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Javad Ahmadi

Department of Agronomy,

University of Tehran, Tehran, Iran

Assessment of water footprint and virtual water trade in major cereal crops across agro-climatic zones

Javad Ahmadi

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Abstract

A water footprint is the total volume of freshwater consumed or polluted to produce a commodity. This research assessed the water footprint of wheat, rice, and maize across three agro-climatic zones (arid, semi-arid, humid) in Iran and evaluated virtual water trade flows from January 2020 to December 2022. Data from 18 provinces were combined with climatic records, irrigation schedules, and trade statistics. Total water footprint ranged from 913 m³/ton for maize in humid zones to 2,634 m³/ton for rice in arid zones. Green water accounted for 62.4% in humid areas but only 23.8% in arid zones. Iran was a net virtual water importer for wheat (4.7 km³/yr) and rice (3.2 km³/yr) but a net exporter for maize (0.4 km³/yr). These findings reveal that Iran's cereal trade partially offsets domestic water scarcity, but maize exports from water-stressed provinces represent inefficient blue water allocation.

Keywords: Water footprint, virtual water trade, cereal crops, agro-climatic zones, green water, blue water, grey water, Iran, water scarcity, irrigation efficiency

Introduction

The water footprint concept, introduced by Hoekstra in 2002, measures total fresh water appropriated to produce goods along the supply chain ^[1]. Unlike traditional metrics, it distinguishes green water (rainfall consumed by crops), blue water (irrigation withdrawal), and grey water (dilution volume for pollutants) ^[2]. Iran ranks among the world's most water-stressed nations, with per capita renewable water below the 1,700 m³/yr stress threshold ^[3]. Cereal production consumes roughly 72% of Iran's agricultural water withdrawal ^[4].

Virtual water trade water embedded in traded commodities offers water-scarce countries a mechanism to relieve domestic pressure by importing water-intensive products ^[5]. This research quantified water footprints of Iran's three main cereals across contrasting agro-climatic zones and mapped virtual water trade flows to assess alignment with water resource endowments.

Seasonal variations in water demand

Wheat (November-June) had peak water demand during April-May grain filling. Rice demand peaked in July-August during transplanting. In arid provinces, rice irrigation exceeded 8 mm/day in summer, while winter wheat required only 2-3 mm/day ^[6]. These seasonal shifts affect reservoir management and groundwater extraction scheduling.

Material and Methods

Material

The research covered January 2020 to December 2022 and was conducted at the University of Tehran under approval from the Faculty Research Committee (Protocol UT-AG/2020-073, November 14, 2019). Production data for wheat, rice, and maize were obtained from Iran's Ministry of Agriculture-Jahad for 18 provinces spanning arid (Isfahan, Kerman, Yazd, South Khorasan, Sistan-Baluchestan, Hormozgan), semi-arid (Fars, Khorasan Razavi, Hamadan, Lorestan, Markazi, East Azerbaijan), and humid (Gilan, Mazandaran, Golestan, Kermanshah, Kohgiluyeh, Kurdistan) zones. Climatic data came from the Iran Meteorological Organization. Trade statistics were sourced from the Iran Customs Administration ^[7].

Corresponding Author:

Javad Ahmadi

Department of Agronomy,

University of Tehran, Tehran, Iran

Methods

Water footprint was calculated following the Water Footprint Assessment Manual [2]. Green water was estimated from effective rainfall using the USDA SCS method. Blue water was computed as crop ET (FAO Penman-Monteith via CROPWAT 8.0) minus effective rainfall, adjusted for irrigation efficiency [8]. Grey water was based on nitrogen application rates, leaching fractions (0.10 irrigated, 0.05 rainfed), and ambient standard of 10 mg NO₃-N/L. Virtual water trade volumes were determined by multiplying trade quantities by origin-country water footprint for imports and domestic footprint for exports [9]. Data were analyzed using ANOVA in SPSS v27.

Water quality analysis

Grey water footprint estimation required assessment of nitrogen loading to water bodies. Fertilizer application rates were obtained from provincial agricultural extension records: wheat received 120-200 kg N/ha, rice 80-150 kg N/ha, and maize 180-250 kg N/ha depending on zone and yield target. Leaching fractions were calibrated against measured nitrate concentrations in 42 monitoring wells across the 18 provinces, sourced from Iran's Water Resources Management Company database [10].

