdom and Japan, which produce less than 80% of their food [3], are highly food-secured as they not only can afford to import food but also have no concerns about being the target of an international embargo. In any case, all countries engage in international food trade because not all crops constituting the food basket of a country can be grown within the political borders of that country due to limitations imposed by the climate. A country may therefore overproduce a specific crop based on its comparative advantage but be an importer of another crop.

The implications of Iran's water crisis will likely go beyond the mere issue of food security. Severe water scarcity can potentially be a cause of civil unrest in Iran, especially when combined with other factors such as high rates of unemployment and the perception of inequality. It can also trigger localized violence between upstream and downstream users over water resources.

In this study, we provide an overview of trends in the supply and demand of food in Iran and evaluate the country's sustainable capacity in terms of land and water endowments, considering potential future gains from investments in irrigation systems and infrastructure. Subsequently, we identify irrigated farmlands located in areas under extreme water stress and/or in areas inherently unsuitable for agriculture due to their land characteristics. We then introduce our proposed country-wide water scarcity adaptation plan to address Iran's water crisis. Finally, we estimate the ultimate changes in Iran's agricultural output and its economic consequences as a result of the implementation of the proposed plan.

1. Food Security: The Supply Side

Between 1989 and 2016, Iran's total agricultural production has increased from 39 million tonnes to 104 million tonnes (**Figure 2**) [4,5]. An analysis of production at the crop level shows an increasing trend for almost all major field crops grown in Iran over the past three decades. The rate of increase in production, however, shows marked disparities among crops due, in part, to shifts in crop patterns. The two crop groups with the highest rate of increase in production are fodders and vegetables. Despite decades of advocacy and support for wheat self-sufficiency, the rate of increase in wheat production lagged behind that of fodders and vegetables: average wheat production in Iran in 1989–92 was about 8 million tonnes, compared to an average of 11 million tonnes produced in 2012–16. Over the same period, the production of silage corn and vegetable crops has increased by eight-fold and three-fold, respectively. This increasing trend in the production of fodder and vegetables has dire consequences for water resources in Iran as the production of these summer-grown crops relies almost entirely on irrigation.

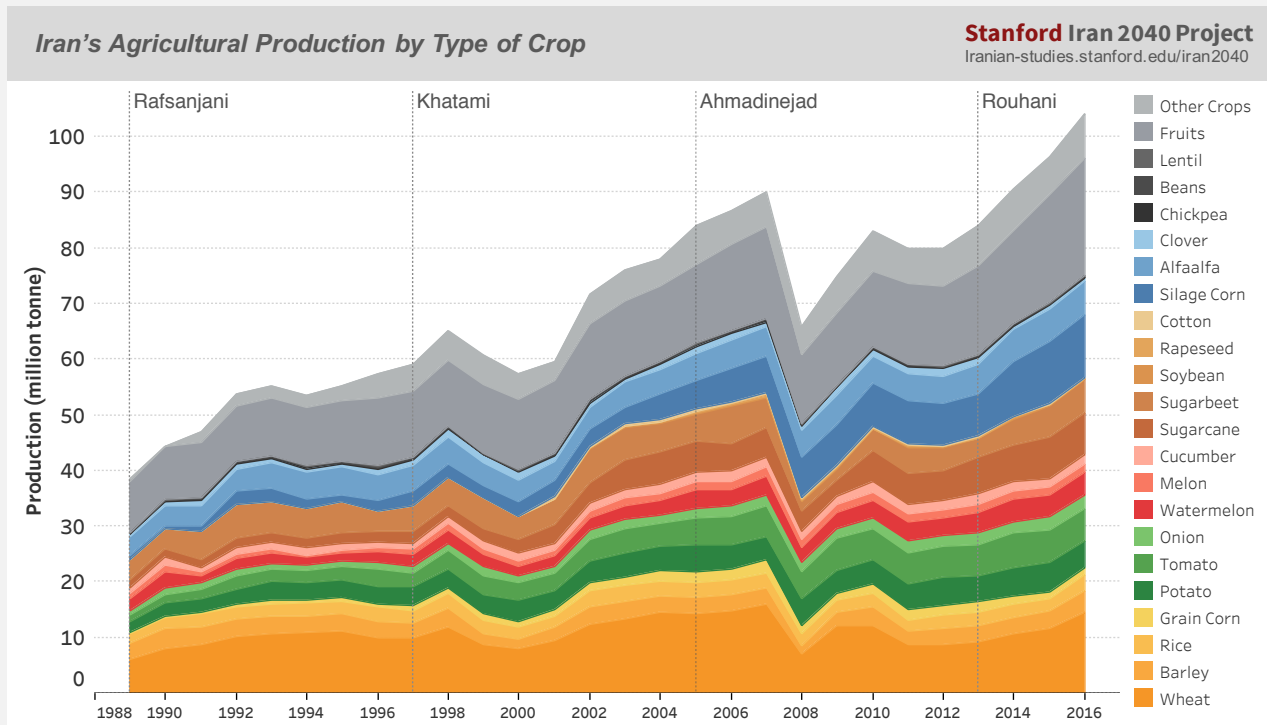


Figure 2. Trends in Iran's agricultural production by type of crop [1,4,5].

As shown in **Figure 3**, the official harvest areas of both field crops and orchards have remained constant since the beginning of the 90s [4,5]. The occasional downward strides observed in the total harvest area are mainly due to severe drought events, predominantly reducing the harvest area of rainfed wheat, which accounts for almost a quarter of the total area under cropping. Although the share of irrigated area in the total cropland increased soon after the 1979 revolution, no major changes in the relative distribution of farmlands with respect to irrigation have been observed since (**Figure 3**). Despite the almost equal areas of rainfed and irrigated lands, about 90% of Iran's agricultural production in Iran is obtained from irrigated farming.

With over three million farm-holdings, the average size of farms in Iran is not only small (**Figure 3**) but is also on a declining trend despite plans for land consolidation. Today, upwards of 85% of the farms are smaller than 100 hectares (ha) [1]. On average, the size of irrigated farms (2.9 ha) is smaller than that of the rainfed farms (6.9 ha) [1] (for comparison, the average size of farms in the U.S. is 175 ha [6]). The size of individual farms has various implications related to the productivity, sustainability, and socioeconomics of agriculture. While smallholder farming is gaining popularity for its ecological (e.g. higher diversity and lower chemical inputs) and societal aspects (e.g. local markets), small farms are deemed to be less efficient, more expensive per unit of output (the economies of scale principle), and associated with agrarian poverty. Furthermore, small and fragmented farms with irregular geometry—typical of most farms in Iran—are less amenable to the use of machinery and implementation of modern irrigation and drainage systems.

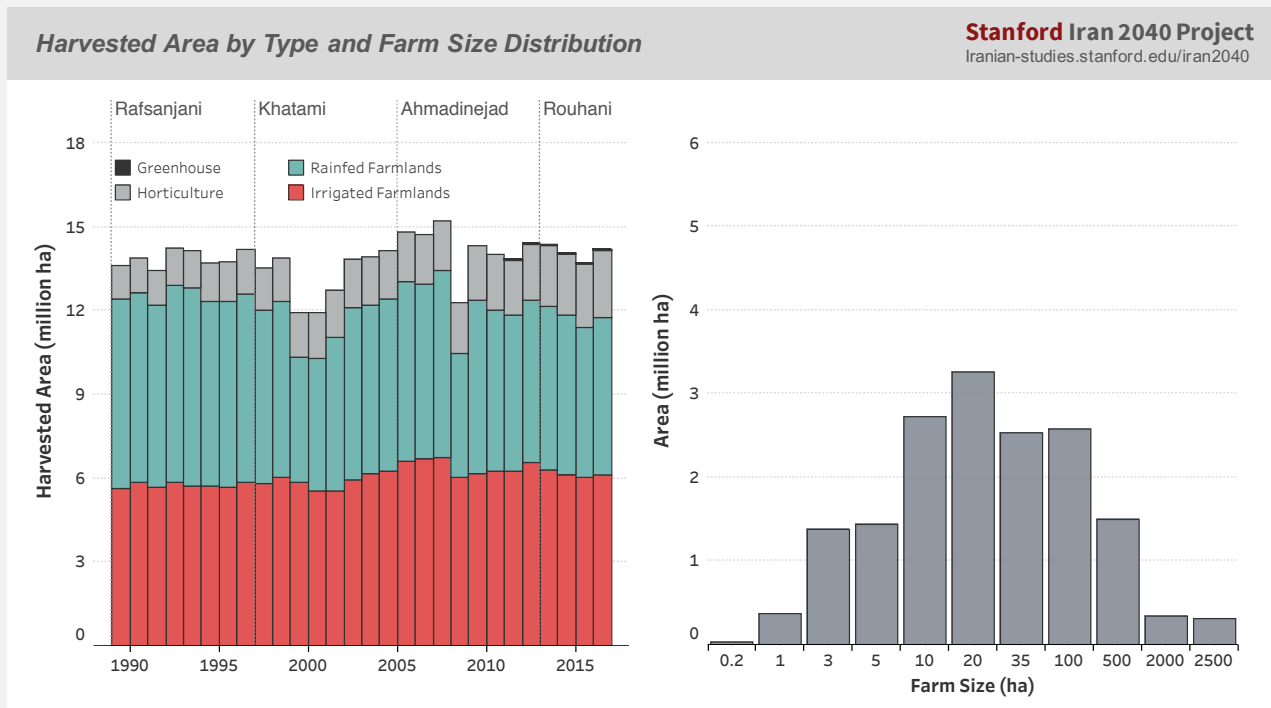


Figure 3. Changes in harvested area by type of farm (left) and distribution of the farm size (right) [1].

Evaluation of Iran's land for agricultural suitability shows that on top of the well-known water limitations, land resources also pose significant barriers to sustainable food production for Iran's growing population [7]. A multitude of factors pertinent to the soil and terrain conditions—such as low organic matter, high salinity, and a mountainous topography—render the vast majority of Iran's land unsuitable for agriculture [7]. Only about 4% of the country's landmass can be considered as prime land with no limitation for cropping, all of which is already in use for agriculture (**Figure 4**). A sizeable acreage (about 50%) of the current farming occurs in poor quality lands: a farming practice that is unsustainable and environmentally consequential. The data presented in **Figure 4** strongly suggest that agriculture has exploited all the suitable land resources in Iran and has no room for further expansion. Further, the land available to agriculture is likely to decrease in the future for various reasons such as land use change (e.g. urbanization) and land degradation (such as soil erosion, desertification, and salinization).

