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Informing National Food and Water Security Policy through Water Footprint Assessment: the Case of Iran

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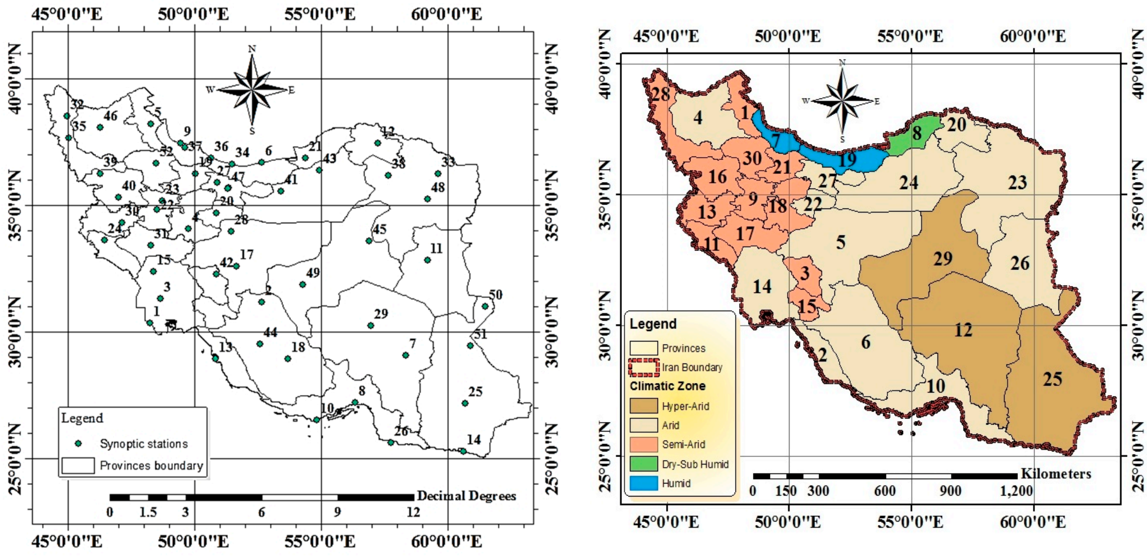
Abstract: Iran's focus on food self-sufficiency has led to an emphasis on increasing water volumes available for irrigation with little attention to water use efficiency, and no attention at all to the role of consumption and trade. To better understand the development of water consumption in relation to food production, consumption, and trade, we carried out the first comprehensive water footprint assessment (WFA) for Iran, for the period 1980–2010, and estimated the water saving per province associated with interprovincial and international crop trade. Based on the AquaCrop model, we estimated the green and blue water footprint (WF) related to both the production and consumption of 26 crops, per year and on a daily basis, for 30 provinces of Iran. We find that, in the period 1980–2010, crop production increased by 175%, the total WF of crop production by 122%, and the blue WF by 20%. The national population grew by 92%, and the crop consumption per capita by 20%, resulting in a 130% increase in total food consumption and a 110% increase in the total WF of national crop consumption. In 2010, 26% of the total water consumption in the semi-arid region served the production of crops for export to other regions within Iran (mainly cereals) or abroad (mainly fruits and nuts). Iran's interprovincial virtual water trade grew by a factor of 1.6, which was mainly due to increased interprovincial trade in cereals, nuts, and fruits. Current Iranian food and water policy could be enriched by reducing the WFs of crop production to certain benchmark levels per crop and climatic region and aligning cropping patterns to spatial differences in water availability and productivities, and by paying due attention to the increasing food consumption per capita in Iran.

Keywords: food security; food self-sufficiency; water footprint; water scarcity; crop trade; virtual water trade; water productivity; water saving

1. Introduction

Iran, the second largest country in the Middle East, is facing great water scarcity, which becomes manifest in drying lakes and rivers, dropping groundwater tables, land subsidence, the increasing contamination of water, water supply rationing and disruptions, crop losses, salt and sand storms, the increasing migration of people away from the hardest hit areas, and damage to ecosystems. Iran is mostly arid to semi-arid (Figure 1), with an average annual precipitation of 228 mm (72% less than the global average of 814 mm), and internal renewable water resources of 129×10^9 $m^3 \cdot y^{-1}$ (0.32% of the global renewable water resources) [1]. Precipitation ranges from less than 50 mm in central Iran to about 1000 mm at the Caspian coast. Most regions receive less than 100 mm of precipitation per year, and 75% of the country's precipitation falls over only 25% of the country's area. About 75% of the precipitation is offseason, i.e., it falls when not needed by the agricultural sector [2]. Over the last 20 years, the per capita renewable water resources in the country decreased by 29.1% and reached

1732 $m^3 \cdot y^{-1}$ in 2014 [1], which is well below the global average of 7000 $m^3 \cdot cap^{-1} \cdot y^{-1}$. The population grew from 38.9 billion in 1980 to 74.5 billion in 2010, and is expected to further increase to 88.5 billion in 2030 [3], which will translate into increasing food and water demands.



(**a**) (**b**)

Figure 1. Provinces and the 52 weather stations (**a**) and the climatic regions of Iran (**b**).

In addition to the physical water scarcity, Iran faces a poor management of its water resources. Major infrastructure works are developed without sufficient concern for their long-term impacts, the water governance structure is weak, water management is done based on administrative instead of watershed boundaries, there is insufficient attention to the linkage between development and environment, different government sectors fail to coordinate, and groundwater abstractions are not properly regulated [2]. The mismanagement of water resources has resulted in the shrinking of Urmia Lake in the western part of the country, which is the largest lake in the Middle East and one of the world's largest hypersaline lakes [4]; the disappearance of Hamun Lake in the eastern region [5,6]; and the seasonally drying up of the Zayandeh Rud River, which is the backbone of development in central Iran [7].

Agriculture is the biggest freshwater user in Iran, accounting for 92% of gross blue water abstractions [1], and 97% of net blue water abstractions [8]. Inefficient water management in this sector is thus a main source of the water shortage in the country. In 2004, about 68% of the total renewable water resources was withdrawn [1]. Even though this may look sustainable at first sight, it is far from so, because a substantial percentage of the flow needs to be maintained to protect ecosystems and the livelihoods that depend on them [9–12]. Issues in agricultural policy that require critical attention are the country's aim to achieve food self-sufficiency, the mismatch between the spatial cropping pattern and the geographic spread of water availability, the heavy reliance on irrigation, the low water use efficiency, the low share of rain-fed agriculture in total crop production, the low water and energy prices, the overdraft of aquifers, and the low income level of farmers and their associated inability to adopt better farming practices. The role of the agricultural sector in alleviating the current water scarcity in Iran also gets clear when considering the historical development of the harvested irrigated crop area. The irrigated land area grew by 117% in the period 1980–2010, while the total harvested area, including both rain-fed and irrigated lands, increased only slightly. The growth in irrigation was introduced to meet the increasing food demand of the rapidly increasing population and keep a high food self-sufficiency level. Based on the national statistics, total crop production within the country grew by 175% over the period 1980–2010. With continued population growth as predicted, food demand will keep increasing, as well as the associated water demand when sticking to the food self-sufficiency policy, which again will further aggravate the existing overexploitation of water resources in the country.

As a consequence of Iran's focus on food self-sufficiency, the emphasis has been on increasing the water volume available for irrigation. Little attention has been paid to water use efficiency, and no attention at all has been paid to the role of consumption and trade. In order to better understand the historical development of the relation between food production, consumption, trade, and water consumption, we carried out the first comprehensive water footprint assessment (WFA) for Iran, for the period 1980–2010. In addition, we estimated the water saving per province associated with interprovincial and international crop trade. The water footprint (WF) is a spatially–temporally explicit measure of freshwater used directly or indirectly by a producer or a consumer [13], and could facilitate the analysis of how patterns of consumption, production, and trade relate to patterns of water consumption [14]. The WF of producing a crop comprises a consumptive component, measuring water consumption, and a degradative component, measuring water pollution. In this paper, we focus on the consumptive WF, which again includes two components: the green WF, which refers to the consumption of rainwater, and the blue WF, which refers to the consumption of irrigation water [15]. The WF related to human consumption within a specific region will include an internal and an external component. The former refers to the amount of water consumed within the region for producing products that are consumed within the region; the latter refers to the amount of water consumed in the other regions to produce products that are imported and consumed within the considered region [15]. The trade of food between regions implies a virtual water (VW) flow, which refers to the water consumed in the region of the food origin.

This is the first comprehensive research on the water footprint and virtual water trade for Iran, whereby we also assess the added value of the water footprint assessment for informing Iran's food and water security policy. The main focus in this paper is water use and scarcity, which means that we do not consider other economic, social, and environmental factors that are relevant in policy making, such as labour and land prices, the competitive advantages of different provinces for certain crops, employment, soil degradation, water quality deterioration, and climate change.

2. Results

2.1. Harvested Area and Crop Production

Over the period 1980–2010, the population in Iran grew by 91.5%, but the total harvested area (HA) for the eight crop categories increased by 129%, and total crop production (CP) by 175% (Figure 2). CP grew faster than HA because crop yields increased (by 20% as a weighted average over all crops). Increased crop yields could be attributed to improved field management practices over the period, including better irrigation and soil management practices, and a higher application rates of fertilizers. The percentage of HA irrigated reduced slightly, from 57% in 1980 to 54% in 2010 (with the most pronounced decrease for cereals, but an increase for oil crops). Even though the irrigated percentage in HA decreased, irrigated HA in absolute terms increased by 117%, which aggravated the pressure on the available blue water resources.

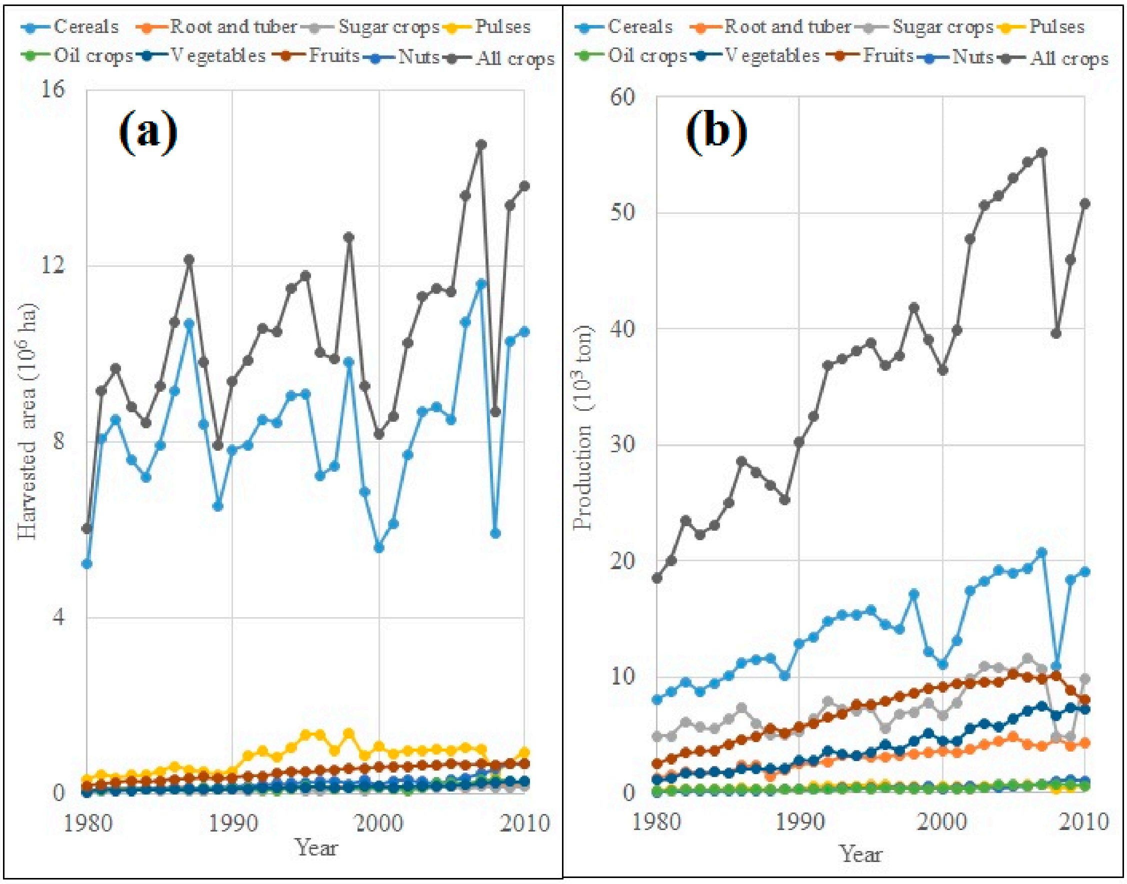


Figure 2. Harvested area (**a**) and production (**b**) in Iran per crop category over the period 1980–2010.

