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Future food self-sufficiency in Iran: A model-based analysis

A. Soltani[a,*], S.M. Alimagham[a], A. Nehbandani[a], B. Torabi[a], E. Zeinali[a], E. Zand[b], V. Vadez[c,d], M.P. van Loon[e], M.K. van Ittersum[e]

[a] Agronomy Group, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, 49138-15739, Iran
[b] Iranian Research Institute of Plant Protection, Agricultural Research Education and Extension Organization (AREEO), Iran
[c] Institut de Recherche pour le Developpement (IRD) – Université de Montpellier – UMR DIADE, 911 Avenue Agropolis, BP 64501, 34394, Montpellier Cedex 5, France
[d] International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh, 502 324, India
[e] Plant Production Systems Group, Wageningen University, PO Box 430, NL-6700 AK, Wageningen, the Netherlands

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ABSTRACT

Iran, with its more than 80 million people, is located in a politically unstable region. The country's future food supply and sufficiency is at stake because of the over-exploitation of land and water resources. In this study, a modeling framework was used to estimate production of plant species as influenced by different scenarios for the year 2030. The scenarios capture different agricultural water resources, improved irrigation efficiency and narrowing of crop yield gaps (i.e, difference between current farm yield and potential yield). Food demand, given a range of diets and loss and waste scenarios was also evaluated using the modeling framework. We found that limiting current agricultural water withdrawal to a safe level for the environment (from 86.0 to 38.5 billion m^3 per year) until 2030, along with an increase in population (from 80 to 90 million people) during the same period led to a decline in self-sufficiency from of 83% to only 39%, assuming current production management, current diet and food loss and waste. Implementation of a highly-improved production scenario (narrowing relative yield gap from the current 60% to 40% and increasing irrigation efficiency from the current 38% to 53%) restored self-sufficiency to 61% using the current diet, loss and waste and to 69% using a medium-change demand scenario (a modified diet and 15% reduction in loss and waste). Avoiding water over-withdrawal by agriculture until 2030 won't be possible without sacrificing a degree of self-sufficiency. To achieve the highest self-sufficiency results, a combination of increased production and controlled demand are necessary.

1. Introduction

Feeding the world's 9–10 billion people in 2050 has been recognized as one of the most important challenges of mankind (Tilman et al., 2011; Cassman, 2012; Smith, 2013). Iran, with more than 80 million people, is geo-politically connected to an unstable region, the Middle East. Iran is characterized by its high population growth, low and erratic rainfall, limited arable land, and severely limited water resources (Soltani et al., 2016). The country's population has increased from about 30 million to more than 80 million during the last 50 years. During the same time agriculture has expanded and intensified. The country's population is predicted to surpass 89 million by 2030 (WPP, 2017). Supplying enough food for the population is a major challenge, especially since exploitation of land and water resources has already surpassed sustainable boundaries (Soltani et al., 2020).

More than 90% of the current crop products in Iran are harvested from irrigated farming (Soltani et al., 2020), which is much higher than the global average of 20% (Keating et al., 2014), indicating agriculture in Iran is highly irrigation dependent. Current water withdrawal for agriculture is 86 billion m^3, which is 90% of the country's water use (Soltani et al., 2020). According to estimates of the Ministry of Energy (MoE), the allowable, i.e. sustainable, level of agricultural water withdrawal, is 61.7 billion m^3 per annum (ABFA, 2018). Hence, there is at least 24 billion m^3 per year water over-withdrawal by agriculture, due to over-expansion of irrigated agriculture. The estimate of water over-withdrawal is even higher when internationally known standards (e.g. Smakhtin et al., 2004; Fader et al., 2013) and current droughts in the country (Abbasi et al., 2017) are considered. The water over-withdrawal in agriculture is known to be responsible for the country's water crisis or water bankruptcy (Madani, 2014; Madani et al., 2016) and environmental problems which are observable everywhere within the country: problems like disappearing wetlands, lakes and rivers, decline in groundwater water-tables, drying wells, land subsidence, dust storms and

* Corresponding author.
E-mail address: Afshin.Soltani@gmail.com (A. Soltani).

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ecosystem damage (Moridi, 2017). Thus, it seems agriculture and the environment are in an unsustainability spiral.

For this reason, urgent plans are needed to reduce water use in agriculture before the environmental consequences become irreversible. Reducing water withdrawal for agriculture may exacerbate the challenge of sufficient food production and may reduce food self-sufficiency. The country's food self-sufficiency is defined here as the ratio (or percentage) between national food production and the national food demand. The main question of our research is therefore, whether it is possible to maintain the current level of food self-sufficiency with less agricultural water use. To answer this, we assess the contributions of increased irrigation efficiencies and exploitation of untapped potential yields. Higher irrigation efficiency results in less water use per unit area and the saved water can be set aside for the environment or can be used to irrigate more land, if available (Jagermeyr et al., 2015, 2016). Narrowing yield gaps, the difference between farmers' yields and potential yields, has been identified as a promising option in improving food supply and food self-sufficiency (Van Ittersum et al., 2016; van Loon et al., 2018; Timsina et al., 2018). One other important question is: how effective are the measures for managing food demand such as diet modification and reducing food loss or waste. We are aware that food self-sufficiency is not equal to food security and is not a prerequisite for food security. However, it helps quantitative evaluation of different measures in food production and/or demand.

Soltani et al. (2020) set up a tested simple simulation model (SSM-iCrop2) for Iran using the Global Yield Gap and Water Productivity Atlas (GYGA; Van Ittersum et al., 2013) protocol. The modeling setup successfully simulated irrigated (Y_p) and rainfed (Y_w) potential yield and net irrigation water requirement (for irrigated conditions) of major plant species in Iran. The modeling setup was coupled with two modules that calculate crop production at province and country level as a function of Y_p and Y_w, relative yield gap, irrigation efficiency, and land and water allocation and resources.