Although not very efficient, thus far, the agriculture sector in Iran has responded to the immediate food demand of the nation and contributed to Iran's economic growth. However, as discussed earlier, this development has occurred at the huge costs of deteriorating the land and depleting water resources. In fact, even in the absence of intended reduction in farming, it is likely that shortage of water and deterioration of soil will lead to an inadvertent and uncontrolled reduction in the output from the agriculture sector in the long run. However, regardless of being intentional or inadvertent, if reduction in agricultural output will not be accompanied with a sustained economic growth in other sectors, Iran will face a higher level of undernourishment and hunger.

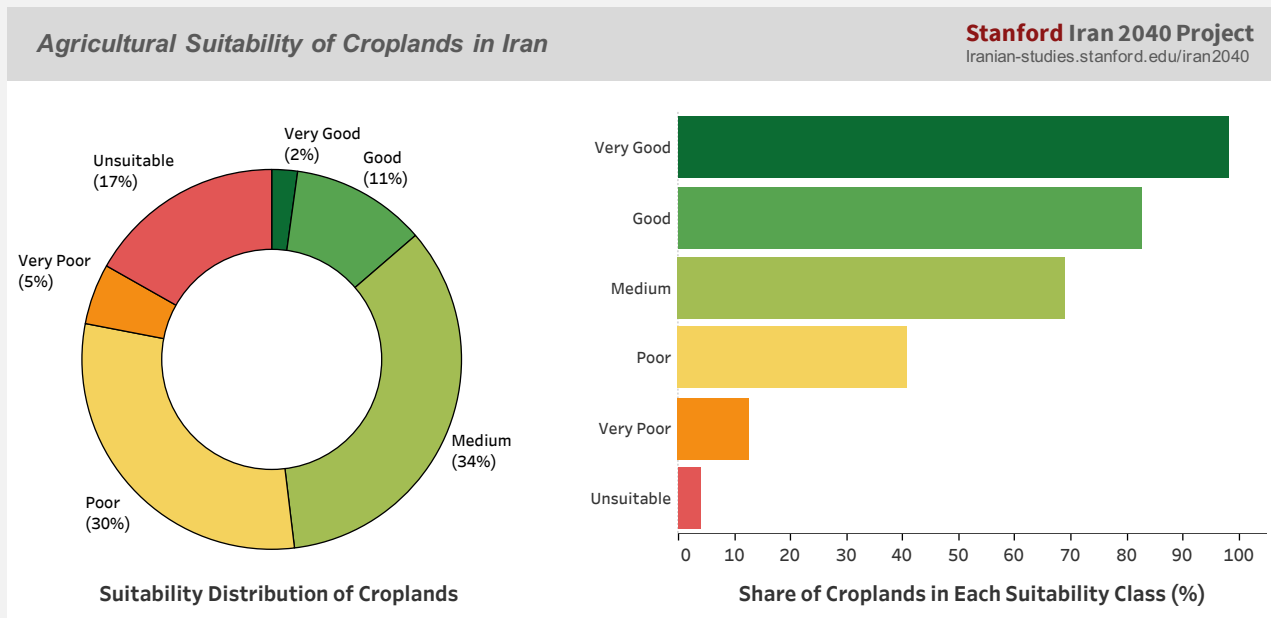


Figure 4. Agricultural suitability of existing croplands in Iran (left) and share of croplands from all lands within each suitability class (right).

2. Food Security: The Demand Side

Population size, per capita income, and diet constitute the fundamental determinants of food demand in a country. In contrast to very low-income and very high-income countries, the middle-income countries, such as Iran, are likely to experience food demand pressure from both the growth in their population size and people's income level. Therefore, in addition to the natural resource endowments of Iran that determine the country's inherent potential for domestic food supply, the current and future stages of the country's development should be taken into account when designing food security and environmental policies. In this section, we evaluate the historical contributions of population and income growth rates to the food demand in Iran and project their future trends. To this end, we assume that the relationship between the changes in food demand with the growth rates of population and the real per capita income can be expressed by $d = p + n \cdot pci$, where d is the growth rate of demand for food, p is the population growth rate, n is the average income elasticity of demand for food, and pci is the real per capita income growth rate [8].

Over the past three decades, despite a tremendous decline in the country's total fertility rate (TFR), Iran's population has increased by almost one million people per year (**Figure 5**) to reach 80 million in 2016 [9,10]. However, the population growth rate (p) declined from 2.5% in 1989 to 1.2% in 2016, and it is likely to decline further in the future as the largest cohort of the population, born in the years following the revolution, exits the fertility window. Assuming that Iran's future TFR will continue to stay at its current level (which is close to replacement level of 2.1 births per woman), the population of Iran is projected to reach 87 million by 2025 [9]. This would mean that the annual population growth rate (p) will decline from 1.1% in 2018 to 0.7% by 2025.

The second term in the food demand equation ($n \cdot pci$) accounts for the dynamics of food demand as a country proceeds through different stages of development and per capita income (pci). The income elasticity of demand for food (n) is a measure that quantifies the percentage of change in demand for food (specific product or food as a whole) if the income level of the people in a country changes by one percentage point. The income elasticity of demand for food varies substantially with both the type of commodity and the income level itself. Income elasticities for foods that are considered luxuries (e.g., some animal products) are greater than those for staple crops (e.g., wheat). Food comprises the largest share in the poor people's expenditures, but as their incomes grow, people often spend a smaller proportion of their total income on food—giving rise to a smaller income elasticity of demand for food. The average income elasticity of demand for food for very low-income and very high-income countries is typically around 0.8 and 0.1, respectively [8]. This would imply that the changes in food demand are much more sensitive to income growth when a country is at its earlier stages of development. Besides changes in the amount of food, per capita income also affects the country's food basket composition, which, in turn, affects the water demand by the agricultural sector. With rising incomes, people tend to buy more expensive foods such as fruits, vegetables, and animal products (meat, dairy, and fish) that are often associated with a higher water footprint. Typically, as per capita consumption of animal products rises, the direct consumption of cereals shrinks while their indirect demand for animal feed increases which, in turn, increases the total demand for cereals.

Figure 6 depicts changes in the select food basket of Iranians over the past three decades. Based on long-term averages, wheat (200 kg per capita) has persistently dominated the food basket of Iranians while potatoes (60 kg per capita) and rice (50 kg per capita) constitute the other two major sources of carbohydrates. With a per capita need of 67 kg, tomatoes have acquired the highest share in the food basket among vegetables. An Iranian individual, on average, uses 20 kg of oil and 29 kg of sugar per year. Among crops that are mainly used for oil extraction and as feed to livestock and poultry, grain maize and soybeans have shown substantial increases in demand over the past fifteen years. The aggregate weight and value of the food consumed by Iranians in 2016 were 116 million tonnes and \$37 billion, respectively. Based on the expected trends for population, per capita income (**Figure 5**), and future food prices [11], we project that the total food demand of Iran in terms of monetary value will reach \$46 billion (constant dollar) by 2025.

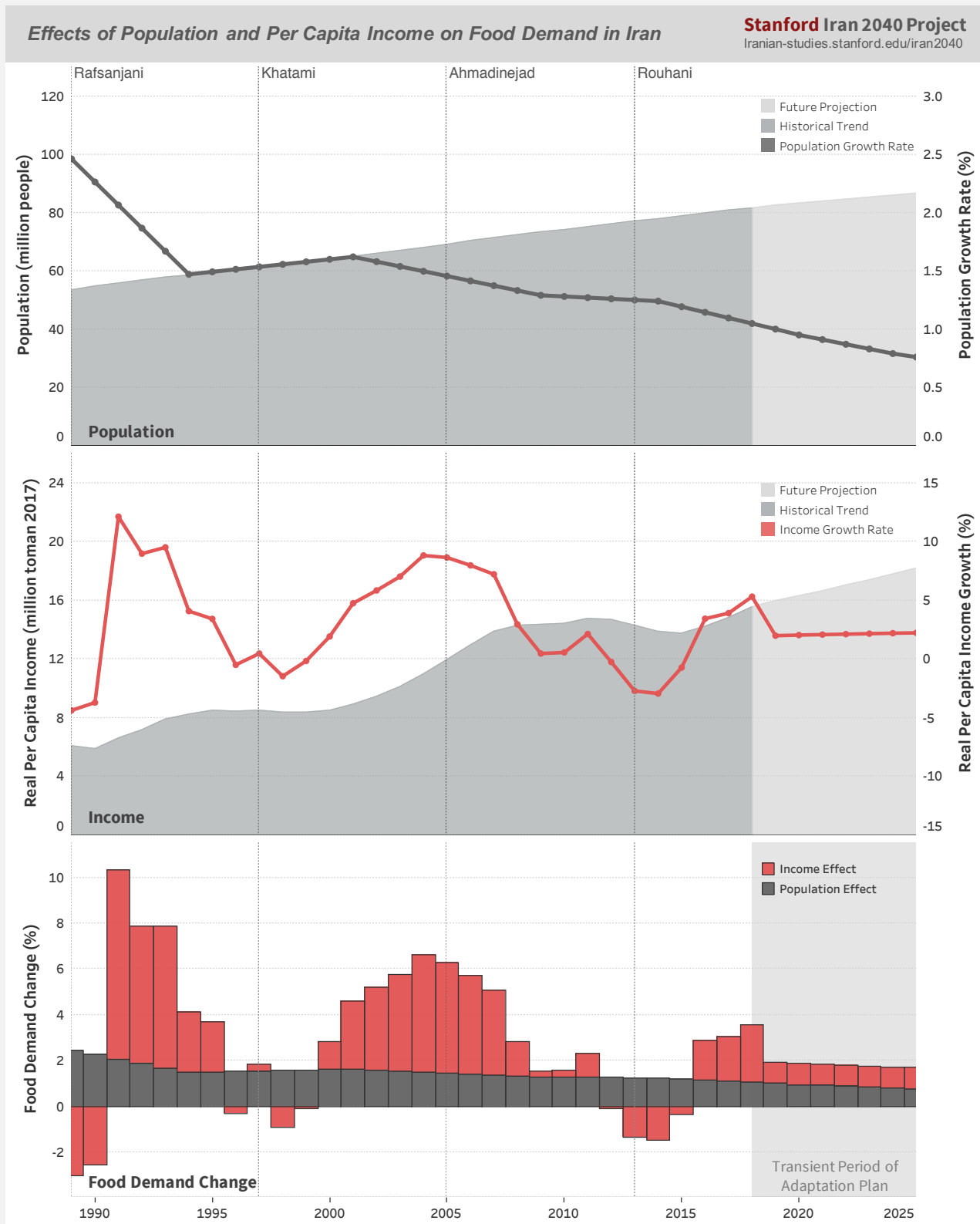


Figure 5. Estimation of the effects of population and real per capita income growth rates on the aggregate demand for food in Iran. A simple moving average was used to smooth out the real per capita income data. The average income elasticity of demand for food was assumed to vary in the range of 0.7 and 0.4 and scaled inversely with the real per capita income.