Figure 3 shows the contribution of the different crop categories to HA and CP, per province, as averages over the period 1980–2010. At the national level, cereals were the main crop category over the whole period, but its importance decreased. The contribution of cereals to total HA reduced from 87% in 1980 to 76% in 2010 (with an average of 79% over the period), while the cereal contribution in CP reduced from 44 to 38% (with an average of 39% over the period). Regarding CP at the national level, sugar crops and fruits ranked next to cereals over the whole period, with an average share over the period of 20% and 19%, respectively (but with an overall contribution of 1% and 4.7% to HA, respectively). Regarding HA at the national level, pulses ranked next to cereals over the whole period, with an average share over the period of 7.6% (and an overall contribution of 1.4% to CP). The quickest growth in both HA and CP over the period 1980–2010 was for nuts.

At the national level, the highest crop yields were observed for sugar crops (28 tonne/ha on average), followed by vegetables (27 tonne/ha) and roots and tubers (21 tonne/ha), while the lowest yields were found for nuts (1.8 tonne/ha), cereals (1.7 tonne/ha), and pulses (0.6 tonne/ha). Although cropping patterns are different across provinces, cereals usually dominate HA. Only in the arid province of Hormozgan do fruits take up most of the HA.

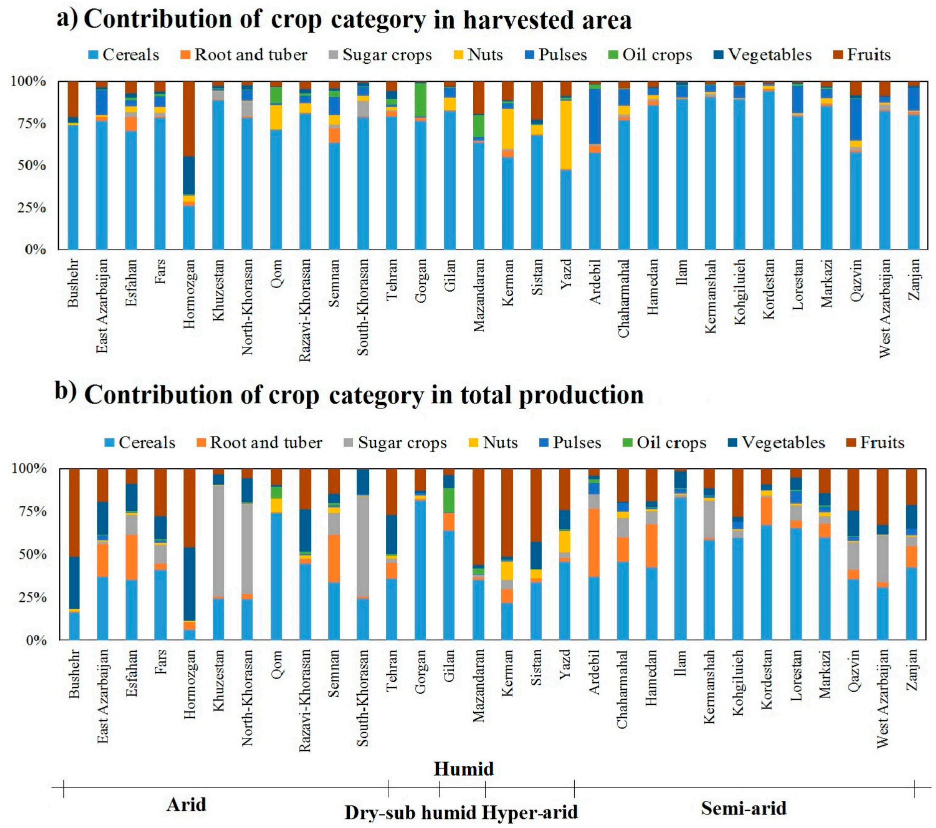


Figure 3. The 30-year average contribution of different crop categories to total harvested area (HA) per province (**a**) and total crop production (CP) per province (**b**). Period 1980–2010.

2.2. WF of Crop Production

The 175% growth in crop production over the period 1980–2010 led to a 122% increase in total WF, from 31.9 × 10^9 $m^3 \cdot y^{-1}$ in 1980 (42.5% blue) to 70.8 × 10^9 $m^3 \cdot y^{-1}$ in 2010 (62.1% blue) (Figure 4). The growth in total WF at the national level holds for all crop categories. For cereals and sugar crops, the total WF in the country increased, despite the fact that the national average WF per tonne for cereals and sugar crops decreased by 29% and 18%, respectively (Table 1), which was mainly due to the increase in crops yields. The national average WF per tonne for oil crops, pulses, nuts, vegetables, roots and tubers, and fruits increased by 14%, 17%, 18%, 23%, 23% and 50%, respectively. The considerable increase in the WF per tonne for fruits was partly due to a national average reduction of 10% in fruit yield.

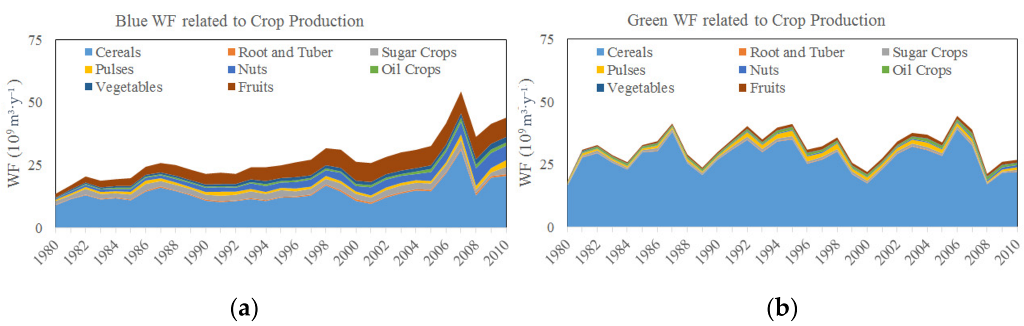


Figure 4. Blue WF (**a**) and green water footprint (WF) (**b**) and per tonne of crop production in Iran over the period 1980–2010.

Table 1 shows that WFs per tonne differ across climatic regions. In general, WFs per tonne are significantly higher in the hyper-arid, arid, and semi-arid regions compared with the dry sub-humid and humid regions. When considering a specific crop category in a specific region, many of the differences between 1980 and 2010 are due to changes in what were the dominant crops per crop category; for instance, rice replaced wheat as the dominant cereal crop in the dry sub-humid region. Differences were also due to changes in the fractions of the land irrigated (for instance, a 420% increase in the irrigated HA in a dry sub-humid region), in changes in yields (for instance, 23%, 12%, and 6.5% reductions in crop yield in semi-arid, arid, and humid regions, respectively), and in changes in climate (as demonstrated by Karandish et al. [16]).

The spatial distribution of the 30-year average total WF of crop production and the blue fraction in the total is shown in Figure 5. The highest WFs, when measured as the total WF in a province divided by the area of the province (expressed in mm·y^{-1}), are found in the semi-arid climatic region, because this region has the highest cropland density, while water consumption per unit of cultivated land is also high (at least relative to the humid and dry sub-humid regions). The largest shares of blue WF in the total are found in the provinces where irrigated agriculture dominates over rain-fed agriculture, which is obviously particularly the case in the hyper-arid region, where 93% of the harvested land was irrigated (as an average over 1980–2010). The 30-year total WF (m^3·y^{-1}) of crop production, per province, is summarized in Table 2. The provinces located in the arid and semi-arid regions, the water-scarce regions of the country, are responsible for 87% of the total WF of Iranian crop production of 59.6 billion m^3·y^{-1}. The hyper-arid region ranked next to arid and semi-arid regions, with a contribution of 6.5% to the national WF of crop production over the period.

The 30-year total WF (m^3·y^{-1}) of crop production, per province, is summarized in Table 2. The provinces located in the arid and semi-arid regions, the water-scarce regions of the country, are responsible for 87% of the total WF of Iranian crop production of 59.6 billion m^3·y^{-1}. The hyper-arid region ranked next to arid and semi-arid regions, with a contribution of 6.5% to the national WF of crop production over the period.

Table 1. Regional and national averages of the WF of crop production and the blue share in the total, per crop category, for the years 1980 and 2010.

Climatic Region	Crop Category	1980		2010	
		WF of Crop Production (m^3·$tonne^{-1}$)	Blue Share (%)	WF of Crop Production (m^3·$tonne^{-1}$)	Blue Share (%)
Hyper-arid	Cereals	2275	67	2614	85
	Root and tuber	202	59	230	85
	Sugar crops	761	84	953	90
	Pulses	5073	93	5817	96
	Nuts	4948	93	5891	95
	Oil seeds	5728	88	5666	88
	Vegetables	370	80	432	93
	Fruits	1293	94	1541	97
Arid	Cereals	2729	29	2298	54
	Root and tuber	179	69	223	79
	Sugar crops	452	70	343	82
	Pulses	6452	89	7180	84
	Nuts	4397	61	5008	78
	Oil seeds	3595	63	3946	68
	Vegetables	267	84	325	92
	Fruits	885	88	1394	91
Semi-arid	Cereals	4400	39	2600	38
	Root and tuber	167	71	204	75
	Sugar crops	368	63	492	78
	Pulses	4431	78	5842	83
	Nuts	4286	55	5216	70
	Oil seeds	4639	42	4639	70
	Vegetables	323	81	437	88
	Fruits	499	74	835	82
Dry sub-humid	Cereals	570	5	1178	41
	Root and tuber	114	0	132	63
	Sugar crops	1099	21	1973	89
	Pulses	3164	53	5409	91
	Nuts	2438	29	3428	67
	Oil seeds	1785	11	2478	75
	Vegetables	114	46	181	85
	Fruits	352	27	503	88

Table 1. *Cont.*

Climatic Region	Crop Category	1980		2010	
		WF of Crop Production ($m^3 \cdot tonne^{-1}$)	Blue Share (%)	WF of Crop Production ($m^3 \cdot tonne^{-1}$)	Blue Share (%)
Humid	Cereals	1070	36	1182	53
	Root and tuber	192	11	229	20
	Sugar crops	519	8	611	19
	Pulses	4460	38	6299	51
	Nuts	3006	29	3292	45
	Oil seeds	2669	6	2425	13
	Vegetables	287	19	274	39
	Fruits	297	33	364	43
Iran	Cereals	3158	35	2239	48
	Root and tuber	172	67	212	76
	Sugar crops	440	69	362	82
	Pulses	5405	87	6331	87
	Nuts	4289	57	5077	73
	Oil seeds	2663	35	3031	62
	Vegetables	277	82	341	91
	Fruits	732	83	1094	88

Table 2. The 30-year average total water footprint of crop production and the blue share in the total, per province and crop category.