In this study, we used the SSM-iCrop2 setup for Iran and its two modules for water allocation between species and plant production (Soltani et al., 2020) to estimate production of plant species at the province and country level, as influenced by different scenarios of agricultural water resources, improved irrigation efficiency and narrowing crop yield gaps. In addition, we developed and utilized a procedure to assess food demand for a range of diets and loss and waste scenarios for the year 2030. Iran's food self-sufficiency by 2030 was examined for different combinations of production and demand scenarios in order to explore some strategies for the country's future food security. We are not aware of similar analyses for Iran, or other countries in the region.

2. Methods

2.1. Design of the framework

The scheme presented in Fig. 1 was used for calculation of food self-sufficiency. Demand for plant and plant products to feed the country, directly or indirectly via animal products, was obtained as a function of population, diet, food loss and waste and conversion coefficients of plant products to food items. Demand for livestock products, e.g. meat, milk and eggs, was converted to the corresponding plant products needed for their production. Using this scheme, the effect of various diets, loss and waste and population scenarios can be evaluated. The country's plant production was calculated as a function of potential yield of the cultivated plant species under irrigated (Y_p) and rainfed (Y_w) conditions, the relative yield gap (the relative gap between Y_p or Y_w and actual or target farmers' yield), irrigation efficiency (for irrigated conditions only) and available land and water resources.

2.2. Calculation of plant production with the Water and Production modules

Calculation of plant production for Iran was done using the SSM-iCrop2 model setup for Iran as described by Soltani et al. (2020; shaded part of Fig. 1). Briefly, they parameterized and evaluated a simple crop growth model (SSM-iCrop2) for more than 35 major plant species of Iran (see the SI for the country map and the list of plant species). Then, they applied the model using a bottom-up approach, which entails that local information was used as input for the model to estimate crop production, which was then scaled-up to regional and country level 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 provides representative estimates of Y_p and Y_w and net irrigation water requirement to reach Y_p for the plant species at province level as influenced by climate, soil, management and genetics (cultivar). The estimates are used in two modules (*Water* and *Production* modules; Soltani et al., 2020) to calculate total production of plant species at province and country levels as a function of available land and water resources and the efficiency of utilizing the resources as quantified by relative yield gap (RYG) and irrigation efficiency (IE) (Fig. 1). RYG was estimated as '$1 - Y_a/Y_p$' for irrigated conditions and as '$1 - Y_a/Y_w$' for rainfed conditions. *IE* definition used in the present study is the same as in Soltani et al. (2020), and is the ratio between net irrigation water requirement and water withdrawal (i.e. the amount of water diverted from rivers, reservoirs, lakes, or underground).

The modules include statistics of the area under cultivation and actual yield (Y_a) of plant species at province level obtained from the Ministry of Agriculture for the period of 2011–2017 along with data of provincial current water withdrawal for irrigation from the Ministry of Energy (MoE). They also include RYG estimates obtained using Y_p, Y_w and Y_a data for the plant species at province level. Data of total water withdrawals for agriculture is available from MoE at province level, but the allocation of agricultural irrigation water resources to different plant species in each province is not available. This allocation is therefore estimated by the *Water* module based on area under cultivation of different species (cropping pattern) and their net irrigation water requirement.

2.3. Calculation of demand for plant products with the demand module

A module (*Demand* module) was developed to calculate the country's demand using the framework presented in Fig. 1. The demand for each plant product (e.g. wheat grain) per capita in the country is derived from the per capita consumption of the related food item(s) (e.g. flour as bread, pasta and bran) in the average diet of the country and the country's population, taking into account (i) the conversion factor of the product to the food item (e.g. wheat to flour), (ii) loss and waste of the product from farm gate to the consumer, and (iii) other non-food uses of the product (e.g. as seed) (Fig. 1).

The average diet (known also as food basket) of every Iranian has been studied by various centers in the country; here we use the values of the National Nutrition and Food Technology Research Institute of the Ministry of Health (MoH) (Salehi, 2012), revised with minor changes during recent years (Table 1). MoH also provided an 'optimal diet' for Iranians based on agricultural and economic conditions of the country. The 'optimal diet' includes less oil and sugar and more fruits, vegetables, meat, milk and eggs. Loss and waste for each product was estimated as per capita supply of each product minus per capita consumption of the same product and minus non-food consumption using 2011–2015 statistics from Commerce Chamber of Iran and Ministry of Agriculture (Shariatmadar et al., 2017) (Table S2 in SI).

The conversion factors of plant and livestock products to food items were obtained from local references and when necessary weighted averages were used (Table S3 in SI). Animal products are derived from plant products. Representative estimates of required plant products to