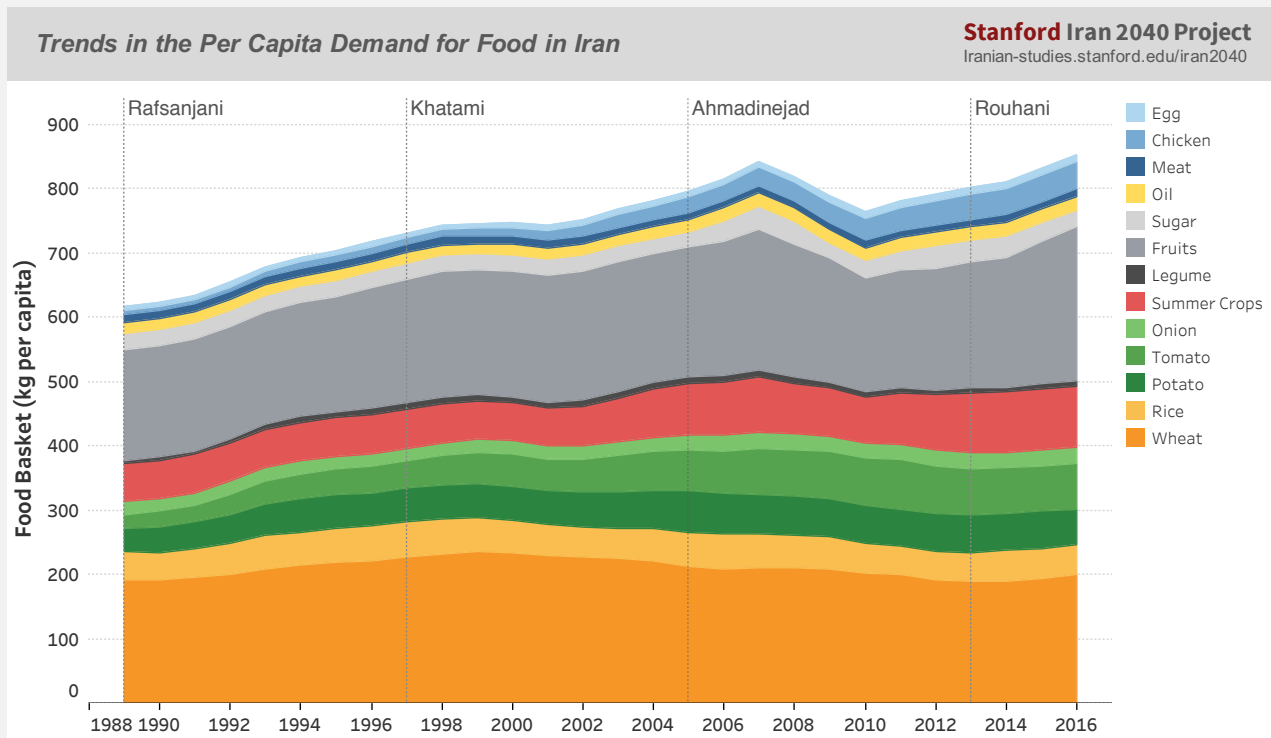


Figure 6. Trends in the per capita demand for select food (direct and indirect) in Iran. Summer crops include melon, watermelon, and cucumber; legume comprises common beans, lentils, and chickpeas. For each crop, the per capita demand was calculated as the ratio of total demand of that crop (production plus import minus export) to population.

3. Water Scarcity, Agriculture, and Food Security

In this section, using recent estimates of total actual renewable water resources (TARWR), we first calculate Iran's water scarcity threshold, which defines the absolute maximum amount of water that can be used sustainably in the country. Subsequently, after accounting for future municipal and industrial water demands as well as potential water savings from investment in technology and infrastructure, we quantify the (maximum) amount of water left for the agriculture sector. We then introduce our proposed country-wide water scarcity adaptation plan that will bring the total water use in Iran to an environmentally sustainable level. Finally, we calculate the amount of reduction in agricultural products as a result of the implementation of the proposed adaptation plan and estimate the associated economic costs both in absolute terms and relative to the future GDP.

Based on data presented in NASA's Climate Forcing Dataset for Agricultural Modeling (AgMERRA) [12], the long-term (1980–2010) mean annual precipitation of Iran is about 236 mm (382 billion cubic meter), which is consistent with data from precipitation monitoring stations in the country (**Figure 7**) [13]. Temporal analysis indicates that the average precipitation has declined by 1.5 mm per year between 1980 and 2010. However, not all regions have been affected to the same degree, with the west and northwest of Iran showing the largest drop in precipitation. In general, about a quarter of the country has experienced a significant decrease in precipitation (**Figure 7**).

Besides this decrease in precipitation, the average annual temperature of Iran has increased by 0.4 °C per decade, which has given rise to higher water loss through evapotranspiration [13]. As a result of the combined effects of these two factors, the availability of TARWR in Iran, on average, has declined from upwards of 125 to 89 BCM [13] (TARWR is defined as the sum of the volumes of surface run-off, groundwater recharge, and the net cross-boundary water). A detailed account of Iran's water balance is provided in **Appendix A**.

A summary of the underlying assumptions used in this analysis is provided in **Table 1**. Currently, total water consumption in Iran is estimated at 96 BCM, exceeding TARWR by 8%, while to sufficiently mitigate the current water crisis, total freshwater consumption typically should not exceed 60% of TARWR [14]. That is, the total freshwater use should decrease to 53.4 BCM. Due to higher priority of municipal and industrial water uses, we assumed that irrigated farming will be the only sector subject to reduction in water allocation. Hence, after subtracting future municipal and industrial water uses (12.1 BCM by 2025), 41.3 BCM freshwater will remain for irrigation. However, a proportion of the output loss caused by reduction in irrigation can be recovered by practicing rainfed farming on the affected irrigated lands. We have incorporated this factor in our analysis (see below). Under the proposed adaptation plan, the quantity of Iran's surface outflow will rise to 50 BCM (from primary and secondary sources) and the groundwater recharge and withdrawal will be fully balanced. More information on Iran's water resources and consumptions as well as the impacts of environmental flow on the ecosystem services in Iran is provided in **Appendix A**.

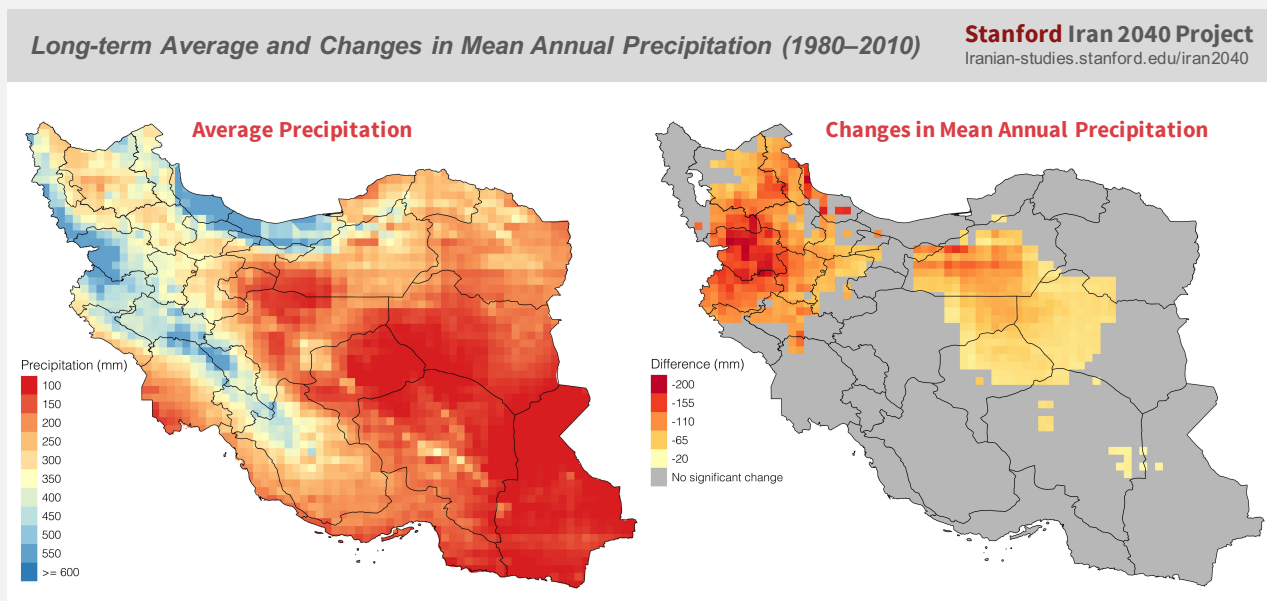


Figure 7. Long-term average (left) and changes in mean annual precipitation of Iran (right) between 1980 and 2010 based on data from AgMERRA [12]. For each individual pixel, the temporal change in precipitation was estimated based on the slope of a linear regression model fitted to time series of mean annual precipitation. Areas with no significant changes in precipitation are shown in gray.

In order to accurately evaluate the effects of reduction in agricultural water availability, one should also take into account potential gains from technology in the future, including modernization of irrigation, expansion of greenhouses, and improvements in drainage systems and water distribution networks.

There is a common belief that adaptation of high-tech irrigation techniques (e.g., drip irrigation) brings about significant water savings by increasing irrigation efficiency, typically from below 50% to upwards of 80% [15]. While such statements can be valid for savings at individual farms, they tend to overlook two unintended consequences that occur at the watershed scale when switching from traditional to modern irrigation. First, part of what is considered to be water loss in traditional irrigation is in fact recoverable and contributes to the environment water by returning to rivers and lakes or by percolating into the ground to recharge aquifers [16]. However, the quality of the return flow from farms are often lower than the primary water used for irrigation (e.g., contaminated with pesticides, fertilizers, and salts). Second, in the absence of physical control of water resources by the government, modernization of irrigation systems naturally leads to the expansion of croplands because, in a water-scarce country such as Iran, as long as water is available there is a tendency to use it. Owing to these commonly overlooked factors, the actual water savings by high-tech irrigation at a basin level is often less than that of individual farms [15,16].