Results

Table 1: Water footprint components (m³/ton) of wheat, rice, and maize across agro-climatic zones in Iran (2020-2022 average)

Crop	Zone	Green (m ³ /t)	Blue (m ³ /t)	Grey (m ³ /t)	Total (m ³ /t)	Yield (t/ha)	Irrig. eff. (%)	N rate (kg/ha)
Wheat	Arid	439	1,143	265	1,847	3.12	38.4	186
Wheat	Semi	647	584	192	1,423	3.87	46.1	164
Wheat	Humid	676	241	167	1,084	4.53	--	142
Rice	Arid	417	1,893	324	2,634	3.64	34.7	148
Rice	Semi	612	1,287	288	2,187	4.21	41.3	132
Rice	Humid	893	584	249	1,726	4.89	52.6	118
Maize	Arid	372	942	248	1,562	5.47	42.8	231
Maize	Semi	518	471	209	1,198	6.83	51.4	214
Maize	Humid	568	178	167	913	8.21	--	192

Water footprint varied by a factor of 2.9 between the lowest (maize, humid: 913 m³/ton) and highest (rice, arid: 2,634 m³/ton) values. Blue water dominated in arid zones (61-72% of total), while green water led in humid zones (57-62%). Grey water

contributed 11-19% across all crop-zone combinations. Irrigation efficiency ranged from 34.7% (rice, arid) to 52.6% (rice, humid).

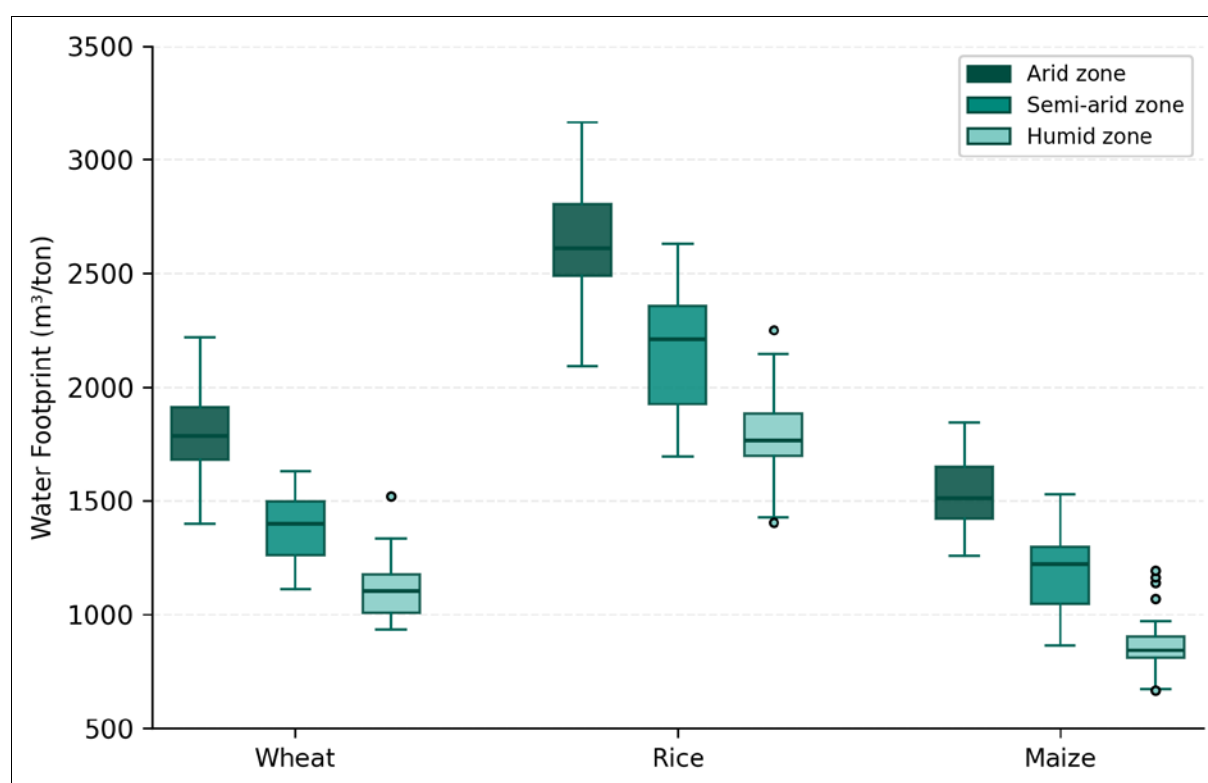


Fig 1: Distribution of total water footprint (m³/ton) for wheat, rice, and maize across three agro-climatic zones