Climatic Region	Province Code *	Total WF of Crop Production ($10^6 \cdot m^3 \cdot y^{-1}$)									Blue Share (%)
		Cereals	Root and Tuber	Sugar crops	Pulses	Nuts	Oil crops	Vegetables	Fruits	All crops	All crops
Hyper-arid	12	758	27	59	38	623	27	15	588	2136	89
	25	505	2	0.0	5	114	1	30	568	1225	87
	29	156	1	4	3	303	6	6	59	538	91
Arid	2	415	0.48	0.0	0.06	22	1	39	460	939	56
	4	3088	88	17	287	111	44	122	319	4076	40
	5	1056	84	110	44	84	24	47	183	1632	74
	6	4221	37	313	213	280	109	135	1090	6398	55
	10	70	4	0.0	1	24	1	93	599	793	89
	14	3029	9	634	67	33	5	95	387	4260	53
	20	1582	14	518	58	9	15	95	86	2377	50
	22	147	0.12	0.00	3	58	33	1	11	253	81
	23	2147	8	0.00	43	299	93	123	271	2984	58
	24	362	32	34	16	58	30	11	39	581	61
	26	1861	6	823	52	158	19	117	40	3076	47
	27	823	19	8	13	30	38	68	94	1094	60
Semi-arid	1	1407	68	21	385	11	156	9	46	2103	28
	3	635	12	24	80	59	4	1	44	860	40
	9	2464	69	66	66	103	13	23	145	2948	35
	11	740	0.30	1	45	6	2	29	10	834	24
	13	2037	4	127	43	52	15	26	66	2370	25
	15	895	0.17	5	38	7	5	5	77	1033	40
	16	2472	27	3	16	87	4	16	46	2671	13
	17	2115	11	59	266	50	53	37	50	2640	31
	18	1645	19	21	115	93	28	18	93	2033	43
	21	651	9	54	98	61	10	30	129	1042	52
	28	1959	14	154	47	34	4	29	307	2549	36
	30	1826	33	26	190	18	6	57	108	2264	30
Dry sub-humid	8	899	25	0.04	11	0.21	557	22	29	1542	27
Humid	7	649	2	0.38	29	77	1	4	32	794	45
	19	860	7	4	18	5	198	9	454	1555	37

Note: * The province codes refer to the provinces shown on the map in Figure 1.

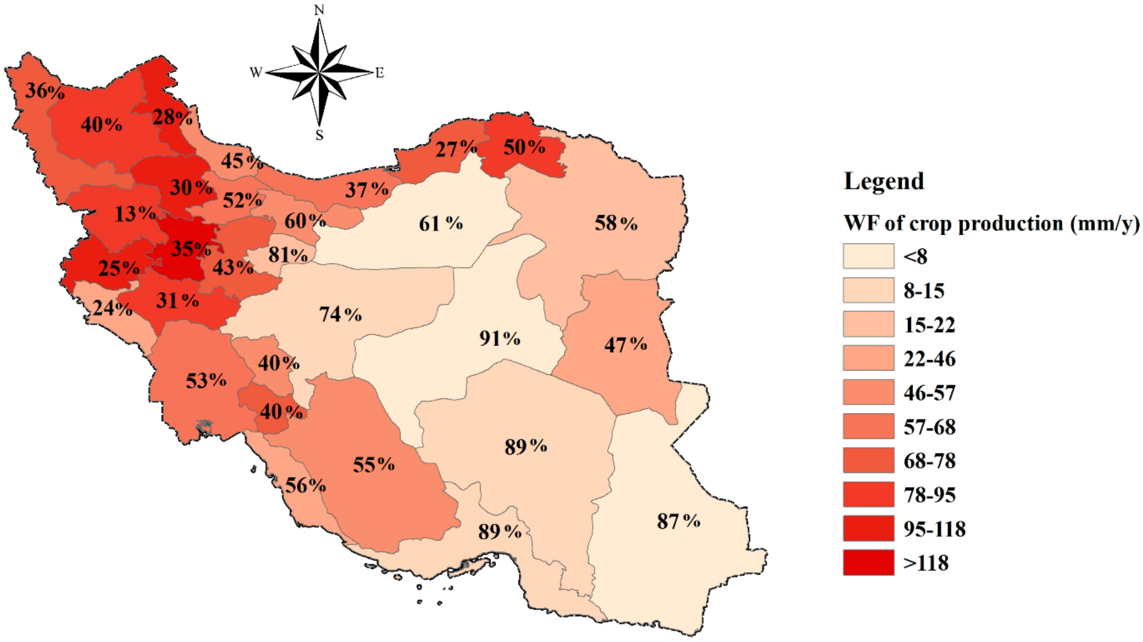


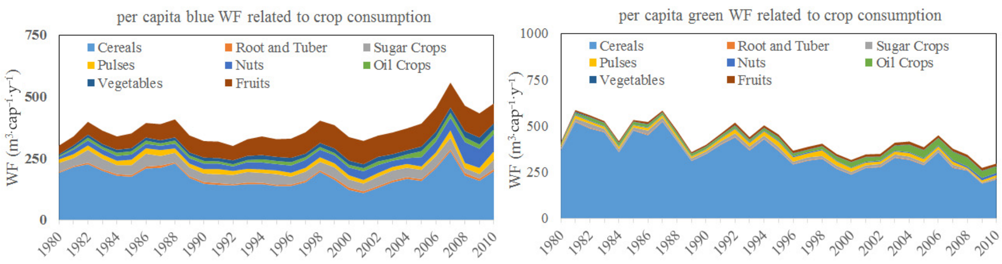
Figure 5. The 30-year average WF of Iranian crop production, per province. The WF in mm·y^{-1} is obtained by dividing the total WF of crop production in the province by the area of the province. Period: 1980–2010. The numbers in the map refer to the blue share in the WF of crop production.

2.3. *WF of Crop Consumption*

The Iranian crop consumption per capita (considering the 26 crops studied) increased by 20% in the period 1980–2010, from 460 to 552 kg·cap^{-1}·y^{-1}. Given the 92% population growth over this period, total crop consumption (again considering the 26 crops studied) increased by 130%, from 17.9 to 23.7 million t·y^{-1}. The total WF of crop consumption increased by 110%, from 27.7 × 10^{9} m^{3}·y^{-1} in 1980 to 57.3 × 10^{9} m^{3}·y^{-1} in 2010 (Table 3). The blue water fraction increased from 42% to 62% (Figure 6). The increasing WF of consumption per capita is the net result of the growing consumption volume per capita, the changed diet composition, and changes in the WFs per tonne of crop (a decrease for cereals and sugar crops, and an increase for the other crop categories). The contribution of different crops to the WF of consumption considerably changed over the study period. The contribution of cereals to the total WF of crop consumption decreased from 78% in 1980 to 53% in 2010. The contribution of sugar crops decreased as well, from 7.6% to 6.1%. The contributions of all of the other crop categories to the WF of consumption increased. Growing from 1.7% in 1980 to 11% in 2010, the share of the WF related to the consumption of nuts showed the highest increase, followed by oil crops (from 1.7% in 1980 to 7.1% in 2010) and fruits (from 5.8% to 12%), mainly due to the increased proportion of these crops in Iranian consumption and/or increase in WF per tonne of crops in some climatic regions (Table 1).

Table 3. Regional and national averages of the water footprint of crop consumption in Iran per capita and the blue share in the total, per crop category, for the years 1980 and 2010.

Climatic Region	Crop Category	1980		2010	
		WF of Crop Consumption ($m^3 \cdot cap^{-1} \cdot y^{-1}$)	Blue Share (%)	WF of Crop Consumption ($m^3 \cdot cap^{-1} \cdot y^{-1}$)	Blue Share (%)
Hyper-arid	Cereals	494	53	409	62
	Root and tuber	6	63	11	80
	Sugar crops	60	73	51	83
	Pulses	11	93	77	96
	Nuts	25	67	44	77
	Oil seeds	14	56	53	35
	Vegetables	8	83	29	92
	Fruits	41	98	99	93
Arid	Cereals	536	38	397	51
	Root and tuber	6	67	10	76
	Sugar crops	55	69	48	82
	Pulses	12	88	84	85
	Nuts	24	61	46	76
	Oil seeds	12	46	53	35
	Vegetables	7	83	25	91
	Fruits	42	88	96	87
Semi-arid	Cereals	739	27	478	40
	Root and tuber	6	70	11	76
	Sugar crops	47	67	45	81
	Pulses	10	81	75	84
	Nuts	25	57	54	70
	Oil seeds	12	38	61	42
	Vegetables	8	81	31	90
	Fruits	39	81	93	82
Dry sub-humid	Cereals	139	24	225	50
	Root and tuber	4	0	6	63
	Sugar crops	56	69	48	82
	Pulses	11	87	77	86
	Nuts	22	53	40	71
	Oil seeds	7	9	56	78
	Vegetables	5	65	17	84
	Fruits	38	78	85	88
Humid	Cereals	344	22	338	41
	Root and tuber	5	58	10	65
	Sugar crops	56	69	48	81
	Pulses	11	71	77	69
	Nuts	22	48	38	61
	Oil seeds	12	17	52	25
	Vegetables	7	72	25	83
	Fruits	38	78	78	79
Nationwide	Cereals	558	34	408	48
	Root and tuber	5	66	11	76
	Sugar crops	54	69	47	82
	Pulses	12	85	81	85
	Nuts	24	59	47	74
	Oil seeds	12	42	55	37
	Vegetables	7	81	27	90
	Fruits	41	86	94	86



(**a**) (**b**)

Figure 6. Blue WF (**a**) and green WF (**b**) of Iranian crop consumption per capita, over the period 1980–2010.

The WF of consumption per capita varies across the provinces and climatic regions (Figure 7 and Table 4) as a result of provincial differences in the WF per tonne of crop (Table 1). The 30-year average WF of consumption per capita varies across provinces, in the range of 212–1061 $m^3 \cdot cap^{-1} \cdot y^{-1}$ for cereals (10–54% blue), 7–14 $m^3 \cdot cap^{-1} \cdot y^{-1}$ for roots and tubers (17–80% blue), 31–67 $m^3 \cdot cap^{-1} \cdot y^{-1}$ for sugar crops (61–80% blue), 19–83 $m^3 \cdot cap^{-1} \cdot y^{-1}$ for nuts (51–96% blue), 25–51 $m^3 \cdot cap^{-1} \cdot y^{-1}$ for pulses (31–78% blue), 30–52 $m^3 \cdot cap^{-1} \cdot y^{-1}$ for oil crops (11–54% blue), 14–26 $m^3 \cdot cap^{-1} \cdot y^{-1}$ for vegetables (73–93% blue), and 76–124 $m^3 \cdot cap^{-1} \cdot y^{-1}$ for fruits (77–98% blue). The largest WFs of crop consumption per capita are mainly found in the provinces located in the hyper-arid and semi-arid regions, followed by those located in the arid region.