About four million hectare of irrigated farmlands (including both field crops and orchards) in Iran are deemed suitable for upgrading to modernized irrigation systems with current development occurring at nearly 100,000 ha per year. The expected water saving from the implementation of modern irrigation systems for each hectare has been estimated at 4,000 cubic meters at the farm level. Based on data reported for the agricultural return flow in Iran (**Table A2, Appendix A**), we assume that the basin-level water saving is 75% that of the farm-based estimates (3,000 cubic meters per hectare). Further, based on the recent data published by the Ministry of Agriculture in Iran [4], we assume that the improvements in drainage (*zehkeshi*) and water transfer and distribution networks would result in an additional water saving of 0.2 BCM per annum.

Expansion of greenhouses could be another development that affects future agricultural water consumption in Iran. Since 2010, the total area of greenhouses in Iran has increased at an average annual rate of 620 ha to reach 11,200 ha in 2016. In the analysis presented here, we assume that the rate of expansion of greenhouses will accelerate in such a way that the total greenhouse area will reach 25,000 ha by 2025. Assuming 50% reduction in evapotranspiration (ET) and based on the latest data on Iran's crop mix produced in greenhouses (e.g., tomatoes, cucumbers, and peppers) [4], we estimate average water savings per hectare of greenhouse to be about 40 thousand cubic meters. Given the above assumptions, we estimate the total additional water supply and savings from future expansions of high-tech irrigation, greenhouses, reclaimed water, and improvement in the drainage and water transfer infrastructure would add 6.9 BCM to agriculture's available water—implying a total annual

allowable water use of 48.5 BCM for farming by 2025. Therefore, by the end of the transient period of the adaptation plan, the effective water availability for agriculture will be reduced by 43% relative to its current level. The subsequent part of this section explains how such a reduction in agricultural water allotment would affect the amounts, composition, and value of Iran's agricultural output.

Table 1. Assumptions used in the analysis (2025 is the end of the transient period). See **Table A2, Appendix A**, for more information on Iran's water balance.

Parameter	2016	2025 (Adaptation Scenario)
Population	80 million	87 million
Iran's GDP (constant 2016\$)	\$349 billion	\$467 billion
Real per capita income (constant 2016\$)	\$4400	\$5400
Food intake basket	Same as Figure 4	Same as Figure 4
Food price index	100	115
Value of total food consumed	\$37 billion	\$46 billion
TARWR	89 BCM	89 BCM
Total water consumption	96.4 BCM	53.4 BCM
Urban/rural and industrial water use	10.8 BCM	12.1 BCM
Agricultural freshwater use	85.6 BCM	41.7 BCM
Modernized irrigation area	1.6 million ha	3.0 million ha
Greenhouse area	11.2 k ha	25.0 k ha
Wastewater treatment and reuse	1.2 BCM	1.5 BCM
Additional water savings or supply		6.9 BCM
Expansion of modernized irrigation	-	4.2 BCM
Improvement of drainage and water transfer	-	1.8 BCM
Expansion of greenhouses	-	0.6 BCM
Additional reclaimed water	-	0.3 BCM
Compensation for set-aside land	-	30% of opportunity cost

Currently, 23% and 24% of Iran's total area is under *critical* and *high* groundwater stress, respectively. Our analysis indicates that 34% of Iran's existing irrigated lands (including both field crops and orchards) are located in areas classified as *critical stress*, 19% are on lands with *high stress*, and 47% are located on lands with no or minimal groundwater stress, though these values vary significantly among different provinces (**Figure 8**, top panel). By assessing soil and terrain characteristics of Iran's land, as discussed earlier in this paper, our analysis also reveals that 19% of Iran's existing irrigated lands are located in areas classified as *unsuitable*, and 33% are on lands with *very poor* suitability class (**Figure 8**, bottom panel). To meet the sustainability criteria for water use in our proposed adaptation plan, the exclusion of irrigated lands under *critical stress* took precedence over those with low soil and topography suitability scores.

We followed the steps outlined below to estimate the impact of the adaptation plan on the output from the agriculture sector.

- (i) We first eliminated irrigated lands located at the *critical* water stress zones (regardless of their land suitability score) to form an initial list of *unsustainable irrigated lands* (UIL).

About 34% of irrigated lands were removed from production at this stage. However, this amount of reduction in irrigation farming was not sufficient to reduce the water consumption below the scarcity threshold.

(ii) From the remaining irrigated lands, we eliminated more irrigated lands that had the least suitability scores and appended the UIL accordingly.

(iii) For each province, knowing the cultivated area and crop production from irrigated lands, we estimated the change in the production of each crop after elimination of the UILs. For example, if 10% of the irrigated lands in a province fell within the UIL list, we reduced the irrigation production of each individual crop by 10% and estimated the corresponding reduction in water consumption. If the reduction in the total water use was still not enough, step (ii) was repeated by adding more unsuitable lands to the UIL list.

(iv) Finally, using crop simulation models (**Appendix B**), we estimated the rainfed yields of wheat, barley, and chickpea as the potentially proper rainfed crops to be cultivated on the eliminated UILs (**Figure 9**). These crops constitute vast majority of rainfed farming in Iran. Then, for each point, based on the relative producers' price (**Appendix C**) we identified the best performing crop for rainfed farming in terms of economic return (**Appendix D**) and added the potential additional production of these crops to the existing rainfed production values.

The final results obtained by pursuing the above procedure are listed in **Table 2**. Overall, once the adaptation plan is in full effect, we project that the weight and added value of Iran's agricultural production would shrink by 41% and 44%, respectively. However, not all crops will be affected equally. The production of wheat, barley, and rice will contract by only 21%, 17%, and 13%, respectively. In contrast to the staple crops, the production of less strategic products such as vegetables and summer crops will slump by some 50%.

Distribution of Croplands by Water Stress Level and Land Suitability

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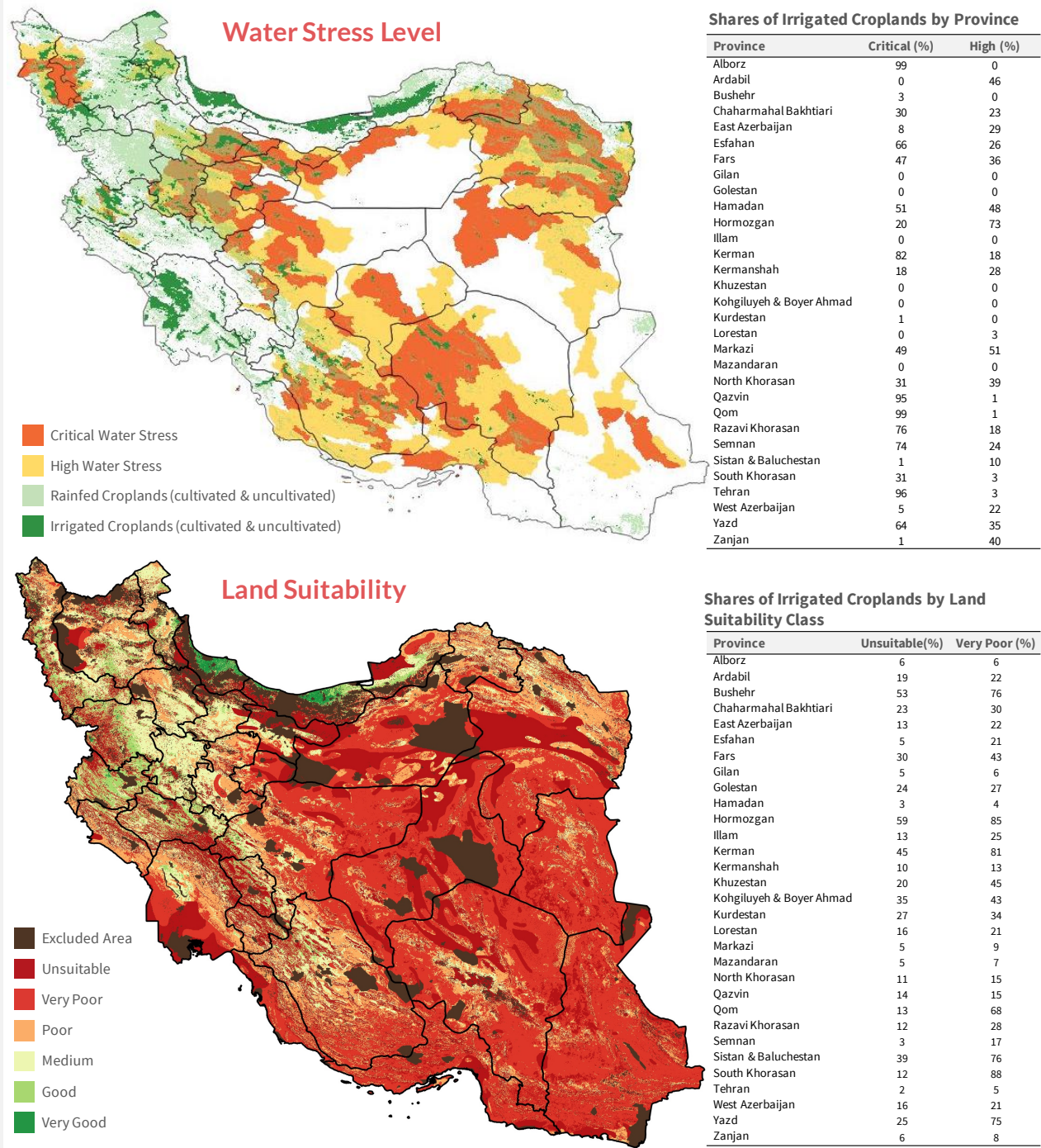


Figure 8. Map of croplands (irrigated and rainfed) both cultivated and uncultivated [17] and water stress by the study zone [18] (top panel) and map of Iran's land suitability for agriculture (bottom panel) [7]. The top and bottom tables list shares of irrigated croplands in each province by water stress level and land suitability, respectively. See **Appendix A** for more information on Iran's basins, sub-basins, and study zones.