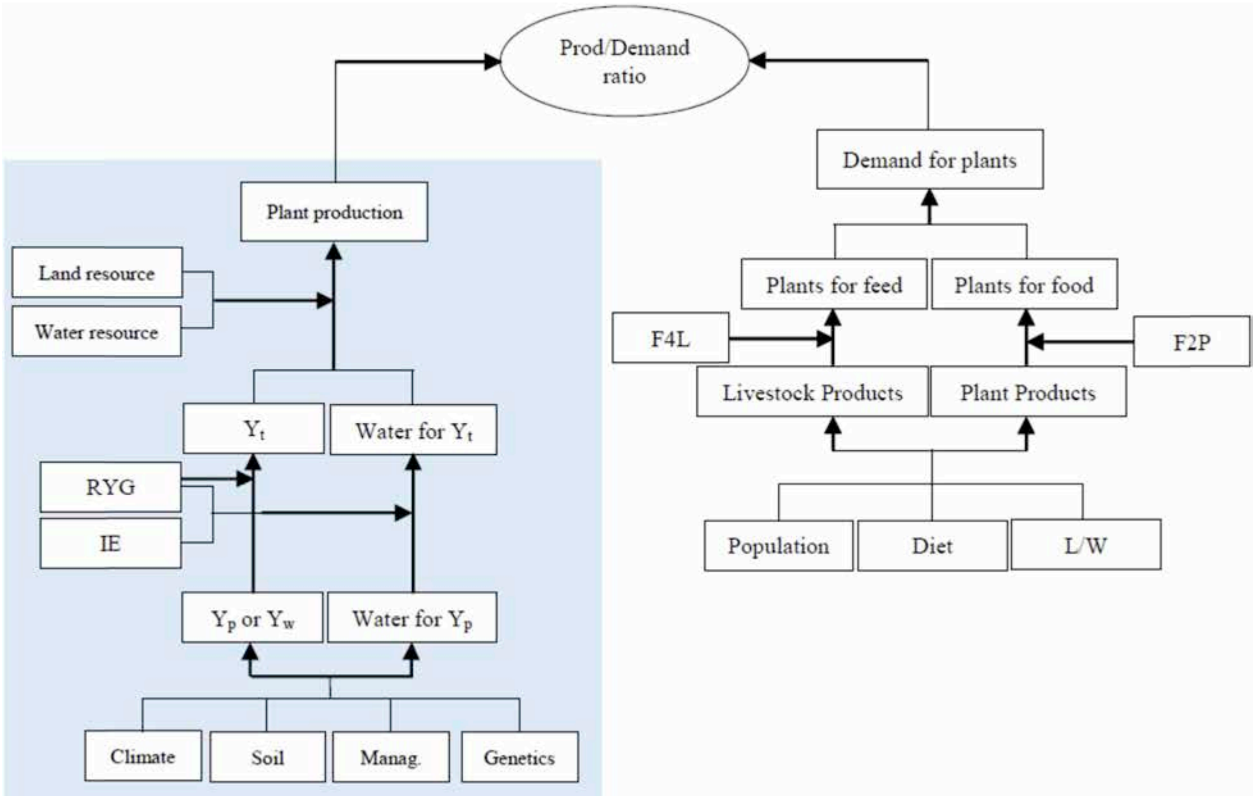

Fig. 1. Flowchart for calculation of food production-demand ratio or food self-sufficiency. Shaded area includes production related variables. Abbreviations are: L/W: food lost and waste and other non-food uses; F2P: coefficients for the conversion of plant products to plants such as flour to wheat grain; F4L: coefficients for conversion of forages to livestock products; Y_p: potential yield under irrigated conditions; Y_w: potential yield under rainfed conditions; IE: irrigation efficiency; RYG: relative yield gap; Y_t: the target yield.

Table 1
'Optimal' and current diets of Iranians as proposed or estimated by the Ministry of Health (MoH) (Salehi, 2012). Current diet as used in the present study is the current diet of the Ministry of Health adjusted for the changes during recent years. In modified diet 30% red meat in current diet is replaced with chicken meat, 30% chicken is replaced with pulses and 30% rice is replaced with wheat (changed items are indicated in italic). All units are g fresh weights per person per day.

Food Item	MoH Optimal diet	MoH current diet	Current diet in present study	Modified diet
Wheat flour	*330*	*336*	*337*	*364*
Rice	*95*	*100*	*90*	*63*
Pulses	*26*	*18*	*18*	30
Potato	70	68	109	109
Oil	35	46	46	46
Sugar	40	66	66	66
Fruits	280	212	212	212
Vegetables	300	228	228	228
Red meat	*38*	*34*	*27.2*	*19.1*
Chicken meat	*46*	*44*	*63*	*49*
Eggs	35	25	25	25
Milk	250	190	190	190
Fish meat	18	18	18	18

produce each unit of animal products were necessary for the current analysis. Estimates of plant products required for each unit of animal product were calculated considering current production systems and other influencing factors, like the length of growth period, lactation period, fattening period and dominant feeds in the country (Table S4 in SI).

Demand, calculated using above information, was compared with production statistics for the period of 2011–2017 to test the robustness of the framework used. In this comparison a country population of 80 million people was used. Calculated excesses/deficiencies in plant products and self-sufficiency were then compared with reported export (import) and self-sufficiency for the same period (Shariatmadar et al., 2017). Although the estimated and reported data may share some common data, the comparison of the two is to some extent an independent model evaluation.

2.4. Scenario analysis

The SSM-iCrop2 model setup for Iran together with *Water*, *Production* and *Demand* modules were used to estimate the production and demand of plants for a range of scenarios in 2030 compared to present conditions (2015). (The SSM-iCrop2 model setup together with the three modules is called *SEA* system). We selected the year 2030, because it has been shown that the need for the higher yield growth rates and improved food security is greatest before 2035 due to anticipated population dynamics (Rosegrant et al., 2013; Fischer and Connor, 2018). Plant production was estimated for combinations of two levels of irrigation water resources, three levels of RYG and three levels of IE improvement. As the time period between 2015 and 2030 is relatively short, it was assumed the estimates of Y_p and Y_w in 2030 are the same as for current conditions and the impact of climate change and possible improvements of Y_p and Y_w due to plant breeding were ignored. Further, it was assumed that the cropping pattern (relative area of cultivation of different plant species) and also the allocation of water to the different crops within the provinces remains unchanged.

Various population estimates for the year 2030 in Iran have been made. The United Nations medium fertility variant projects 88.9 million (WPP, 2017). However, the estimation of the Ministry of Social Welfare is slightly higher, i.e. 90.6 (Shakouri, 2009). Here, we used the average of these two estimates (i.e., 89.7 million).

2.4.1. Water availability variants

Iran's renewable blue water resource (RWR, long-term mean) is 137.5 billion m^3 (Faramarzi et al., 2009; FAO, 2016). Current water withdrawal for agriculture is 86 billion m^3 per year as estimated by MoE (ABFA, 2018; FAO, 2016; Nasseri et al., 2017). The allowable level of water withdrawal for the country's agriculture (agricultural utilizable water; AUW) as estimated and declared by MoE is 61.7 billion m^3 per year (31.4 billion m^3 from underground sources and 30.3 billion m^3 from surface sources) (ABFA, 2018). The logic of this estimate is that 65% of RWR can be exploited and 70% of the available water can be devoted to agriculture ($137.5 \times 0.65 \times 0.7 = 62$). Current MoE estimates of water withdrawal for agriculture and AUWs are available at provincial levels (Soltani et al., 2020). The MoE estimate of AUW is debatable because it over-estimates the fraction of RWR which is exploitable and because it is based on data and measurement before 2006. Currently, MoE is revising its estimates of AUW, but no formal data has been released so far.