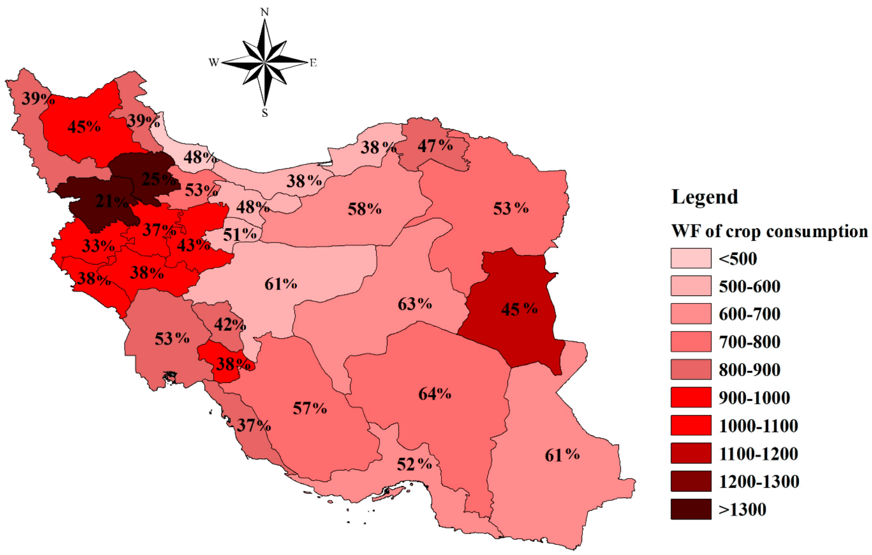


Figure 7. The 30-year average WF of Iranian crop consumption per capita, per province. Period: 1980–2010. The numbers in the map refer to the blue share in the WF of crop consumption.

Table 4. The 30-year average water footprint of crop consumption per capita and the blue share in the total, per province and crop category. Period: 1980–2010.

Climatic Region	Province Code *	WF of Crop Consumption ($m^3 \cdot cap^{-1} \cdot y^{-1}$)									Blue Share (%)
		Cereals	Root and Tuber	Sugar crops	Pulses	Nuts	Oil crops	Vegetables	Fruits	All crops	All crops
Hyper-arid	12	456	9	51	30	35	35	23	113	753	62
	25	377	10	53	83	34	35	19	108	718	64
	29	448	12	63	30	38	40	22	80	733	65
Arid	2	690	10	51	53	37	37	19	90	987	45
	4	598	9	52	22	34	35	21	110	880	39
	5	349	8	49	35	34	30	14	103	624	61
	6	515	11	63	35	34	35	15	95	803	57
	10	387	10	52	43	35	37	19	94	675	54
	14	362	8	51	40	33	35	21	111	661	56
	20	555	9	48	42	38	34	20	100	846	54
	22	650	11	45	33	37	37	19	89	920	47
	23	493	10	52	61	33	37	20	95	801	53
	24	442	11	53	22	25	34	23	96	706	58
	26	815	12	67	69	43	41	25	124	1195	45
	27	367	9	51	34	34	34	18	81	628	50
Semi-arid	1	612	7	31	43	51	52	20	96	912	39
	3	629	10	35	42	38	34	18	80	886	39
	9	611	10	53	26	34	36	19	81	870	42
	11	491	11	46	65	45	35	18	90	801	53
	13	819	9	53	43	38	34	22	78	1098	37
	15	782	10	52	30	41	35	23	103	1076	38
	16	699	11	55	24	32	38	25	82	965	34
	17	773	10	47	19	29	37	23	124	1063	38
	18	1061	11	52	25	39	35	26	88	1336	22
	21	659	11	58	28	30	45	25	97	953	39
	28	679	13	53	33	35	38	17	94	961	43
	30	921	14	49	25	45	37	26	81	1198	32
Dry sub-humid	8	365	10	53	38	30	32	19	80	625	43
Humid	7	342	10	52	33	30	34	17	76	593	42
	19	212	8	52	38	31	34	14	85	474	50

Note: * The province codes refer to the provinces shown on the map in Figure 1.

The hyper-arid region, in which crops usually have the largest WF per tonne, had the highest population growth (2.4-fold over 1980–2010), followed by the arid region (2.0-fold). The humid region, which had the smallest WF per tonne of crops, also had the lowest population growth (1.6-fold).

2.4. Crop and Virtual Water Trade

Crop trade balance per province. While Iran on the whole was a net crop importer over the whole period of 1980–2010, most provinces in the semi-arid and dry-sub humid regions were net crop exporters, due to a large export of cereals to other provinces (Figure 8). Mazandaran province in the humid region was the largest rice-producing province in the country throughout the period. However, upon considering all crops and the whole humid region—which consists of Mazandaran and Gilan provinces—we observe that the region was a crop importer throughout the period. The provinces in the hyper-arid region, which includes Sistan-Baluchestan, Kerman and Yazd provinces, were always the largest net crop-importing provinces, with the crop trade balance (CTB) of the region as a whole increasing from 0.84 million tonnes in 1980 to 2.27 million tonnes in 2010. However, these provinces remained net exporters of fruits and nuts over the period. While most provinces in the arid region were a net crop importer, with an overall regional CTB of 0.84 in 1980 and 2.27 million tonnes in 2010, they had a large contribution in vegetable and fruit exports over the period.

International crop trade. In 1980, the CTB of the country as a whole was 1.91 million tonnes, resulting from a crop import of 1.94 million tonnes and a crop export of 0.03 million tonnes. In 2010, the CTB had not changed, even though both imports and exports increased considerably. CTB was 1.89 million tonnes in 2010, resulting from 3.19 million tonnes of crop import, and 1.30 million tonnes of crop export. Expressed per capita, the national CTB reduced by 49%, from 49.1 to 25.3 $kg \cdot cap^{-1} \cdot y^{-1}$ over the period 1980–2010, which reflects the increased self-sufficiency of the country. Cereals were dominant in the national CTB, both in 1980 (imports of 2.07 million tonnes) and 2010 (imports of 2.31 million tonnes). Oil seeds import grew by 0.86 million tonnes and took second place in the CTB in 2010. The import of pulses increased from 0.004 million tonnes in 1980 to 0.14 million tonnes in 2010. For sugar crops, the CTB changed from zero trade in 1980 to an import of 0.014 million tonnes in 2010. A considerable increase occurred in exporting vegetables and roots and tubers, reaching total exports of 0.002 million tonnes and 0.71 million tonnes in 2010, respectively. The CTB for nuts changed from an export of 0.005 million tonnes in 1980 to an export of 0.16 million tonnes in 2010, respectively.

Interprovincial crop trade. The interprovincial crop trade increased from 5.22 million tonnes in 1980 to 13.6 million tonnes in 2010, which was mainly due to increases in sugar crop and cereal trade (increases of 4.0 and 3.0 million tonnes, respectively). Fruits also experienced a considerable trade increase over the period (of 1.9 million tonnes).

Virtual water (VW) trade balance per province. Net VW import per province for the years 1980 and 2010 is shown in Figure 9. Most of the provinces located in the semi-arid region were VW exporters over the period 1980–2010 (Figure 10). The arid region as a whole was a VW importer over the whole period, although some of the provinces in the arid region had VW exports. In 1980, the largest VW export was from Kohgiluieh-Boyerahmad province in the semi-arid region (4.6 billion $m^3 \cdot y^{-1}$ of which 87% was blue water), while in 2010 the largest VW export came from Fars province in the arid region (3.1 billion $m^3 \cdot y^{-1}$ of which 68% blue water). In both cases, this was the result of the relatively large VW export related to cereal exports from these provinces. In 2010, 26% of the total water consumption in the semi-arid region served the production of crops for export to other regions (mainly cereals) or internationally (mainly fruits and nuts).