Average Yields of Rainfed Cultivation of Selected Crops

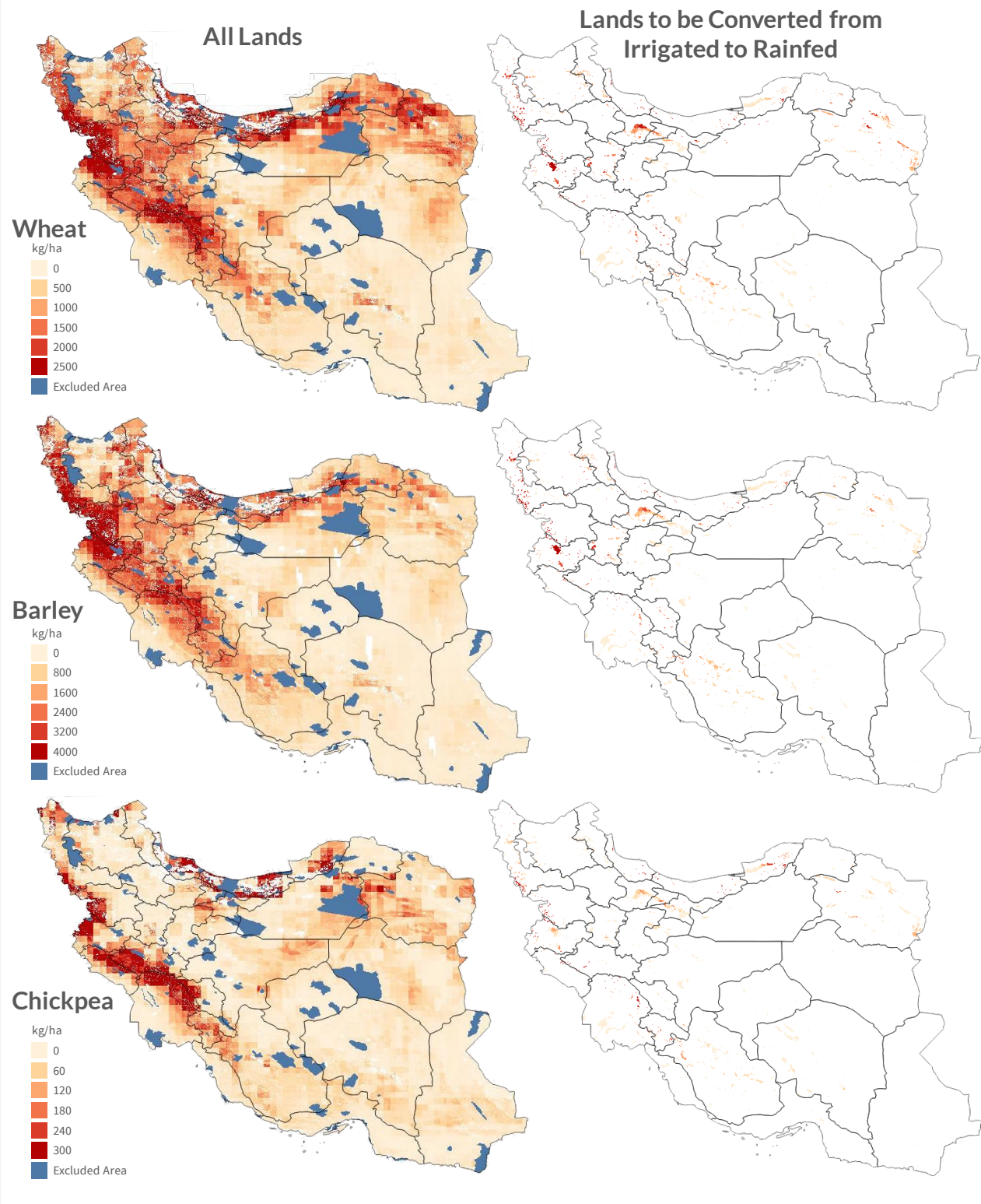
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Figure 9. Estimation of the average yields of rainfed wheat, barley, and chickpea for the entire country (left column) and lands to be converted from irrigated to rainfed (i.e., those located on critical water stress zones and/or extremely unsuitable in terms of soil properties or terrain, right column).

Table 2. Changes in agricultural production after the implementation of water scarcity adaptation plan.

Crop	Irrigated (k tonne)		Rainfed (k tonne)		Net Change (wt%)
	2016	Post-adaptation	2016	Post-adaptation	
Alfalfa	5894	3048	148	148	-47
Barley	2355	934	1369	2166	-17
Beans	229	148	1	1	-35
Chickpea	17	8	255	298	+12
Clover	270	193	230	230	-15
Cotton	159	67	2	2	-57
Cucumber	1672	805	9	9	-52
Fruits	19661	9190	1346	1346	-50
Grain corn	1171	669	0	0	-43
Lentil	9	5	74	74	-5
Melon	1477	522	13	13	-64
Onion	2395	1172	6	6	-51
Other crops	184	114	4	4	-37
Other fodders	2591	1397	255	255	-42
Other legumes	69	48	18	18	-24
Other oil crops	64	45	5	5	-27
Other summer crops	731	280	52	52	-58
Other vegetables	3667	1885	122	122	-47
Potato	4984	2817	11	11	-43
Rapeseed	55	34	13	13	-31
Rice	2921	2544	0	0	-13
Safflower	5	2	0	0	-64
Sesame	35	14	2	2	-58
Silage corn	11277	4462	39	39	-60
Soybean	124	97	16	16	-19
Sugar beet	5966	3413	0	0	-43
Sugarcane	7480	6014	0	0	-20
Sunflower	10	7	3	3	-24
Tobacco	21	11	0	0	-48
Tomato	5807	2551	21	21	-56
Water melon	3905	1864	188	188	-50
Wheat	8843	5046	5749	6485	-21
Total	94049	49405	9950	11526	-41

Here, we estimate the costs of our proposed adaptation plan as related to the development of modern irrigation systems and greenhouse structures. Typically, the capital costs of construction of a greenhouses is in the range of \$100k to \$500k per hectare depending on the type and available facilities. Considering an average cost of \$300k per hectare an average life expectancy of twenty years, the annual depreciation costs associated with the additional greenhouse farms to be built in the future are approximately \$15k per hectare. Similarly, assuming a capital costs of construction of \$1,800/ha and life expectancy of fifteen years, the annual depreciation costs associated with high-tech irrigation are estimated at \$120 per hectare. Therefore, an annual capital investment of \$380 million is needed in order to maintain the *additionally installed* greenhouse capacity (14,000 ha) and high-tech irrigation (1.4 million ha) in the long run. Finally, there is no doubt that the losers of the proposed paradigm shift will need to be compensated as they will otherwise oppose any change. To this end, compensation equal to 30% of the opportunity cost of farming was assumed to be paid to the affected farmers for their set-aside lands. The net additional expenditures on agricultural products are defined as the sum of Iran's net international trade of foodstuffs and the annual costs associated with

maintenance of additional installed greenhouses and high-tech irrigation systems, plus the compensation paid to the farmers for the set-aside lands. Iran's future GDP growth rate (including the impact of reduction in agricultural activities) is assumed to be 3% per year. Since the consequences of reducing agricultural activities involve predominantly lower groundwater withdrawal and allocation of more surface water to the environment, the issues related to the quality of water were not considered in this study.

Additional factors that can potentially affect the food-water nexus in the future but omitted in the analysis (either due to the high uncertainties associated with them or their small effects) along with a brief assessment of their potential impacts on Iran's water situation are provided in

Appendix E.

The final results of the analysis in terms of economic costs under the two scenarios of *business as usual* and the proposed *adaptation plan* are presented in **Figure 10**. We project that while Iran's agricultural trade deficit under the *business as usual* scenario will remain near \$5 billion in the mid- to long run, the annual costs associated with the adaptation plan, which include agricultural trade deficits and depreciation of additional equipment, will reach \$25 billion by the end of its transient period. After the transient period of the adaptation plan, annual expenditures will rise at a smaller rate. Similarly, the ratio of adaptation costs to the GDP (bottom panel of **Figure 10**) will peak at 5.5% by the end of the transient period before it declines again thanks to future economic growth. However, if the current trend in agricultural production continues in the future, the ratio of food imports to GDP will likely decline in the long run because the growth rate of the economy will outstrip the rise in food demand (note that the income elasticity of demand for food (n) will decrease as the real per capita income (pci) rises).

To put the implications of the proposed adaptation plan into context, we compare the ratio of food import to GDP for a number of countries with different levels of income and water availability (**Figure 11**). Over the past decades, trade of foodstuff among countries has substantially expanded and as a result, the global food security as a whole has improved. In the meantime, the national agricultural policies aimed at maintaining a high degree of food self-sufficiency have been replaced by those that seek to maximize benefits from the country's comparative advantages. Although the share of agriculture in the economy typically decreases as a country becomes more developed, countries with higher income generally spend smaller parts of their income on import of foods from abroad [8]. It is expected that the adaptation plan outlined in this study increases the Iran's ratio of food import to GDP from its current level of 2.5% to 5.5%—which will still be well within a reasonable range considering Iran's per capita income level and water availability. Beyond the transition period, however, the ratio will likely decline.