In Iran 75% of precipitation occurs in 25% of the country's area and 75% of precipitation occurs off-season as well (Madani, 2014). Several sources (e.g. Smakhtin et al., 2004; Fader et al., 2013) have suggested that only 40% of RWR is exploitable, because of a mismatch between spatiotemporal variability of water availability and water demand, and because part of the RWR needs to be reserved for the functioning of ecosystems and to sustain environmental flows. Thus, an environmentally safe estimate of the country's total exploitable water would be 55.0 billion m^3 ($137.5 \times 0.4 = 55.0$) and AUW would be 38.5 billion m^3 assuming 70% of the available water can be devoted to agriculture ($55 \times 0.7 = 38.5$). With this estimate of AUW, there will be at least 16.5 billion m^3 of water for non-agricultural uses (household and industry) in 2030 which is deemed sufficient. Provincial AUWs were estimated in the same way.

Nasseri et al. (2017) showed that the country's RWR has declined to 106 billion m^3 per year (a 23% reduction) based on weather data of 2007–2014. If we assume these recent changes in climate are sustained and we are faced a new normal, then the above estimate of 38.5 billion m^3 is the result of 52% of RWR of 106 billion m^3 as the country's total exploitable water and 70% thereof as AUW ($106 \times 0.52 \times 0.7 = 38.5$).

2.4.2. Irrigation efficiency variants

Today's average IE in Iran is estimated to be 38%, but it varies between provinces (Soltani et al., 2020). According to FAO, scheme irrigation efficiency (efficiency of conveyance and application) of 50–60% is good (Brouwer et al., 1989). Therefore, IE of 60% was considered as a final target IE. Three variants of IE improvement by 2030 were defined:

- No improvement: it was assumed IEs in 2030 are identical to current estimates (i.e. 38%).
- 33% improvement of the difference between target IE of 60% and current provincial IEs, so in 2030 the country reaches IE of 45% (0.5% improvement per year).
- 67% improvement of the difference between target IE of 60% and current provincial IEs, so in 2030 the country reaches IE of 53% (1% improvement per year).

2.4.3. Yield gap variants

Normally, realizing a RYG of 20% is considered to be the minimum under good farm management because of economic and environmental constraints (Cassman, 1999; Cassman et al., 2003; Van Ittersum et al., 2013). Iran's current country average RYG is estimated to be 60%, but varies by species and province (Soltani et al., 2020). Opportunities to increase plant production by 2030 were then explored for three narrowing yield gap variants:

(i) No change in yield gap: it was assumed current yield levels remain unchanged until 2030.
(ii) 25% reduction of the difference between a RYG of 20% and the current RYGs, such that the average country RYG reduces from the current 60% to 50%.
(iii) 50% reduction of the difference between a RYG of 20% and the current RYGs, such that the average country RYG reduces from the current 60% to 40%.

2.4.4. Combining irrigation efficiency and yield gap variants into scenarios

The final scenarios for self-sufficiency analysis are three combinations of the above mentioned IE and RYG variants:

(i) Non-improved production scenario (NIP): RYG and IE levels in 2030 are equal to their current (2015) levels (variant *i* of both RYG and IE).
(ii) Medium-improved production scenario (MIP): RYG of 50% and IE of 45% are achieved in 2030 (variant *ii* of both RYG and IE).
(iii) Highly-improved production scenario (HIP): RYG of 40% and IE of 53% are achieved in 2030 (variant *iii* of both RYG and IE).

In scenarios in which irrigation water resources were not sufficient to support irrigated production at current area under cultivation (2015), the non-irrigable area was calculated and devoted to rainfed production of the same plant species (Fig. S2 in SI).

2.4.5. Food demand scenarios

It has been indicated that diets with less animal products can contribute to food security as they decrease the overall demand for plant products and resources (Jalava et al., 2014; Springmann et al., 2018; Willett et al., 2019). Similar to changes in diet, reduction of loss and waste may help in reducing demand (Jalava et al., 2016). It has been reported that the maximum reduction in loss and waste is around 50% (Kummu et al., 2012). The demand scenarios used for self-sufficiency analysis were therefore:

(i) No-change in per capita demand scenario (NDS): current (2015) diet and food loss and waste remain unchanged until 2030.
(ii) Increase in per capita demand scenario (IDS): MoH 'optimal' diet is implemented in 2030 and food loss and waste remain unchanged until 2030
(iii) Decrease in per capita demand scenario (DDS): a modified diet (Table 1) plus 15% reduction in loss and waste are implemented in 2030.

In the modified diet, 30% red meat in current diet is replaced with chicken meat, 30% chicken is replaced with pulses and 30% rice is replaced with wheat (Table 1). The replacements were done so that protein content and energy of the modified diet remained unchanged. No dramatic change in diet, e.g. huge reduction in animal protein and using meat substitutes, were imposed until 2030. The modifications were in accordance of current trajectories: consumption of rice and red meat has declined and that of potato and chicken meat has increased because of the economic sanctions on Iran. This is confirmed by the comparison of current diet reported by Salehi (2012) with the current diet used in the present study which is revised for the changes in recent years (Table 1). Consumption of red meat in the modified diet may seem low (19.1 g d^{-1}), but it is higher than the maximum level recommended (14 g d^{-1}) for healthy, plant-based (flexitarian) diets (Springmann et al., 2018; Willett et al., 2019). The consumption of oils and sugar remained unchanged in the modified diet (Table 1) although their current consumption is higher than levels recommended by MoH. The reason is that these are cheap food items and trying to decrease the items seems challenging, especially given the sanctions. The consumption of milk remained unchanged as the item is partially subsidized by the government. Table S5 in SI compares the diets with respect to quality measures and limits.