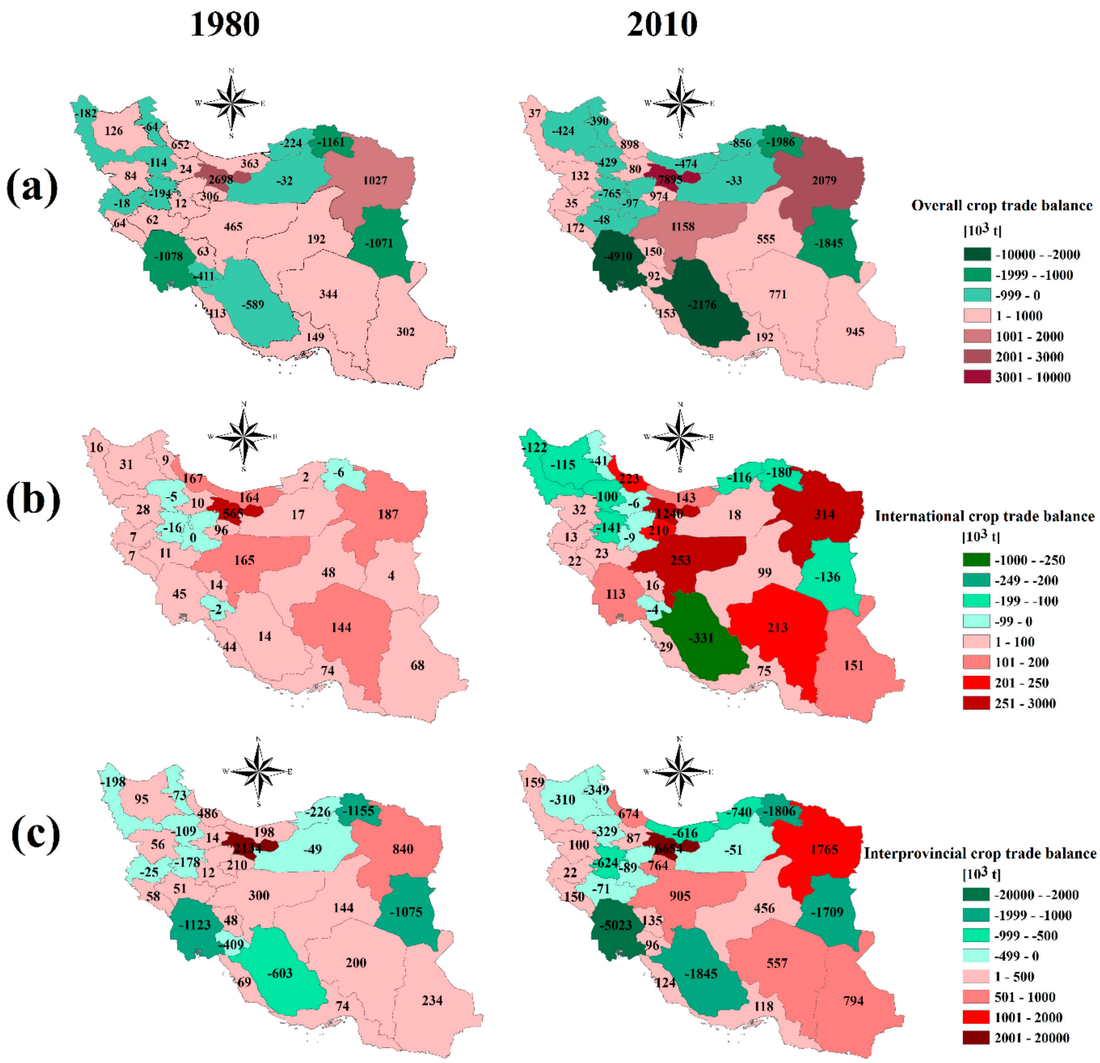
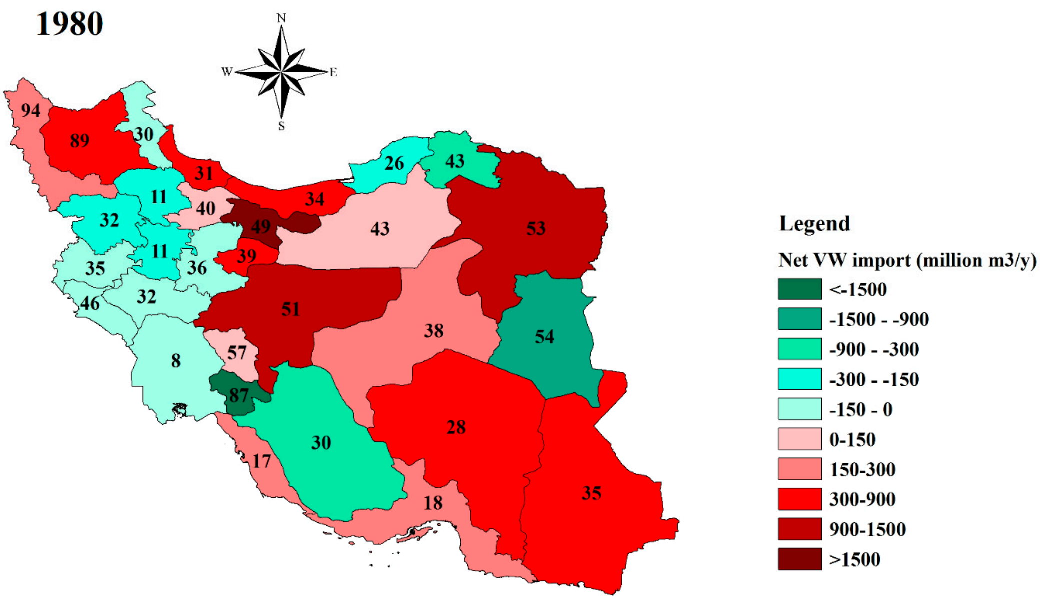
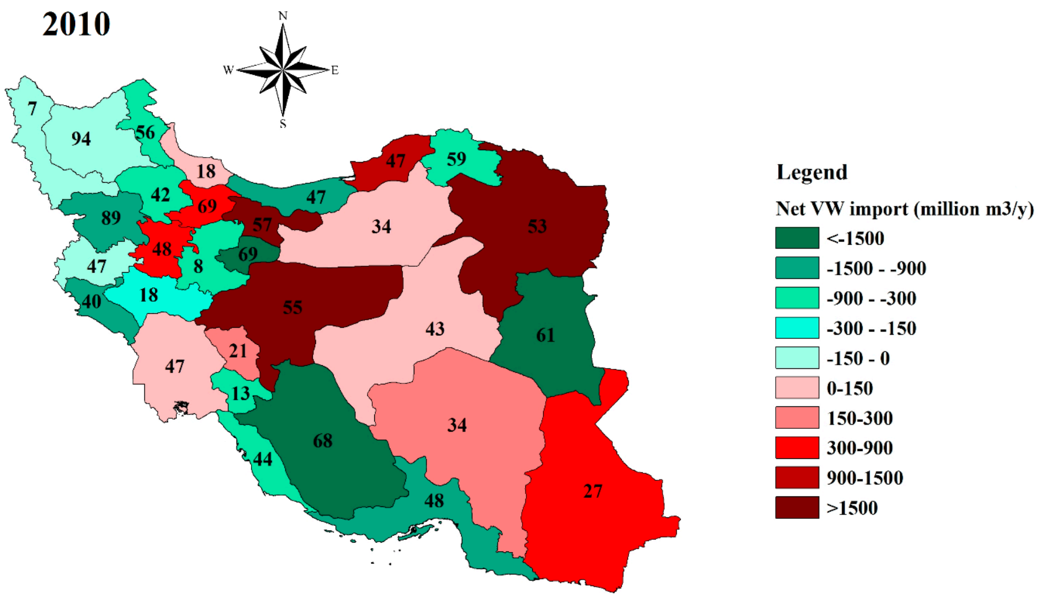


Figure 8. Overall net crop import per province in Iran (**a**), net crop import from abroad (**b**), and net crop import from other provinces (**c**), in the years 1980 (**left**) and 2010 (**right**). Positive signs refer to import; negative signs refer to export.

The changes in crop trade patterns over the period 1980–2010 led to a change in the VW trade pattern as well. Three provinces, namely Golestan (in the dry sub-humid region), Khuzestan (in the arid region) and Kohgiluieh-Boyerahmad (in the semi-arid region), changed from net VW exporters in 1980 to net VW importers in 2010. Vice versa, five provinces in the arid and semi-arid regions, namely Tehran, Qom, Bushehr, East Azarbaijan, and West Azarbaijan, changed from net VW importers in 1980 to net VW exporters in 2010. Besides, Mazandaran province in the humid region changed from a net VW importer to a net VW exporter.



(**a**)



(**b**)

Figure 9. Net total virtual water (VW) import per province in Iran, in the years 1980 (**a**) and 2010 (**b**). Positive signs refer to net virtual water import; negative signs refer to net virtual water export. The figure within each province denotes the percentage of blue water in the VW import of the province.

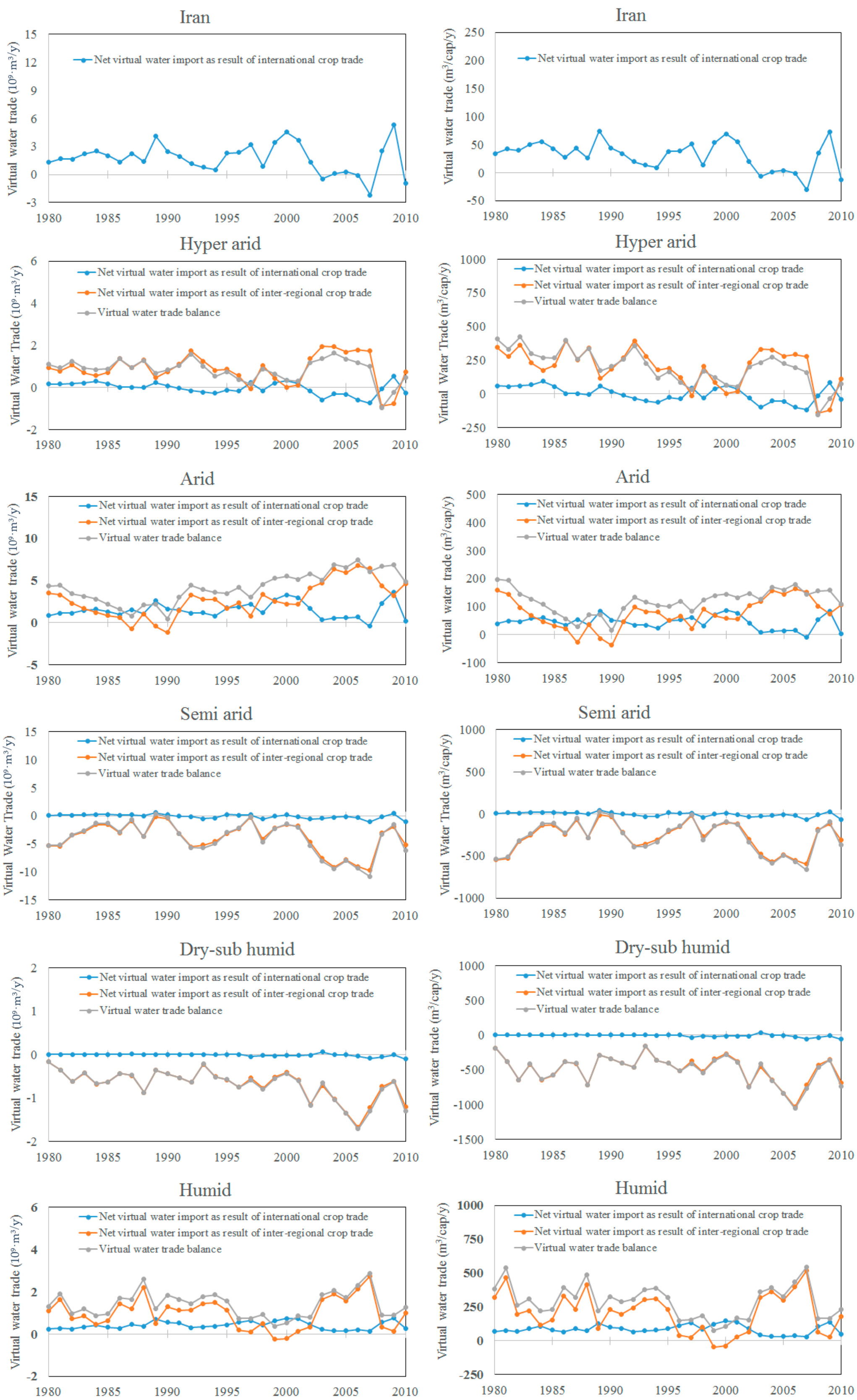


Figure 10. Overall net virtual water trade balance (VWB) and net virtual water import as a result of international and interprovincial crop trade, per climatic region, and for Iran as a whole. Total values in billion $m^3 \cdot y^{-1}$ (**left**) and in $m^3 \cdot cap^{-1} \cdot y^{-1}$ (**right**). Period: 1980–2010.

International virtual water trade. In 1980, the international VW trade of the country as a whole was 1.34 billion $m^3 \cdot y^{-1}$ (with a blue water share of 12.6%), which resulted from a VW import of 1.33 billion $m^3 \cdot y^{-1}$ and a VW export of 0.01 billion $m^3 \cdot y^{-1}$ (Figure 11). In 2010, international VW trade was −0.96 billion $m^3 \cdot y^{-1}$, which resulted from a VW export of 2.68 billion $m^3 \cdot y^{-1}$ and a VW import of 1.72 billion $m^3 \cdot y^{-1}$. While international import in cereals had the largest contribution to the overall VW import in 1980, the import of oil seeds took the first place in 2010. Internationally, Iran exported 0.17 billion $m^3 \cdot y^{-1}$ of blue VW in 1980, and 2.40 billion $m^3 \cdot y^{-1}$ in 2010. The dramatic increase was mainly due to a significant increase in exporting irrigated nuts and fruits in 2010, which are mainly exported from the semi-arid and hyper-arid regions (Figure 12).