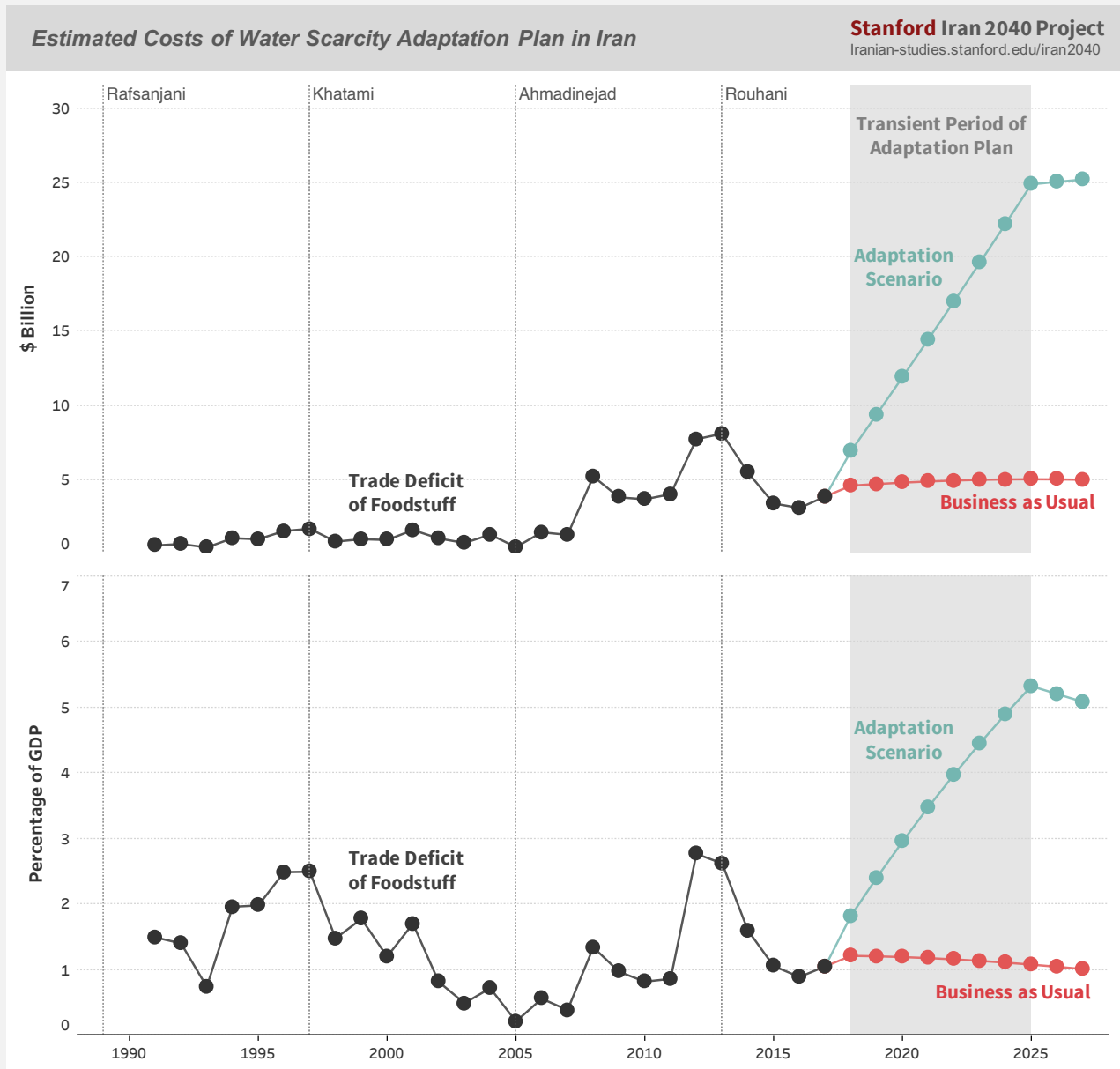


Figure 10. Historical trend and future projections of the agricultural trade deficit (top panel). Projected values for the costs under the *business as usual* scenario represent Iran's future trade deficit of foodstuff (import minus export) while in the case of the *adaptation* scenario they include the future trade deficit of foodstuff, the estimated depreciation costs of additional facilities and equipment (high-tech irrigation and greenhouses), and the compensations paid to the affected farmers for their set-aside lands. The bottom panel shows the ratios of the above variables to Iran's GDP. We note that the *business as usual* scenario is based on the assumption that the current levels of soil fertility and water availability for farming will remain unchanged in the future. As such, this scenario represents an overoptimistic case which is unlikely to be realized in the future.

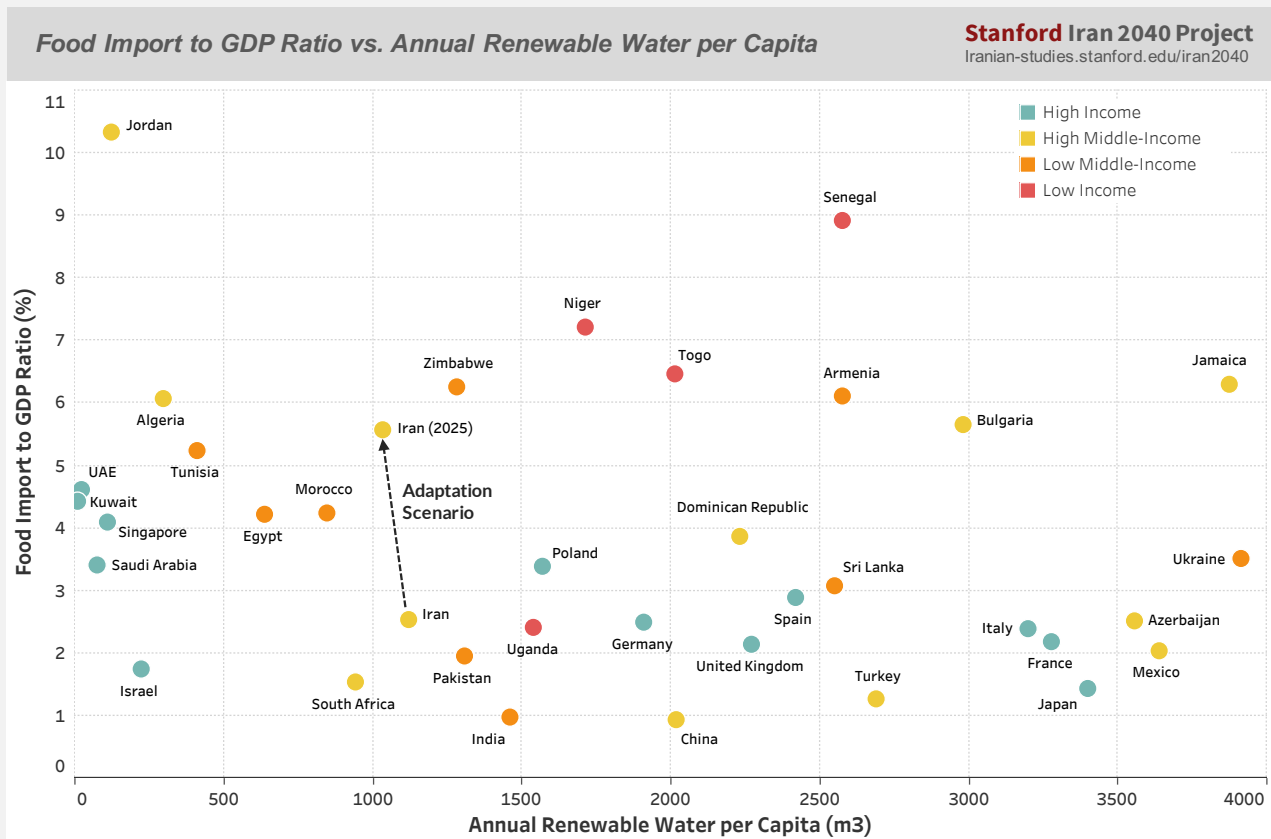


Figure 11. The ratio of food import to GDP (2016) versus total annual renewable water per capita for selected countries with annual TARWR of less than 4000 cubic meter per capita [19,20,21].

Finally, we note that changes to the agriculture sector of Iran, be they part of an *adaptation plan* or simply as an inadvertent consequence of lack of water for farming, could affect the well-being and distribution of millions of people living in rural areas. According to the latest census data [10], of the 80 million people in Iran, about three-quarters live in the urban areas (roughly 430 cities or *shahrestans*) and one quarter live in rural areas (about 2600 rural agglomerations or *dehestans*). Currently, about 6.4 million people, equivalent to 31% of Iran's rural population, live in areas known to have a *critical* condition with regard to groundwater stress and another 4.0 million people live in the rural areas experiencing high levels of groundwater stress (**Figure 12**). This would mean that Iran's water crisis can cause a massive redistribution of population from the rural parts of the water-scarce regions toward the cities.

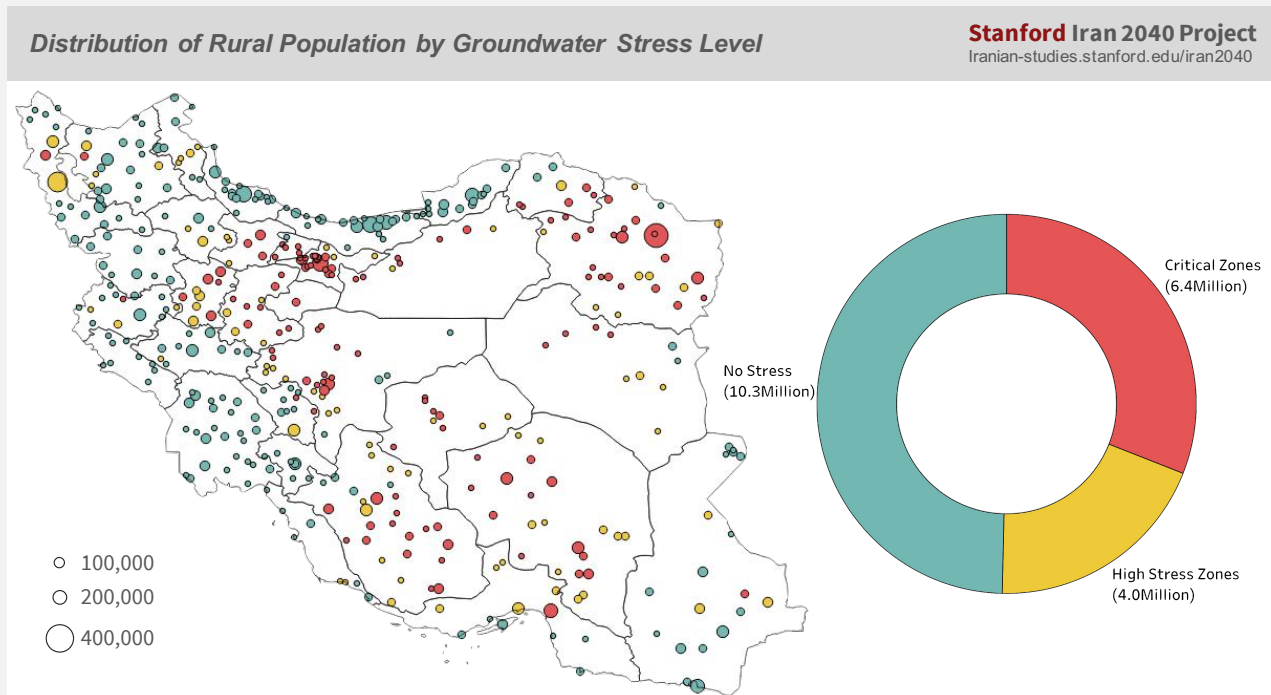


Figure 12. Distribution of Iran's rural population by groundwater stress level. Raw population data and water stress levels were obtained from references [10,18].

Concluding Remarks

Over the past decade, Iran's water crisis has morphed into a new paradigm with its impacts now visible in the daily lives of millions of people. The underlying reasons that contributed to the genesis and exacerbation of this crisis are

- The country's large and growing population;
- Increased per capita food demand, especially for water-intensive crops, due to increase in per capita income;
- Insufficient job creation in other sectors to absorb farmers which has raised the social costs associated with potential restrictive measures aimed at reducing farming activities;
- Decades of irresponsible and ideologized policies that have advocated and incentivized food self-sufficiency as one of the main pillars for the country's independence;
- Poor water resource management and governance with bias in favor of increasing water supply while making little effort to improve consumption efficiency. This is in part due to the presence of strong interest groups and corruption in the system that allowed for the construction of a large number of unnecessary dams from the public budget while overlooking the development of several hundred thousand illegal water wells;
- Increase in average temperature and decrease in average precipitation, both likely due to climate change.