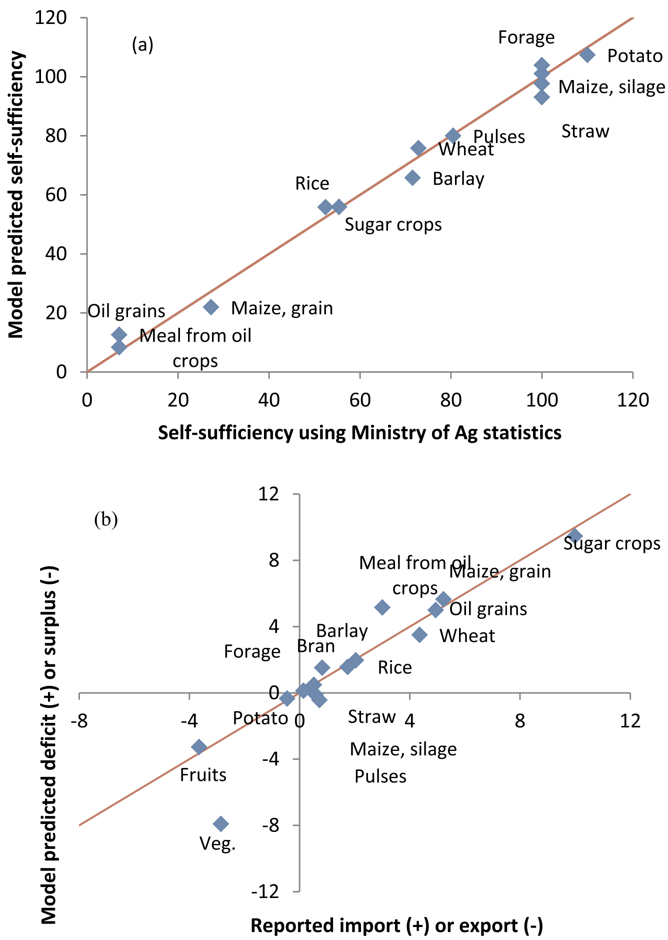

Fig. 2. (a) Estimated country deficit/surplus vs reported import/export for agricultural products over the period of 2011–2017. Exports are negative and imports are positive in million ton (MMT). (b) Estimated vs. reported self-sufficiency for selected plant products over the period of 2011–2017.

3. Results

3.1. Model evaluation

There was a good agreement between calculated deficit or excess in plant products and the country's import or export for the same products for the period of 2011–2015 (Fig. 2a). Calculated self-sufficiency of agricultural products matched the reported ones by Shariatmadar et al. (2017) (Fig. 2b).

3.2. Food production, demand and self-sufficiency in 2015

While current demand for agricultural products is 152 million tons per year using the current diet, Iran's agriculture produces 129 million tons per year (Table 2). With respect to plant products, Iran's agriculture produces 106 million tons per year (mostly under irrigated conditions; Table S6 in SI), but the demand is 128 million tons per year (Table 2). To produce all agricultural products within the country, 128.1 billion m^3 of irrigation water is required under current climate, agricultural management and cropping pattern. The current water withdrawal for agriculture is 86.0 billion m^3 (Table 2).

Iran's average relative yield gap (RYG) for plant agriculture was ca. 60% (range: 44–69%) (Table 3). The gap was lower for rice (44%), sugar crops (48%) and silage maize (46%) and higher for wheat (62%), oil grains (59%), fruits (69%) and forage legumes (68%). To fill 25%, 50% and 100% of the difference between a RYG of 20% and current gaps, average annual and linear yield increases of 1.5%, 3.0% and 5.9%

Table 2
Current food demand, production and self-sufficiency (SS) in Iran along with estimates of irrigation water needed to produce for self-sufficiency within the country and current water withdrawal for production of the products. A population of 80 million was used for demand calculations.

Product	Weight (million tons) Demand	Production	SS (%)	Water (billion m^3) Requirement	Withdrawal
Wheat	14.47	10.97	75.8	13.54	10.26
Unpolished Rice	4.46	2.49	55.8	16.29	9.10
Pulse	0.65	0.52	80.0	1.11	0.89
Potato	4.59	4.93	107.4	1.63	1.75
Oil grains	5.72	0.72	12.6	24.44	3.06
Sugar Crops	21.45	11.99	55.9	7.67	4.29
Fruits	14.51	17.78	122.5	20.96	25.68
Vegetables	14.36	22.27	155.1	4.12	6.39
Barley	4.56	3.00	65.8	4.30	2.83
Maize, grain	7.24	1.59	22.0	14.53	3.20
Maize, silage	9.28	9.38	101.1	2.75	2.78
Forage, legumes	11.02	11.45	103.9	11.06	11.49
Straw	7.07	6.58	93.1	0.0	0.00
Bran	3.36	1.84	54.8	0.0	0.00
Meal form oil crops	5.62	0.47	8.4	5.54	0.00
Forage, rangeland	10.24	10.00	97.7	0.00	0.00
Red meat	0.9	0.77	85.6	0.076	n.d.
Chicken meat	2.09	1.96	93.8	0.016	n.d.
Eggs	0.90	0.87	96.7	0.007	n.d.
Milk	8.64	8.37	69.9	0.053	n.d.
Fish	0.81	0.84	103.7	–	n.d.
Sum	151.9	128.8	84.8	128.1	86.1

n.d. not determined; all the n.d. cases were estimated at 4.4 billion m^3.

(relative to 2015 yields) are required, respectively (Table 3). At the same time, evaluation of actual increase in yield of major crops of Iran from 2005 to 2014 revealed that crop yield has been stagnant, except for potato and sugar beet for which a significant increase was detected (Table 4).

Self-sufficiency is different for various products: it is more than 100% for potato, fruits, vegetables, silage maize, forages and fish, more than 90% for straw, chicken eggs and milk, and more than 65% for wheat, pulses, barley and red meat (Table 2). However, self-sufficiency is low for rice (56%), oil grains (13%), sugar crops (56%), grain maize (22%), cereal bran (55%) and oil-gains meal (8%). Food self-sufficiency is 85% for all agricultural plant and animal products jointly, if considering only plant products, self-sufficiency is 83%.