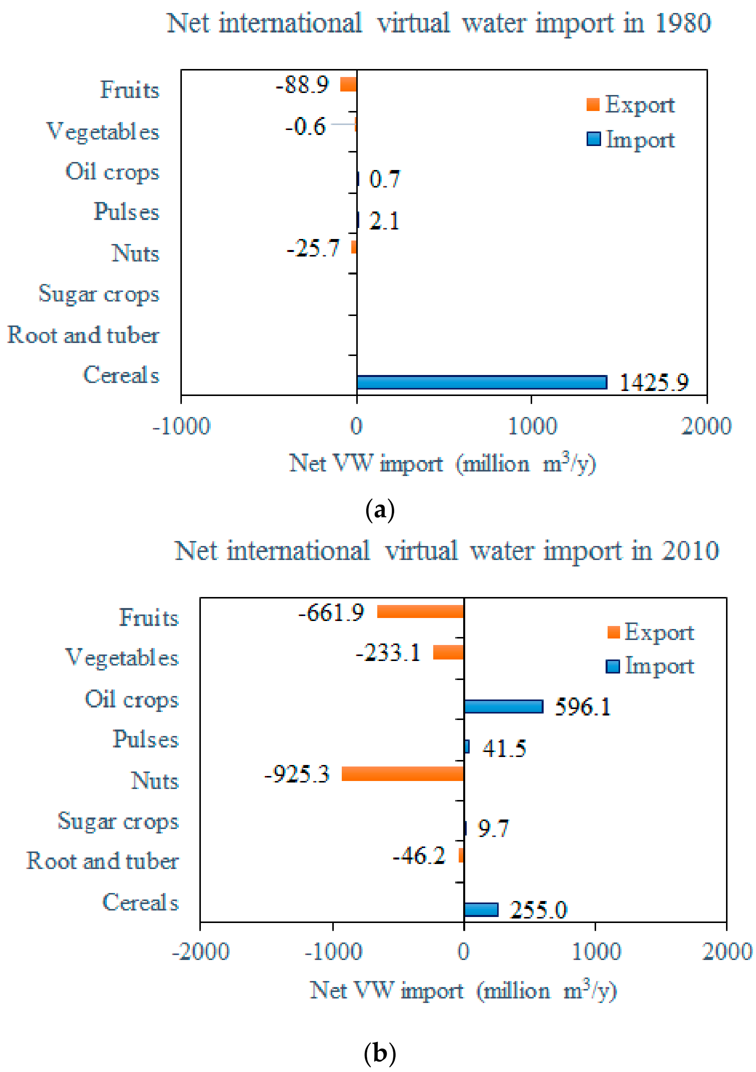


Figure 11. Net international virtual water import per crop category in 1980 (**a**) and 2010 (**b**).

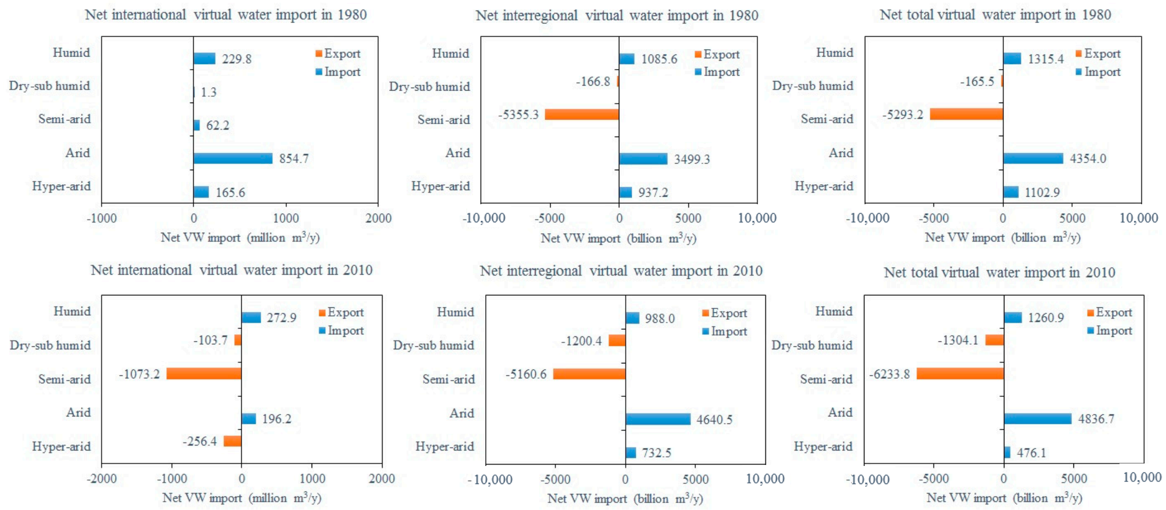


Figure 12. Net international, interregional, and total virtual water import per climatic region in 1980 (**top**) and 2010 (**down**).

Interprovincial virtual water trade. The interprovincial VW trade grew from 9.1 billion $m^3 \cdot y^{-1}$ (59% blue water) in 1980 to 14.8 billion $m^3 \cdot y^{-1}$ (57% blue water) in 2010, which was mainly due to increased interprovincial trade in cereals, nuts, and fruits. The spatial pattern of interprovincial VW trade within the country remained more or less the same over the period, with the semi-arid region responsible for the largest VW export, and the arid region responsible for the largest VW import (Figure 12).

2.5. Water Saving through Crop Trade

Water saving per province. The largest water savings due to trade in the country are found in some provinces in the arid region, most notably Razavi Khorasan and Esfahan (Figure 13). Total water saving in the arid region increased from 5.05 billion $m^3 \cdot y^{-1}$ in 1980 to 13.1 billion $m^3 \cdot y^{-1}$ in 2010. Blue water saving in the arid region increased from 3.71 billion $m^3 \cdot y^{-1}$ in 1980 to 12.0 billion $m^3 \cdot y^{-1}$ in 2010 (Figure 14). However, within the arid region, there are also provinces with water losses due to trade, namely Fars, South Khorasan, and North Khorasan. Most of the provinces in the semi-arid region saved water in relation to international crop trades over the period, but experienced water losses in relation to interprovincial crop trade. The net result of international and interprovincial crop trade for the semi-arid region is an overall water loss of 5.25 billion $m^3 \cdot y^{-1}$ in 1980, and 1.49 billion $m^3 \cdot y^{-1}$ in 2010. For the semi-arid region as a whole, the 3.27 billion $m^3 \cdot y^{-1}$ of blue water loss in 1980 had become 2.35 billion $m^3 \cdot y^{-1}$ in blue water saving in 2010. All three provinces in the hyper-arid region had considerable water saving related to their crop trade, with an increasing trend over time. The two provinces in the humid region, and the one province in the dry sub-humid region, had water savings due to crop trade as well, with again an increasing trend except for Mazandaran province. In 1980, Mazandaran still had a blue water saving due to trade, but in 2010, it had a blue water loss due to the export of irrigated rice.

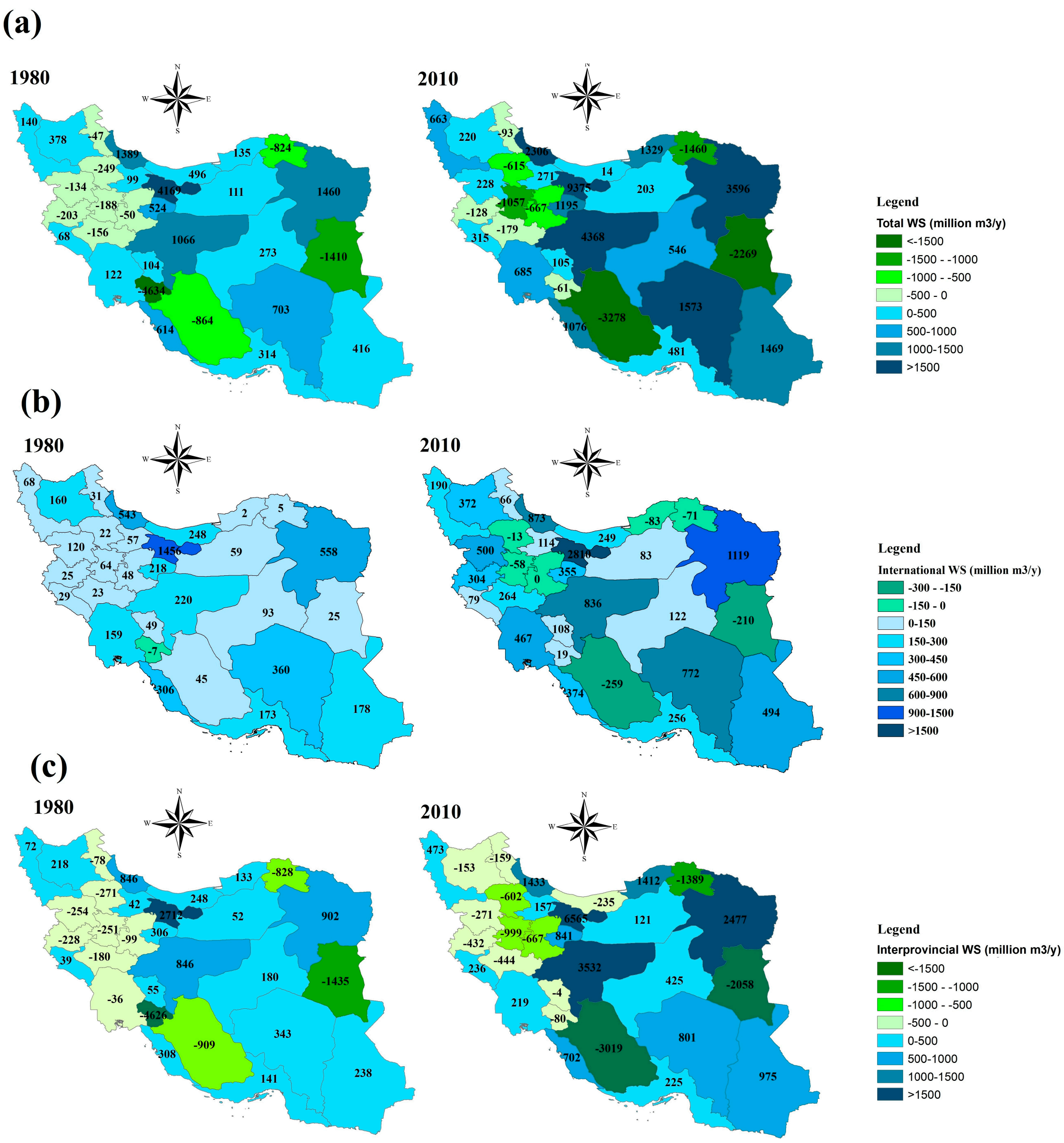


Figure 13. Total (green plus blue) water saving (WS) as a result of total (**a**), international (**b**), and interprovincial (**c**) crop trade, per province, in 1980 (**left**) and 2010 (**right**).