Today, the share of the environment from the total renewable water in the country has reached such low levels that diverting water from the environment has no additional capacity to alleviate water deficits in other sectors. Henceforth, the system nearly represents a zero-sum situation where a mere geographical or sectoral redistribution of the country's water endowment will only relocate the pain from one point to another within the system. The longer the situation persists, the more frequent will become the inter-regional or inter-sectoral disputes over water rights that have occurred recently.

As long as water is available in Iran, there is a tendency to use it. Therefore, restoring a sustainable balance in the supply and demand of water in Iran cannot be achieved without a physical control of the water resources by the government. Once the government is able to enforce a cap on the amount of water to be consumed, implementation of more efficient allocation rules and high-tech irrigation should be considered as supplementary steps. It is important to realize that without physical control of water by the government, the use of high-tech irrigation could in fact lead to an increase in water consumption as the irrigated areas can expand when upgrading from traditional irrigation to high-tech irrigation. Further, the losers of the proposed paradigm shift will certainly need to be compensated from the public budget as they will otherwise oppose any reform.

Due to their high capital costs, enormous energy consumption, and massive environmental footprint, desalination (for purposes other than providing urban water) is ruled out as a potential solution to Iran's water crisis at large. Therefore, Iran's water scarcity problem should be addressed through a combination of water productivity gain (e.g., modernized irrigation), selective termination of some water-intensive activities, and an increased use of reclaimed water. The proposition presented in this report indicates that the potential gain from enhancement of agricultural water productivity (output per drop) in Iran, estimated at about 7 BCM, is not sufficient to fundamentally change the calculus given that about 44 BCM water needs to be saved. Therefore, the ultimate resolution, to a large extent, should rely on reduced water allotments to agriculture. We estimate that the resultant agricultural contraction would correspond to \$300 of additional spending on food imports per person per year. The total value of the imported foods (virtual water) will roughly equal a maximum of 5.5% of Iran's expected future GDP level.

Given the realities of the water and soil landscape of Iran, we conclude that the hope for a high level self-sufficiency in the long run is only an elusive notion. Instead of self-sufficiency, policymakers should make it their primary goal to ensure the nation's food security, which can be achieved by boosting other sectors of the economy to allow for the import of more food. Furthermore, the pronatalist agenda seeking to increase the total fertility rate above the current level, which is indeed close to the replacement level, should be abandoned as it will only exacerbate the ongoing water shortage and risk the food security of future generations. In order for policymakers to make informed decisions, experts and researchers should develop a modern

water governance structure for Iran that encompasses a detailed spatial and temporal account of water availability at various scales, the maximum allowable use, and fair and economically viable water distribution among various stakeholders. Of particular importance is the determination of regional crop patterns optimized for water use, the suitability of climate, and economic profitability. Experts should therefore devote their efforts to research and outreach activities that produce tangible outcomes. They should also clearly and truthfully explain the realities of the matter to the policymakers and the public to help developing a national plan to address the formidable water crisis facing Iran.

Glossary

BCM	Billion Cubic Meter
d	Growth Rate of Demand for Food
DSSAT	Decision Support System for Agricultural Technology Transfer
EMC	Environmental Management Class
ET	Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
GDP	Gross Domestic Product
ha	Hectare
n	Income Elasticity of Demand for Food
p	Population Growth Rate
pci	Per Capita Income Growth Rate
TARWR	Total Actual Renewable Water Resources
TFR	Total Fertility Rate
UIL	Unsustainable Irrigated Lands

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Appendix A: Iran's Water Resources

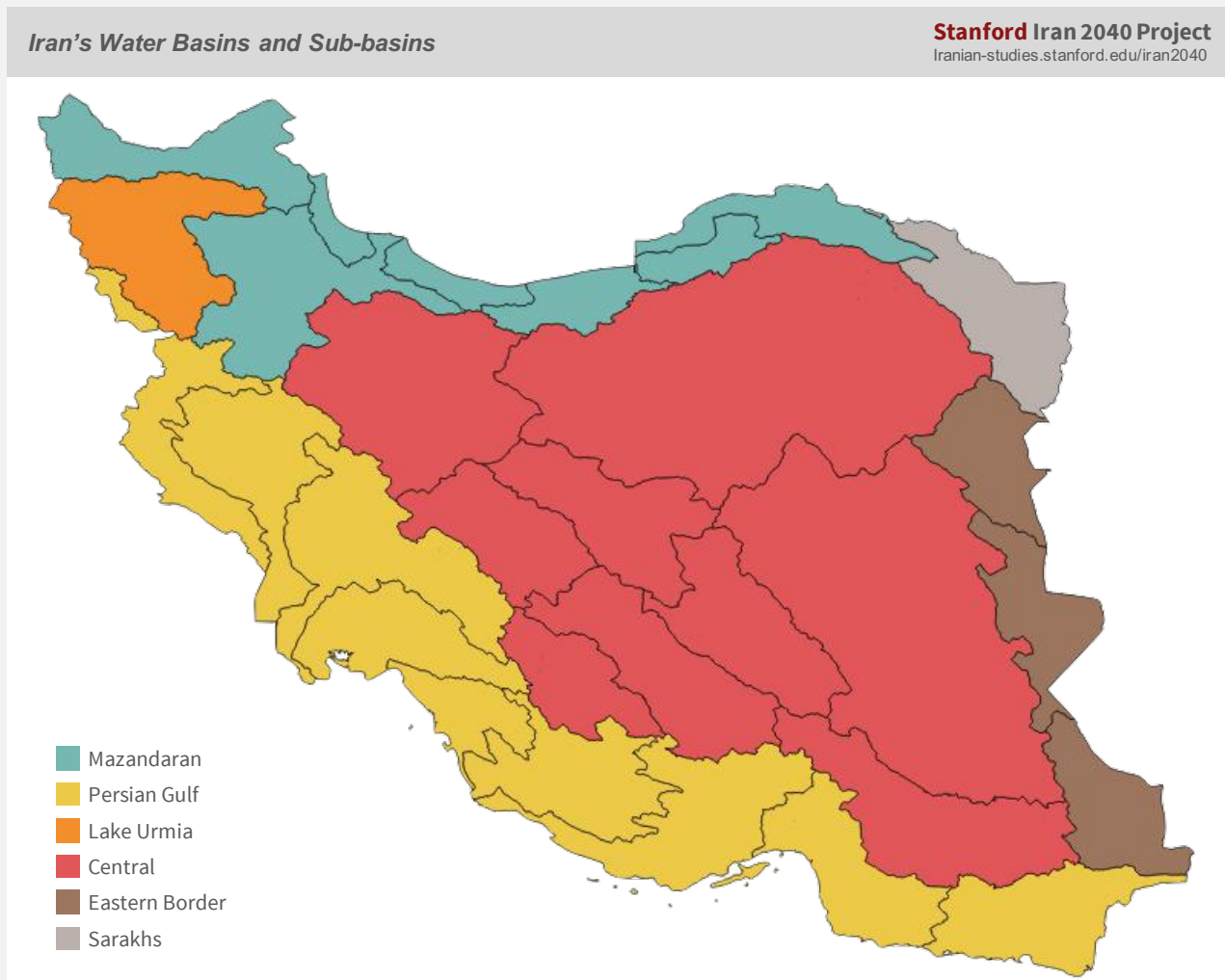


Figure A1. Iran's water basins and sub-basins.

Table A1. The number of sub-basins and study zones by basin in Iran.

Basin	Sub-basins	Study Zones
Mazandaran (Caspian Sea)	7	43
Persian Gulf and Sea of Oman	9	265
Lake Urmia	1	25
Central (Markazi)	9	233
Eastern Border (Hamoun)	3	30
Sarakhs	1	13
Total Iran	30	609

Table A2. Iran's water balance data [13,22].

Resource / Withdrawal	Parameter	Amount of Water (BCM)		
		2001	2016	Post-adaptation
Renewable Water Resources	TARWR	130	89	89
	Surface flow	92	63 ^a	63 ^a
	Groundwater recharge	38	26 ^a	26 ^a
Freshwater Withdrawal	Surface	42	40	23
	Groundwater	51	56	30 ^b
	Total	93	96	53
Freshwater Use	Municipal	6	8	10
	Industrial	1	2	2
	Agriculture	86	86	41
	Total	93	96	53
Return Flow	From agriculture	26	27 ^a	15 ^a
	From industrial	1	1 ^a	1 ^a
	From municipal	2	2 ^a	1 ^a
	Total	29	30	17
	To surface	19	20 ^a	11 ^a
	To groundwater	10	10 ^a	6 ^a
	Groundwater recharge by return flows	7	7 ^a	4 ^a
Balance	Sustainable groundwater resources ^c	45	33	30
	Surface Outflow ^d	69	43	50
Stress Level	Withdrawal to TARWR ratio (%)	72	108	60

^a Estimated by proportional adjustment of data from 2001.

^b Assumed to be equal to sustainable groundwater resources.

^c Sum of annual recharge of aquifers from renewable resources and return flow.

^d Sum of renewable surface flow and return flow (to surface) minus surface withdrawal.

Table A3. Iran's environmental flow (EF) under different environmental management classes (EMC) [23,24].

EMC Class	EF (BCM)	EMC Description
Class A	123.5	Protected rivers and basins, no new water project
Class B	87.9	Slight basin modification and water resources development
Class C	64.8	Intact basic ecosystem function
Class D	50.2	Visible basin disturbances (dams, diversions, transfers)
Class E	na	Extensive water resources exploitation, only tolerant species survive
Class F	na	Basic ecosystem functions have been destroyed

Appendix B: Prediction of Rainfed Yields of Wheat, Barley, and Chickpea

We used Decision Support System for Agricultural Technology Transfer [25,26] to project yields of rainfed wheat, barley and chickpea across Iran at ~1 km resolution. These crops represent the major rainfed crops grown in Iran, accounting for 94% and 85% of total rainfed acreage and production of field crops, respectively [4]. Equipped with various crop and soil-water dynamics models, DSSAT is a modular platform that uses four major groups of inputs (i.e., crop, soil, weather, and management) to simulate crop growth and yields as well as a large number of soil-water parameters(e.g. daily water use and evapotranspiration). DSSAT has been widely used for projection of crop productivity at both the regional [27] and global scales [28].

Crop and Management Specification

DSSAT provides a variety of tools (sub-models) for incorporating the effect of farm management practices such as fertilizer application, irrigation, tillage, and planting density. **Table B1** summarizes farming practices implemented in DSSAT's simulations. All simulations were initiated one month before the planting date to inform the model about the soil conditions prior to and at the planting date. As the planting date for a given crop can vary across the country, we ran simulations over a wide range of planting dates (see **Table B2**). The planting dates used in simulations include both the autumn and spring cultivations, which are common practices for these three crops in Iran. The yield data reported in this study are based on the average of the three planting dates resulting in the highest yields. The genotypic coefficients for wheat and barley were obtained from previous studies calibrated for *Sardari* [29] and *Valfraj* [30] cultivars, respectively. For chickpea we used DSSAT default coefficients available for cultivar *Annigeri* [31].