3.3. Production scenarios

Using current management (RYG = 60%, IE = 38%), reducing agricultural water withdrawal from 86 to 38.5 billion m^3 resulted in a decline in plant production from the current level of 106 to 56 million tons per year (a 47% reduction; Fig. 3). Narrowing yield gaps and increasing IE under MIP (RYG = 50%; IE = 45%) and HIP (RYG = 40%; IE = 53%) scenarios compensated part of the decline; the decline was 32% with MIP scenario and 17% with HIP scenario.

A major consequence of decline in water withdrawal for agriculture would be that part of the irrigated area cannot be irrigated anymore. The average irrigated area that would not be irrigated is 4.54 million ha, which corresponded to 54% of current irrigated area (8.42 million ha). (Fig. S2 in SI for details).

3.4. Demand scenarios

With current diet and loss and waste (NDS), demand for plant products increases from currently 128.3 million tons to 144.1 million tons in 2030 (due to population growth), which means that 16 million tons more plant products are required (Fig. 4). Using MoH optimal diet and current loss and waste (IDS), demand in 2030 was predicted to be

Table 3
Actual yield (Ya, t/ha), potential yield (Y_p or Y_w, t/ha) and relative yield gap (RYG, %) under current (2015) conditions, target yields (t/ha) at 25%, 50% and 100% reduction of the difference between RYG of 20% (exploitable yield gap) and current RYGs and the required (linear) rate of yield increase (% per year, relative to yields of 2015) to reach target yields in 2030.

Plant	Ya	Yp or Yw	Current RYG	Target yield (t/ha)[a]			Rate of required yield increase (% per year)[a]		
				25%	50%	100%	25%	50%	100%
Irrigated									
Wheat	3.2	8.5	62	4.1	5.0	6.8	1.8	3.6	7.3
Unpolished rice	4.4	7.9	44	4.9	5.4	6.3	0.7	1.4	2.9
Pulses	1.8	4.2	56	2.2	2.6	3.4	1.4	2.8	5.5
Potato	30.8	69.6	56	37.0	43.2	55.7	1.3	2.7	5.4
Oil grains	1.9	4.7	59	2.4	2.8	3.7	1.6	3.1	6.3
Sugar crops	62.1	119.3	48	70.4	78.8	95.5	0.9	1.8	3.6
Fruits	8.1	26.5	69	11.4	14.7	21.2	2.7	5.4	10.7
Vegetables	32.7	73.9	56	39.3	45.9	59.1	1.3	2.7	5.4
Barley	2.9	6.9	58	3.6	4.2	5.5	1.5	2.9	5.9
Maize, grain	7.0	16.0	56	8.5	9.9	12.8	1.4	2.7	5.5
Maize, silage	50.7	93.1	46	56.7	62.6	74.5	0.8	1.6	3.1
Forages (legs.)	9.7	30.2	68	13.4	17.0	24.2	2.5	4.9	9.9
Rainfed									
Wheat	0.9	2.3	60	1.2	1.4	1.9	1.6	3.3	6.5
Unpolished rice	–	–	–	–	–	–	–	–	–
Pulses	0.5	1.4	66	0.6	0.8	1.1	2.2	4.5	9.0
Potato	–	–	–	–	–	–	–	–	–
Oil grains	1.0	2.4	60	1.2	1.5	1.9	1.7	3.4	6.8
Sugar crops	–	–	–	–	–	–	–	–	–
Fruits	3.2	8.0	60	4.0	4.8	6.4	1.7	3.3	6.7
Vegetables	–	–	–	–	–	–	–	–	–
Barley	1.0	2.6	61	1.3	1.6	2.1	1.8	3.5	7.1
Maize, grain	–	–	–	–	–	–	–	–	–
Maize, silage	–	–	–	–	–	–	–	–	–
Forages (legs.)	6.6	12.1	46	7.4	8.1	9.7	0.8	1.6	3.2

[a] Target yield (Y_{target}) and linear rate of required yield increase (g; % per year) are related as $Y_{target} = Y_a + (g \times Y_a \times 15)/100$, where 15 is the number of years from 2015 to 2030.

Table 4
The actual rate of increase in yield of major field crops in Iran for the period of 2000–2014 based on official statistics from Ministry of Agriculture.

Plant	Actual slope (kg/ha per year)	
	Irrigated	Rainfed
Wheat	-58^{ns}	-41^{ns}
Barley	-25^{ns}	0.2^{ns}
Rice	29^{ns}	
Potato	672**	
Maize, grain	10^{ns}	
Maize, silage	427^{ns}	
Canola (Rapeseed)	-3^{ns}	-14^{ns}
Soybean	-35^{ns}	
Sugar beet	1388**	
Cotton	-26^{ns}	

ns = non-significant, ** significant at 1% level of probability.

157.9 million tons per year, which is 23% higher than the 2015 level.

DDS (modified diet plus 15% reduction in loss and waste) resulted in 17.3 million tons of reduced demand for plant products in 2030, so that demand for plant products in 2030 remained just below the 2015 level (126.9 vs. 128.3) (Fig. 4).

3.5. Self-sufficiency in 2030

Reducing water withdrawal from 86.0 to 38.5 billion m^3, which is assumed safe for the environment, resulted in a substantially reduced self-sufficiency below the current 83%, ranging from 35% to 69% (Fig. 5). The lowest self-sufficiency was 35% under the combination of NIP (no-improved production) and IDS (increased demand) and the highest self-sufficiency was 69% under the combination of HIP (highly-improved production) and DDS (decreased demand) scenarios. (Fig. 5).

4. Discussion

This study is based on simulation of performance of agricultural plant species with the SSM-iCrop2 model setup for Iran and current data and statistics on land and water availability and diet and food loss and waste in Iran. Intensive model testing by Soltani et al. (2020) indicated that the model performance was satisfactory for the major plant species of Iran and that the quality of the inputs for setting up the model (weather, soil and management input) was also satisfactory. The *Demand* module used here worked well in predicting current self-sufficiency of agricultural products. The model-based framework used in the present study may be applicable to other countries in the region or countries where water is the most limiting factor.