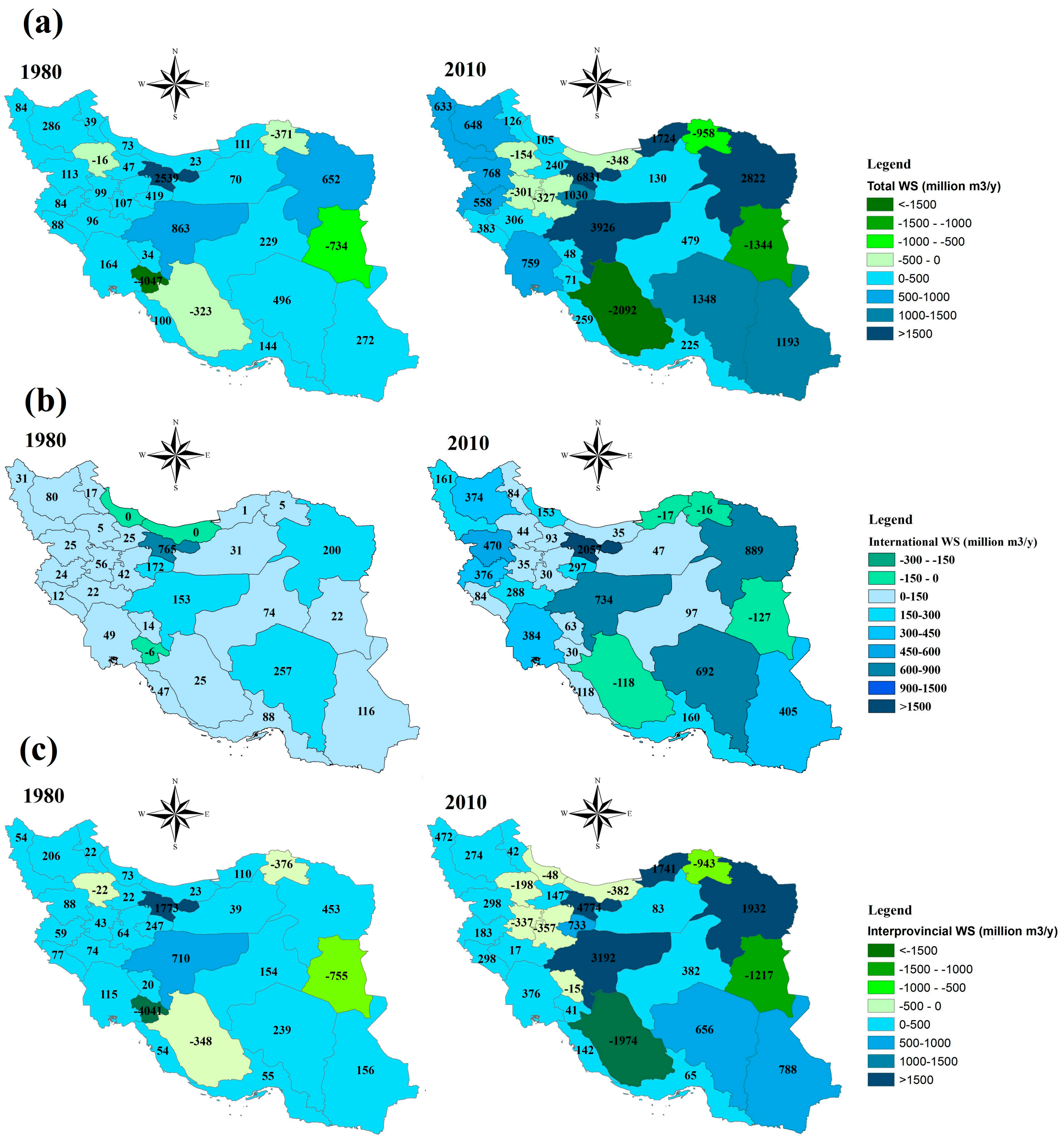


Figure 14. Blue water saving (WS) as a result of total (**a**), international (**b**), and interprovincial (**c**) crop trade, per province, in 1980 (**left**) and 2010 (**right**).

Water saving related to international crop trade. While in 1980, Iran's international crop trade led to a total (green plus blue) water saving of 5.0 billion $m^3 \cdot y^{-1}$ (46% blue), this had grown to 9.8 billion $m^3 \cdot y^{-1}$ by 2010 (80% blue). However, there was also large variability within this period, which related to the variability in traded crops and their volumes. Cereal imports played the biggest role in the national water saving of Iran through international crop trade, followed by oil crop imports. Overall, the international export of nuts, vegetables, fruits, and root and tubers resulted in water losses through 1980–2010.

Water saving related to interprovincial crop trade. In 1980, interprovincial crop trade was still associated with a total water loss of 1.5 billion $m^3 \cdot y^{-1}$, but this turned into a water saving from 1982 onwards. The water saving related to interprovincial crop trade steadily grew until 2010, when the total water saving amounted to 10.1 billion $m^3 \cdot y^{-1}$. Looking at blue water, we find a blue water loss as a result of interprovincial crop trade of 0.6 billion $m^3 \cdot y^{-1}$ in 1980, and a blue water saving of 11.2 billion $m^3 \cdot y^{-1}$ in 2010. The water savings due to interprovincial trade refer to most crop categories, but not for cereals and sugar crops, which are traded from provinces with a relatively large WF per tonne (e.g., Fars province in the arid region, with an average WF of 2288 m^3 per tonne of cereals in 2010) to provinces with a smaller WF per tonne (e.g., Tehran, also in the arid region, with a WF of 1731 m^3 per tonne of cereals in 2010).

3. Added Value of WF Assessment for Iran's Food and Water Security Policy

After the 1979 revolution in Iran, the government implemented agricultural policies aimed at achieving food self-sufficiency. The main current policy frameworks governing agriculture and economic development in Iran are [17]: Vision 2025 (adopted in January 2009), Broad Policies for Agriculture (adopted in July 2005), and the fifth Five-Year National Economic, Social and Cultural Development Plan (FYNDP). While the latter plan refers to the period 2011–2016, the sixth Five-Year Plan is still under debate. One of the main objectives of the Iranian government is to achieve national food security through higher agricultural productivity and self-sufficiency in staple crops. In 1999, the government initiated the self-sufficiency strategy for wheat by adopting different policies, which caused Iran to become the 12th largest producer of wheat in the world by 2012 [17]. Thereafter, a guaranteed purchase price was provided for more than 20 crops, with wheat and rice being the most important, which caused a considerable increase in national agricultural production.

Since water availability has direct bearing on food self-sufficiency, the Iranian policy makers implemented ambitious long-term water management plans in the third Five-Year Development Plan of the country (third FYDP) to address the growing gap between demand and supply. Water policies in Iran during this period mainly focused on increasing the amount of water physically available without considering the long-term consequences of this strategy. One of the quantitative goals that have been accomplished after the third FYDP was the increase of total crop production through changing Iran's agricultural system. About 140,000 hectares of irrigation and drainage networks were constructed during the past two decades. To rapidly expand the irrigated lands, the planners and policy makers focused on increasing water availability through constructing dams and the associated infrastructures. During the third FYDP, 12 new dams were constructed, providing an additional water supply of about 3.7×10^9 $m^3 \cdot y^{-1}$. Globally, Iran ranks third in dam building, with most dams constructed in the period of 1960–1990 [18]. Currently, about 500 dams are operating in Iran, and 100 more dams are under construction. Moreover, the government considers constructing 400 more dams, which are now in the design or feasibility stages [19]. Based on the reported value in 2016, a volume of 40 billion $m^3 \cdot y^{-1}$ of water is currently stored in the Iranian reservoirs [20]. Damming has caused serious environmental problems, such as deteriorating water quality and increasing land desertification and salinization. It has been reported that over two-thirds of Iran's land is rapidly turning into desert as a consequence of environmentally unmanaged damming projects [21].

The expansion of irrigation beyond regional capacity levels caused a dramatic overexploitation of groundwater resources. Now, farmers operate about 500,000 wells in Iran [18], and there is no license or permission for many of them. This has led to the salinization of farmland wells and reduced groundwater access. According to the Institute for Forest and Pasture Research, groundwater levels have dropped by two meters in recent years across 70 plains, affecting as much as 100 million hectares. With little to no metering to ensure that withdrawal limits are not breached, groundwater extraction within Iran has led to a 50% reduction in groundwater availability and significant issues with salinity, as water tables continue to fall [18].

Implementing major interbasin water transfer projects was the other achievement of the third FYDP, mitigating regional water shortages. Transferring desalinated water from the Caspian Sea, and from the Persian Gulf and Sea of Oman to support the dehydrated megacities and parched farmlands within the country are the most recent high-profile projects considered by the Iranian policy makers. While the interbasin water transfer projects are likely to be continued, these plans are unlikely to address water shortages in the long term due to the significant environmental impact these transfers cause. The government also considered the use of unconventional water resources, but as of yet, wastewater use in Iran's agriculture is mostly uncontrolled. There are many local farmers using raw wastewater directly for irrigation without caring about its adverse effects on human health or the environment.

Iran's policy on food self-sufficiency caused a significant increase in total production through increasing water supplies and expanding the irrigated land area, but evaporation losses are large due to the inefficiency of the irrigation systems. Over 70% of the irrigated land is under surface irrigation, with an average irrigation efficiency of 33%, according to the Food and Agriculture Organization of the United Nations (FAO), leaving significant room for water saving through efficiency improvements. Inefficient irrigation can increase the incidence of salinization and waterlogging of agricultural land, and lead to reduced productivity and long-term problems with sustainable land use. In fact, during the past decades, Iran's water problems have mostly been addressed by increasing water availability, while water demand management options have less been considered by the Iranian water authorities.

The water footprint assessment carried out here provides several new insights and management solutions that are currently not considered by the national water strategy of Iran. First, the study shows new insights in how to possibly diminish water consumption in crop production. Our WF assessment demonstrates that the WF per tonne for a specific crop hugely varies within the country, and even within climatic regions. It raises the question of why certain crops are produced in certain provinces, but also why some provinces do better than others. The assessment made here invites the development of benchmarks for the WFs of crops, per crop and per climate region (see for instance Hoekstra [14], Mekonnen and Hoekstra [22], and Zhuo et al. [23]), and for further exploration of what water savings could be achieved when reducing the WF for all crop production in a region to a certain reasonable benchmark level (see for instance Chukalla et al. [24]). WFs can be reduced by diminishing the no beneficial component of evapotranspiration from crop fields, by mulching and better irrigation practices [25]. Adjustments in crop planting dates and selecting appropriate crop varieties that yield more crop per drop are other possible ways to increase water productivity and reduce WFs per tonne of crop [26,27]. In addition, knowledge on the water requirements per unit of crop under certain climatic conditions may result in a reconsideration of the crop production pattern in the country. As we show, for example, oil crops produced in the hyper-arid region have a relatively large WF per tonne of crop, while roots and tubers have a much smaller WF per tonne. Besides, as shown earlier by Karandish et al. [28], roots and tubers also have a smaller WF per hectare, and would give higher economic profit. The question, therefore, is why governmental policies promote planting oil crops in the hyper-arid region.

Second, the study shows how modifying consumption patterns could help to mitigate water scarcity. Iran's water policy makers fully ignore the significant influence of the consumption pattern on exacerbating the water scarcity. Our WF assessment in relation to crop consumption demonstrates the significant influence of diet on water requirements. For example, rice is a common element in the Iranian diet, especially in the northern part of the country, while rice has a much larger WF per tonne compared with alternatives such as wheat or roots and tubers. Besides, even though rice is mostly produced in the humid region, it is mostly irrigated, thus aggravating blue water demands, while wheat and roots and tubers can be produced in the same region under rain-fed conditions.

Third, the analysis in this paper shows that the existing pattern of interprovincial crop trade within the country is counter logical. Although it is the most water-abundant region of the country, the humid region has a net virtual water import through crop trade, due to the relatively small share in total crop production and the decreasing trend in the per capita arable land availability. Economic incentives have encouraged many farmers in northern Iran to change their farms to urban areas. As a consequence, the humid region is a net VW importer, despite being fertile for crop production with a relatively small WF per tonne of crop. On the other hand, the water-scarce semi-arid region, and some provinces in the arid region, produce crops for export to other regions within Iran. Interestingly, the findings here for Iran—of virtual water transfers from water-scarce to more water-abundant regions within a country—is similar to findings for other countries, such as China [29] and India [30]. In recent years, the government has implemented plans for interbasin water transfers, by which water is conveyed from the more water-abundant to the water-scarce regions of Iran. Undoubtedly, this will result in the continued expansion of irrigated agriculture in the arid and semi-arid regions of Iran, where crops have the relatively high WF per tonne. During the few past decades, a strong motivation has been created among local farmers to replace their rain-fed practices with irrigation systems in order to achieve higher annual income through the increased yield. Our findings indeed show that the expansion of the irrigated area has led to a considerable increase in the proportion of the blue WF in the total WF.