Weather and Soil Data

Daily weather data on maximum and minimum temperatures, precipitation, wind speed, and solar radiation were obtained from AgMERRA Climate Forcing Dataset for Agricultural Modeling [11]. The data have a spatial resolution of $0.25^\circ \times 0.25^\circ$ (~ 28 km) and cover the time period from 1980 to 2010. In this analysis, the data from the last three years (2008–10) were used for simulating crop yields: our yield data therefore represent the average of three individual simulations from the respective years.

The soil variables required by DSSAT were mainly sourced from SoilGrids250m [32] and the Global Soil Dataset for Earth Modeling [33]. The spatial resolution of the former dataset is 250 m while that of the latter is ~ 1 km. To create uniform spatial resolution of soil and weather variables, we first created grid points of 30 seconds (~ 1 km) resolution within the administrative boundaries of Iran. For any points, we then sampled the grid value from the global soil and weather raster layers. Some soil parameters required by DSSAT are not available in these datasets but can be estimated from the other soil properties. These were soil hydraulic

properties pertinent to the soil water content at wilting point (SLLL), field capacity (SDUL) and saturation (SSAT), and saturated hydraulic conductivity (SSKS), which were derived from pedo-transfer functions as described by [34]. We used MATLAB (MathWorks 2017a) to convert the soil data from these sources to the format that is readable by DSSAT. A list of major soil attributes used as input by DSSAT is shown in **Table B3**.

Inland water bodies, urbanized areas, and natural forests and pastures were excluded from the analysis. We used GlobCover [35] to identify these land uses. Also excluded were protected areas for which the data were obtained from The World Database on Protected Areas [36]. The excluded areas covered 19.3 million ha (i.e., 12%) of Iran's landmass.

Table B1. Management practices used in DSSAT for simulating the yields of wheat, barley and chickpea under rainfed conditions in Iran.

Crop	Planting Density (No./m ²)	Row Space (cm)	Plant Depth (cm)	N (kg ha ⁻¹) ^a
Wheat	300	16	5	100
Barley	300	16	5	100
Chickpea	30	40	5	50

^a N was assumed to be applied as urea at the time of planting.

Table B2. Planting dates used in DSSAT for simulating the yields of wheat, barley and chickpea under rainfed conditions in Iran.

Crop	Planting Dates									
Wheat	1 Oct	11 Oct	21 Oct	31 Oct	10 Nov	20 Nov	30 Nov	10 Dec	20 Dec	30 Dec
Barley	1 Oct	11 Oct	21 Oct	31 Oct	10 Nov	20 Nov	30 Nov	10 Dec	20 Dec	30 Dec
Chickpea	07 Nov	22 Nov	07 Dec	22 Dec	06 Jan	21 Jan	05 Feb	20 Feb	12 Mar	01 Apr

Table B3. Soil variables used as input in DSSAT.

Soil Variable	Source
Soil depth, cm	SoilGrids250m
Soil family	SoilGrids250m
Bulk density, g cm ⁻³	SoilGrids250m
Organic carbon, %	SoilGrids250m
Clay (<0.002 mm), %	SoilGrids250m
Silt (0.05 to 0.002 mm), %	SoilGrids250m
Coarse fraction (>2 mm), %	SoilGrids250m
pH in water	SoilGrids250m
pH in buffer	SoilGrids250m
Water content: lower limit or wilting point, cm ³ cm ⁻³	Obtained from pedo-transfer functions using SoilGrids250m data
Water content: drained upper limit or field capacity, cm ³ cm ⁻³	Obtained from pedo-transfer functions using SoilGrids250m data
Water content: upper limit or saturated, cm ³ cm ⁻³	Obtained from pedo-transfer functions using SoilGrids250m data
Saturated hydraulic conductivity, cm h ⁻¹	Obtained from pedo-transfer functions using SoilGrids250m data
Runoff curve number	Derived from hydrologic soil group based on Soil Conservation Service (SCS) using SoilGrids250m data
Soil texture	Derived from the soil texture classification of United States Department of Agriculture (USDA) using SoilGrids250m data
Total nitrogen, %	The Global Soil Dataset for Earth System Modeling
Root growth factor, 0.0 to 1.0	The Global Soil Dataset for Earth System Modeling
Cation exchange capacity, cmol kg ⁻¹	The Global Soil Dataset for Earth System Modeling
Calcium carbonate, CaCO ₃ (%)	The Global Soil Dataset for Earth System Modeling
Drainage rate, fraction day ⁻¹	The Global Soil Dataset for Earth System Modeling
Base saturation, cmol kg ⁻¹	The Global Soil Dataset for Earth System Modeling
Electrical conductivity, EC (dS/m)	The Global Soil Dataset for Earth System Modeling

Appendix C: Producer Prices of Agricultural Products in Iran

Table C1. The relative producer prices of major crops and fruits in Iran in 2016 (wheat = 100) [37].

Crop	Price Index
Apples	123
Alfalfa	72
Barley	69
Beans	392
Chickpea	331
Clover	63
Cotton	781
Cucumber	81
Dry clover	63
Eggplant	58
Garlic	258
Grain maize	83
Grapes	81
Lentil	369
Melon	61
Oilseed rape	192
Olives	330
Onion	39
Oranges	61
Pistachios	1977
Potato	34
Rapeseed	192
Rice	288
Sesame	435
Silage corn	52
Soybean	177
Sugar beet	24
Sugarcane	10
Sunflower	207
Tea	127
Tobacco	901
Tomato	31
Watermelon	37
Wheat	100

Appendix D: Determination of Best Performing Crop for UILs

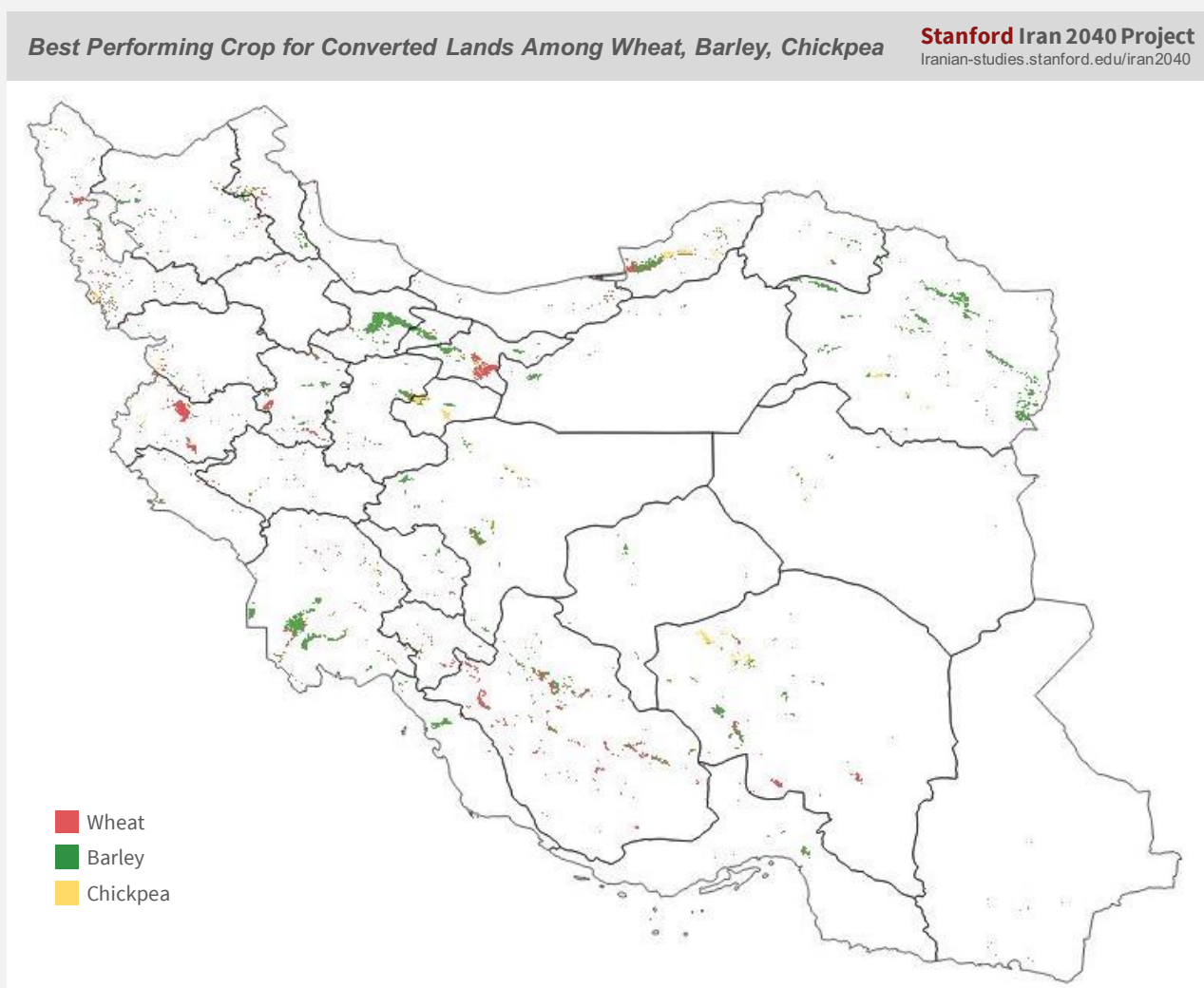


Figure D1. Best performing crop for cultivation on converted lands from irrigated to rainfed among wheat, barley, and chickpea.

Appendix E: Additional Factors Affecting Food-Water Nexus

Table E1. Additional factors that can potentially affect the food-water nexus in the future.

Factor	Main Effects	Impact on Water
Own-price elasticity of demand	For foods with lower domestic prices than their international prices, a reduction in domestic food supply will increase their relative prices, which in turn will reduce both their consumption and wastes	Moderate water savings in the mid- to long run
Climate Change	Likely causes lower precipitation, higher temperature, and higher ET	Moderate reduction in TARWR in the long run
Crop patterns and genotype improvement	Changes in crop patterns and genotypes toward less water-consuming and draught-tolerant products	Low water savings in the mid- to long run
Salinization and soil degradation	Loss of fertile land, increase the need for drainage and soil amendments	Low to moderate reduction in productivity per drop
Desalination	Too expensive for agricultural purposes, energy intensive, and large environmental footprint	Zero to low impact on irrigation water