Although the results obtained are largely plausible, the present study has some limitations. First, this study only addresses the biophysical opportunities and limitations, known today, to increase production or decrease demand. Economic, social and political measures were not considered. Second, it was assumed that the cropping pattern remained unchanged. Modification of the current cropping pattern and expansion of greenhouse cultivation will affect the results and need a separate comprehensive study. Third, there is uncertainty in the definition of fraction of RWR that needs to be set aside for environmental flows and spatiotemporal variability of water availability. Fourth, water available for irrigation through seawater desalinization and treatment and reuse of wastewater has not been considered. The amount of additional irrigation water by reclamation has been estimated to be less than 2 billion m^3 (Mesgaran and Azadi, 2018). Similarly, water saving measures, for example implementation of mulches or water harvesting in rainfed and irrigated farming may increase water availability (Rost et al., 2009; Jagermeyr et al., 2015), which was not included in the present study.

Today's 83% self-sufficiency for plant products in Iran depends on water over-exploitation for agriculture with major, negative

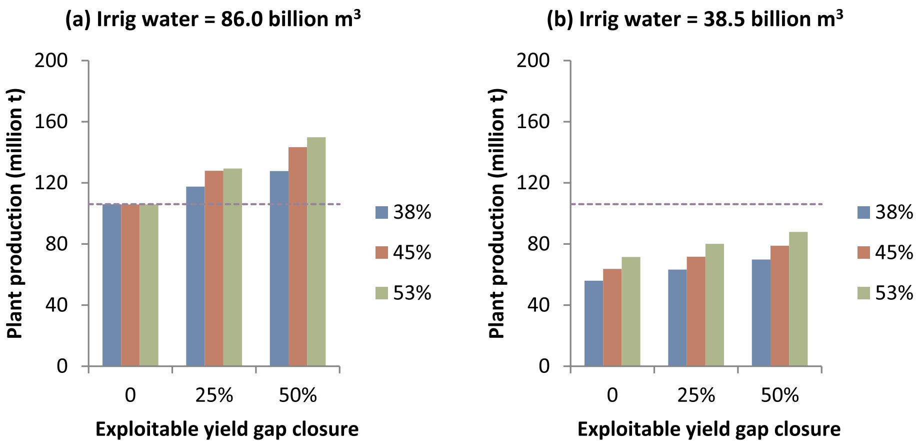

Fig. 3. Calculated national plant production for different scenarios of exploitable yield gap closure (x-axis) and irrigation efficiency (IE) (three colors) in 2030 under 86.0 or 38.5 billion m^3 agricultural water withdrawal. The horizontal dashed line presents current production in 2015. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

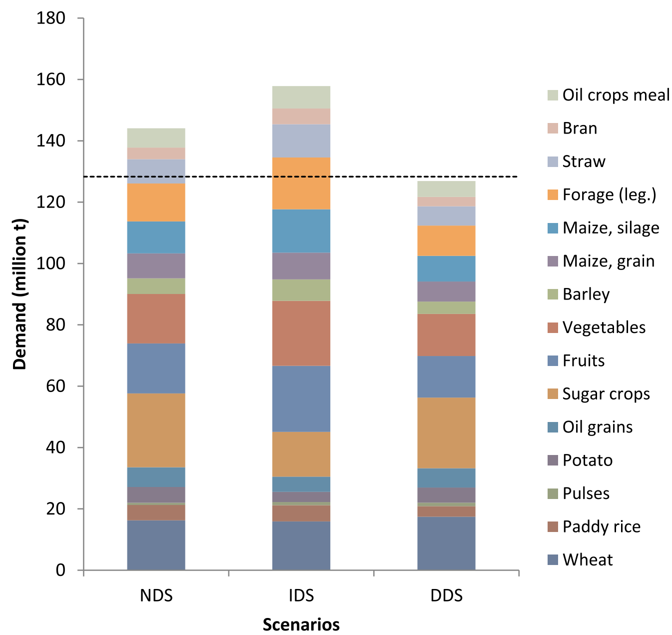

Fig. 4. Demand for plant products (million tons per year) in 2030 calculated for different demand scenarios (NDS, IDS and DDS are no-change, increased- and decreased demand scenarios, respectively, created by modification of diet and loss/waste). The horizontal dashed line presents current (2015) demand which is 128 million tons per year.

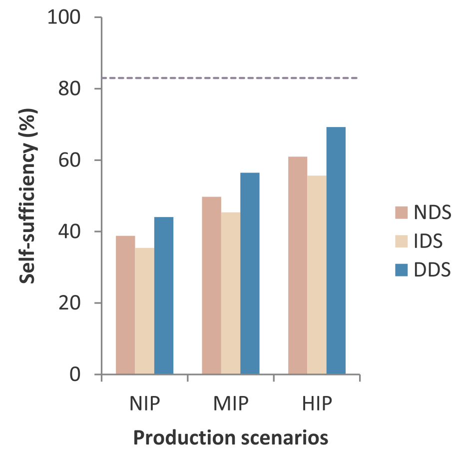

Fig. 5. Calculated national self-sufficiency in 2030 for plant products for different production scenarios (NIP, MIP and HIP are no, medium and highly-improved production scenarios, respectively, created by modification of relative yield gap and irrigation efficiency) and different demand scenarios (different colors: NDS, IDS and DDS are no-change, increased and decreased demand scenarios, respectively, created by modification of diet and loss/waste). Definitions of the scenarios are given in Section 2.4.4. The horizontal dashed line presents current self-sufficiency in 2015. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

environmental consequences for the nation (Moridi, 2017). Current water withdrawal for Iran's agriculture must be reduced by 55% to become safe for the environment (from 86 to 38.5 billion m^3 per year). Necessity of reduction in water withdrawal in Iran's agriculture has been widely recognized (Madani, 2014; Mesgaran and Azadi, 2018). Adjustment of agricultural water withdrawal to a safe level for the environment through 2030, along with an increase in population (from 80 to 90 million people) during the same period led to a simulated decline in self-sufficiency from the current level of 83% to 35 to 69%, depending on production and demand scenarios. Narrowing the yield gap, improvement of *IE*, implementing diets that require less water and reducing food loss and waste were effective in improving food self-sufficiency, but feasibility of the options needs to be investigated.