Finally, the study demonstrates that Iran's food self-sufficiency policy may be detrimental to maintaining food security in the long run. It has promoted the export of water-intensive products from water-scarce regions, such as cereals from Fars province in the arid region for export to other provinces, which results in groundwater level decline, aquifer depletion, soil salinization, and groundwater quality deterioration. Another example is the promotion of growing cereals, fruits, and sugar crops in West Azarbaijan for export to other provinces, which leads to increased water consumption and contributes to the drying of Urmia Lake. Therefore, knowledge about the virtual water flows entering or leaving a province or climatic region can cast a completely new light on how trade mitigates or aggravates the water scarcity of the province or region.

4. Conclusions

Our analysis shows that food self-sufficiency increased in line with Iranian policy. Besides, the water savings related to international and interprovincial trade increased over time. However, the WF of production substantially increased, particularly within the semi-arid region and some provinces in the arid region that are mostly responsible for feeding the country, which resulted in a strong growth of blue WFs and the overexploitation of water resources in these regions. Besides, our analysis shows that consumption increased because of population growth and an increase in consumption per capita. Current Iranian food and water policy could be enriched by reducing the WFs of crop production to certain benchmark levels per crop and climatic region, aligning cropping patterns to spatial differences in water availability and productivities, and reconsidering interbasin water transfer plans to bring water to water-scarce places with relatively high WFs per unit of crop to produce food for export. Furthermore, Iranian food and water policy could be supplemented by paying due attention to the increasing food consumption per capita in Iran. Finally, the country may have to reconsider its food self-sufficiency and food trade policy. Roots and tubers, nuts, vegetables, and fruits were the most exported crops internationally in 2010. Iran may benefit from the international export of vegetables and roots and tubers due to their relatively low WF per tonne, but exporting nuts and fruits, especially from the drier parts of the country to abroad, leads to a significant national water loss. Furthermore, while importing cereals instead of producing them domestically could save a lot of water, our findings indicate that the per capita international cereals import reduced by 42% over 1980–2010, mainly due to Iran's Wheat Self-sufficiency Project over the past decades.

We acknowledge that adapting Iran's food and water policy is a challenge given the conflicts of interests involved, particularly between the short and long term, and between the goal of food self-sufficiency and the need for sustainable water use. Choices that need to be made will need to consider all of the relevant economic, social, and environmental factors, but will include a political component as well, given the trade-offs to be made. While current Iranian food and water policy narrowly focuses on measures to enhance domestic food production through increased water supply, our research suggests that it could be beneficial to additionally consider the potential of measures to improve water productivity, adapt spatial cropping patterns, shift to diets that are less water intensive, and promote forms of trade that save the scarce domestic water resources. Future research will be necessary to quantify the full potential and implications of these alternative measures.

5. Method and Data

5.1. Study Area

Iran lies between 25°00′ N to 38°39′ N latitude and 44°00′ E to 63°25′ E longitude, and spans an area of 1,640,195 km^2, which is divided into 30 provinces, as illustrated in Figure 1a. The elevations range from −32 m below sea level to 5428 m above sea level, with a national average of 1200 m. The long-term areal average of minimum (T_{min}) and maximum (T_{max}) temperature and annual precipitation (P) are 12.4 °C, 25.2 °C, and 244 mm, respectively. The southeastern provinces of Sistan and Balouhestan and the northern province of Gilan receive the lowest and highest annual P, respectively, viz. 104 mm and 1033 mm. Based on the De Martonne climate classification, there are five climatic regions in Iran: hyper-arid, semi-arid, arid, humid, and dry sub-humid (Figure 1b). The dominant climate is arid and semi-arid (Karandish et al., 2016). Despite having the lowest freshwater availability, the arid and semi-arid regions are responsible for producing more than 70% of the total crop production in the country, with most of the crops being irrigated.

5.2. Method and Data

WF of production. All of the calculations were done per crop per province per year for the study period of 1980–2010. The weighted average WF of each crop category (i.e., cereals, root and tubers, sugar crops, pulses, nuts, oil crops, vegetables, and fruits) was then calculated based on the production of different crops in each category. Thereafter, weighted average values were calculated at the climatic region scale. The WFs of crop production were calculated at a daily time step based on the accounting framework of Hoekstra et al. (2011). For each crop, the green and blue WFs (m^3·t^{-1}) were calculated as the daily green and blue evapotranspiration (ET, m^3·ha^{-1}) aggregated over the full growing period, divided by the crop yield (Y, t·ha^{-1}). ET and Y were simulated using AquaCrop, FAO's water balance and crop growth model [31]. The initial soil moisture content was estimated by running the model for a period of five years, and taking the outcome after the five years as the initial value for our calculation, a procedure followed also for example by Siebert and Döll [32] and Zhuo et al. [33]. Per crop, province, and year, yield data were scaled to fit annual yield statistics at the province level. The model simulates a daily soil water balance for the rooting zone:

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

in which $S_{[t]}$ and $S_{[t-1]}$ are the soil water content at the end of day t and t-1, respectively, $P_{[t]}$ is precipitation on day t, $I_{[t]}$ is irrigation applied on day t, $CR_{[t]}$ is capillary rise, $ET_{[t]}$ is evapotranspiration, $RO_{[t]}$ is surface runoff, and $DP_{[t]}$ is deep percolation. All of the flow terms are in mm/day. Capillary rise is assumed to be zero, since groundwater is assumed to be deeper than one meter below the rooting zone all over Iran. P and I were considered as green and blue water, respectively. The contributions of green (P) and blue (I) water to RO were calculated based on the ratio of P and I, respectively, to the sum of P and I. The fraction of green and blue water in the total soil water content at the end of the previous day was applied to calculate green and blue DP and ET. Following Chukalla et al. [25] and Zhuo et al. [33], the green soil water content (S_{green}) and blue soil water content (S_{blue}) were calculated as:

$$\begin{cases} S_{green[t]} = S_{green[t-1]} + P_{[t]} + RO_{[t]} \times \frac{P_{[t]}}{P_{[t]}+I_{[t]}} - \left(DP_{[t]} + ET_{[t]}\right) \times \frac{S_{green[t-1]}}{S_{[t-1]}} \\ S_{blue[t]} = S_{blue[t-1]} + I_{[t]} + RO_{[t]} \times \frac{I_{[t]}}{P_{[t]}+I_{[t]}} - \left(DP_{[t]} + ET_{[t]}\right) \times \frac{S_{blue[t-1]}}{S_{[t-1]}} \end{cases} \quad (2)$$

WF of consumption. Following the bottom-up approach [15], per crop and per province, the WF related to consumption of a specific crop (m^3·y^{-1}) was calculated as the crop consumption volume (t·y^{-1}) multiplied by the average WF of the crop available in the province (m^3·t^{-1}). As consumption in Iran, we counted all of the components reported under 'utilization' in FAO's food balance sheet.

We calculated the average utilization per crop per capita in Iran and assumed this as the consumption level per capita for each province. Total consumption per province follows from multiplying this with the population in each province. Per province, the average WF of a crop was calculated as a weighted average of the WF of the crop produced in the province, and the WFs of the crops imported from other provinces or abroad:

$$WF_{Prov}[P] = \frac{P_{Prov}[P] \times WF_{prod,Prov}[P] + \sum_e \left(I_e[P] \times WF_{prod,e}[P] \right)}{P_{Prov}[P] + \sum_e I_e[P]} \tag{3}$$

where, $P_{Prov}[P]$ (t·y^{-1}) is the production quantity of crop p, $I_e[P]$ (t·y^{-1}) is the imported quantity of crop p from exporting place e (other provinces in Iran or other countries), $WF_{prod,Prov}[P]$ (m^3·t^{-1}) is the specific WF of crop production in the province, and $WF_{prod,e}[P]$ (m^3·t^{-1}) is the WF of the crop as produced in exporting place *e*.

International and interprovincial crop trade and virtual water trade. To understand interprovincial trade, we determined, per crop, which provinces had surpluses and which had deficits. The crop origin (abroad or other provinces) for importing into deficit provinces is estimated, per crop, based on the ratio of total Iranian import of that crop to the sum of surpluses in the provinces that have a surplus of that crop. We add, per crop, all provincial exports and calculate the average WF of that sum of provincial surpluses (as a weighted average of the WFs in the surplus provinces). For all of the importing provinces, we assume the WF of the imported crop from other provinces to equal this calculated average. At the province level, the net VW import (m^3·y^{-1}) related to crops is the sum of the interprovincial net VW import plus the international net VW import in the considered province. Data on the WFs related to the crops imported from abroad were obtained from Mekonnen and Hoekstra [34].

Provincial water savings or losses resulting from trade. Water saving (WS) as a result of international or interprovincial crop trade was estimated per province following the method as introduced by Chapagain et al. [35]. WS related to the international crop trade of a province (m^3·y^{-1}) was estimated by multiplying the net import volume of the province from abroad (t·y^{-1}) by the WF per tonne of the crop in the province (m^3·t^{-1}). Similarly, WS related to interprovincial crop trade (m^3·y^{-1}) was computed per province as the net import volume of the province from other provinces (t·y^{-1}) times the WF per tonne of the crop in the importing province (m^3·t^{-1}). We took the national average WF of a crop (m^3·t^{-1}) in instances in which a specific crop was imported to a province, but not grown in that province at all. The provincial WS resulting from trade has a negative sign when there is gross export of a crop rather than gross import. The overall WS related to all interprovincial trade flows within Iran was calculated as the sum of the water savings (or losses) in all of the provinces.

5.3. Data

For the study period of 1980–2010, all of the required data were obtained per crop per province per year. To get the meteorological data, 52 weather stations (Figure 1) located in the five climatic regions were selected [36]. Based on these data, provincial averages of T_{min}, T_{max} and reference evapotranspiration (ET_o) were calculated. ET_o was calculated based on the FAO Penman–Monteith equation [37]. Soil texture data and the total soil water holding capacity were obtained from Batjes [38]. For the hydraulic characteristics for each type of soil, the indicative values provided by AquaCrop were used. The population statistics were obtained from the Statistical Center of Iran [39]. We consider 26 crops common to Iran, which were classified into eight crop categories based on the FAO classification [37]: cereals (wheat, barley, and rice), roots and tubers (potato), sugar crops (sugar beet and sugar cane), pulses (bean, pea, and lentil), nuts (pistachio, walnut, almond, and hazelnut), oil crops (cottonseed, soybean, and canola), vegetables (tomato and onion) and fruits (apple, banana, date, grape, lime, lemon, tangerine, orange, and grapefruit). Agricultural data for the irrigated and rain-fed crops, including crop sowing area (ha), irrigated area (ha), crop planting and harvesting dates, and crop yield (kg·ha^{-1}), were collected per crop per province per year from Iran's Ministry of Agriculture Jihad [40]. Data on Iran's international trade per crop (in t·y^{-1}) were taken from FAO (2016a). Data on national crop consumption per capita, in terms of primary crop equivalents, were obtained from the Supply and Utilization Accounts of FAOSTAT [17].

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