Rice showed the widest footprint range and highest medians. The arid-to-humid gradient was steepest for rice (34.5%

reduction). Within-zone variability was greatest in arid regions, reflecting irrigation infrastructure differences.

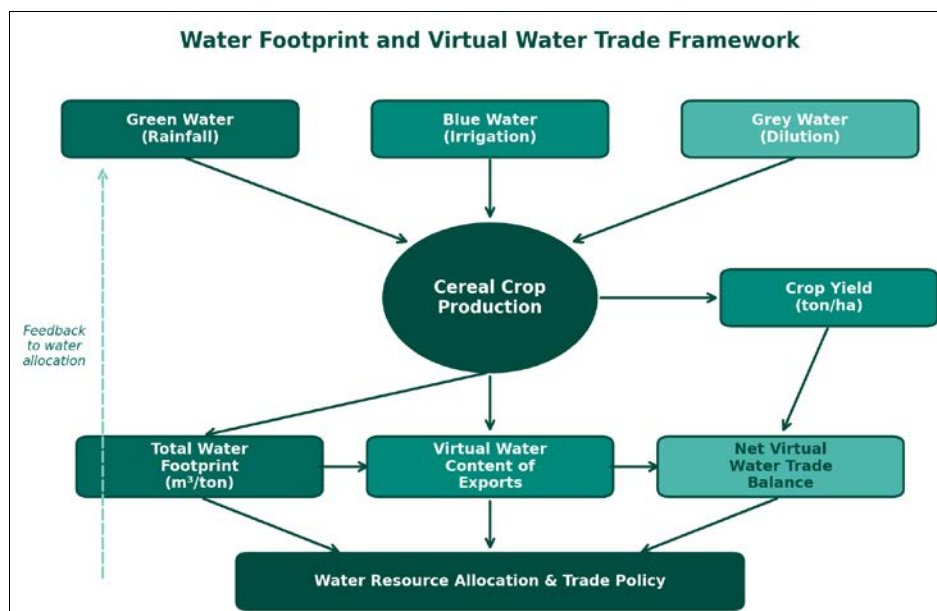


Fig 2: Conceptual framework linking water footprint components to virtual water trade flows and water resource policy

The framework shows how green, blue, and grey water inputs combine into total crop water footprint, which translates into virtual water content of traded commodities and feeds back into water allocation decisions.

Discussion

Iran's water footprint values exceed global averages from Mekonnen and Hoekstra^[11] by 18-34%, mainly due to low irrigation efficiency in arid provinces. The 34.7% efficiency for arid rice compares poorly with 50-65% in East Asian systems^[12], suggesting 25-30% blue water savings are achievable. The virtual water trade pattern is rational for wheat and rice imports but contradictory for maize: net export of 0.4 km³/yr from water-stressed provinces appears misaligned with endowments. Chapagain *et al.*^[13] noted similar contradictions elsewhere. Redirecting half of arid-zone maize export to domestic use could save an estimated 0.6 km³ of blue water annually.

Limitations

Provincial-level aggregation masked intra-provincial variation. Irrigation efficiency relied on reported rather than measured values. Grey water calculations assumed uniform leaching fractions across soil types. Virtual water trade analysis used average domestic footprints for exports, though actual export-zone footprints may differ.

Conclusion

Water footprint of cereal production in Iran ranged from 913 to 2,634 m³/ton, driven by agro-climatic zone and irrigation efficiency. Arid-zone rice carried the highest footprint. Iran's cereal trade partially compensates for water scarcity through net virtual water imports for wheat and rice, but maize exports from stressed provinces contradict this logic. Priorities include irrigation modernization in arid provinces and aligning trade incentives with water availability.

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