The irrigation efficiency (*IE*) in Iran has increased by 0.63% per year during past decade, due to government programs and subsidies (Abbasi et al., 2017). With the same rate of increase, achieving *IE* of 60% would be possible in 2050. *IE* of 60% would be possible by 2037 if the rate of increase could become 1% per year. Due to the current economic sanctions on Iran, a lower rate is more plausible. Improving *IE* substantially decreases demand for water and thus pressure on water resources. However, increased *IE* in Iran during the past decade was not accompanied by reduced water withdrawal. On the contrary, water withdrawal has steadily increased despite increases in IE, as indicated by Nasseri et al. (2017). The reason is that farmers use the saved water to irrigate more land or switch to more water-intensive crops or cropping systems. The paradox of irrigation efficiency has been discussed by Grafton et al. (2018). Higher *IEs* in Iran's agriculture to save water is thus justified only if water withdrawal is legally and physically controlled by the government. Otherwise, low IEs are preferred because part of the water lost in agriculture returns to the environment. A new report by FAO (Perry et al., 2017) concludes that controlled access to water must precede introduction of hi-tech irrigation systems in water-deficit countries.

There is a large yield gap (weighted country average of 60%) and an untapped potential yield for major agricultural plants in Iran (Table 3). Narrowing the RYG to 20% by 2030 (from the reference year 2015) needs about 6% per year increase in yield relative to the 2015 yields. Ray et al. (2013) evaluated the actual increase in yield of maize, rice, wheat and soybean and indicated that a maximum increase has been 3–4% for the period of 1989–2008 depending on crop and country.

Thus, it seems impossible for Iran's plant agriculture to close the current gap entirely by 2030. However, narrowing of the yield gap to 40% of Y_p or Y_w might be feasible by 2030, which requires 3% increase per year in yield (Table 3). With a rate of 3% yield increase per year, a RYG of 20% would be possible in 2046. Therefore, Iran is likely to experience a transient period of lower food supply until 2046, compared to 2015. The rate of 3% increase per year would still be a challenge for Iran's agriculture; especially since such increases have not been observed so far in the country (Table 4). In addition, there is currently no national or provincial program to stimulate yield increases in Iran on the basis of yield gap analysis.

With the MoH 'optimal' diet 13.8 million tons more plant products are required in 2030 compared to the current diet (Fig. 4). This will result in more pressure on water resources or more dependency on food importation. It seems this 'optimal' diet has been proposed without considering the country's biophysical limitations for food production, especially regarding the limited water resources for irrigation and future global environmental change (Willett et al., 2019). Definition and implementation of sustainable and socially-acceptable diets is an urgent issue for Iran, which requires more research. Implementation of a simple modified diet with less animal products and rice (Table 1), plus a 15% reduction in loss and waste (DDS) was effective in reducing food demand, which was in line with previous reports (Jalava et al., 2014, 2016; Alexander et al., 2016, 2017). The modified diet of this study is in line with current trends and trajectories and seems feasible. The consumption of red-meat and rice has already decreased since 2010, although this is largely due to economic sanctions on Iran. Inversely, consumption of wheat, potato and chicken meat has increased (Table 1). Red-meat and rice are expensive food items in Iran and it is expected that the consumption of these two items undergoes more reduction as sanctions become more intensive. If the sanctions are lifted then MoH 'optimal' diet and IDS may have a higher chance of occurrence. However, the government can still target the modified diet using a pricing system.

In the water scenario of 38.5 billion m^3, implementation of a highly-improved production scenario (HIP: RYG = 50% and IE = 53%) recuperated self-sufficiency to 56% assuming increased per capita demand (IDS), to 61% under no-change in per capita demand (NDS) and to 69% under a decreased per capita demand (DDS). Thus, avoiding water over-withdrawal for agriculture until 2030 won't be possible without sacrificing a certain degree of self-sufficiency. It can be concluded that for the best self-sufficiency results, a combination of increased production and controlled demand are necessary. The importance of such a combination has already been highlighted by researchers (e.g. Foley et al., 2011; ; Springmann et al., 2018). Still, many political and socio-economic factors must be coordinated for production to increase and demand to decrease (Van Ittersum et al., 2016).

5. Concluding remarks

This study used a modeling framework to assess the future situation of food production, demand and self-sufficiency of a country, taking Iran as an example. Although the study may not have taken into account all the factors and options, major ones were included, including water scarcity, land and water productivity increases and changes in population, diet and loss and waste. This study indicates which strategies are required for improvement of food self-sufficiency in the country without sacrificing environmental quality. The results of this research can be used by policymakers to define program packages required. Important remarks are:

- Increased irrigation efficiency makes it possible to achieve higher production under the condition of declining water over-withdrawal. However, programs to improve irrigation efficiency may make environmental conditions worse if water withdrawal for agriculture cannot be controlled. The country's current programs for increasing IE have not led to water saving, because water use in agriculture has not been limited.
- Narrowing the yield gap may keep the country's plant production at current levels, while water over-withdrawal for irrigation is reducing to a sustainable level and population is increasing. Thus, yield gap closure should be regarded in that context. Prompt and effective program packages are required to narrow yield gaps, which are currently lacking.
- For the highest self-sufficiency, it is necessary that programs for intensification of plant production are accompanied with programs to manage demand for food. Distinct programs are required for modification of current diet and reduction of food loss and waste.
- The recommended 'optimal' diet of Ministry of Health needs to be replaced with alternate, realistic diets better matching biophysical limitations of the country.
- Further study is required to quantify the effect of water saving and harvesting measures to increase water availability for plant production and the effect of alternate cropping patterns (including increase in greenhouses area) to increase plant production and economic returns.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2020.100351.

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