

Sustainable Dynamic Changes in Global Crop Virtual Water Trade: A Postprint

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Abstract

Integrating crop irrigation water into the global trade chain and analyzing its sustainability is crucial for ensuring water resources and food security. Constrained by the contradiction between economic benefits and water resource development and utilization, the sustainability of virtual water footprint in crop trade has not received sufficient attention. Based on crop production and trade chain matrix data provided by the Food and Agriculture Organization (FAO), this study employs physical trade flow analysis, spatial correlation analysis, and multiscale geographically weighted regression to systematically analyze the spatiotemporal distribution of sustainability, spatial association characteristics, and driving factors of net export water volumes in global crop virtual water trade from 2000 to 2019. The results show that over the past 20 years, both sustainable and unsustainable net export virtual water volumes of global crops (especially cotton) have exhibited a fluctuating upward trend year by year (approximately $0.20 \text{ Gm}^3 \cdot \text{a}^{-1}$); however, with the improvement of agricultural technology levels, the proportion of unsustainable virtual water volume in the total virtual water trade has decreased from 42.31% to 41.40%. Spatial analysis results indicate that through global and local Moran's I index analysis, unsustainable net export virtual water volumes of global crops from 2000 to 2009 exhibited significant spatial clustering characteristics, but this clustering trend has gradually weakened and become more dispersed in the past decade. The growth of net export virtual water volume is primarily driven by changes in cultivated land area, while agricultural added value has a significant negative impact on virtual water volume in trade. The findings of this study emphasize the importance of continuously implementing strict food security policies to promote the sustainable development of global crop virtual water trade and further reduce the proportion of unsustainable water use.

Full Text

Sustainable Dynamics and Driving Factors of Global Virtual Water Trade in Crops

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Abstract

Incorporating agricultural irrigation water into the global trade chain and analyzing its sustainability is crucial for ensuring water and food security. However, the sustainability of virtual water in crop trade has not received adequate attention due to conflicts between economic interests and water resource development. Based on crop production and trade matrix data from the Food and Agriculture Organization (FAO), this study employs physical trade flow analysis, spatial correlation analysis, and multiscale geographically weighted regression to systematically examine the spatiotemporal distribution, spatial association characteristics, and driving factors of sustainability in global crop virtual water trade from 2000 to 2019.

The results show that both sustainable and unsustainable net exported virtual water volumes in global crop trade (especially for cotton) exhibited a fluctuating upward trend over the past two decades, increasing at approximately 0.20 Gm³ per year. However, due to improvements in agricultural technology, the proportion of unsustainable virtual water in total virtual water trade decreased from 42.31% to 41.40%. Spatial analysis reveals that unsustainable net exported virtual water demonstrated significant spatial clustering from 2000 to 2009, as indicated by global and local Moran's I statistics, though this clustering trend gradually weakened and became more dispersed in recent years. The increase in net exported virtual water was primarily driven by changes in cultivated land area, while agricultural value-added had a significant negative impact on virtual water volumes in trade. These findings underscore the importance of implementing stringent food security policies to promote sustainable develop-

ment of global crop virtual water trade and further reduce the proportion of unsustainable water use.

Keywords: global; crops; virtual water; sustainability; driving factors

1. Data and Methods

1.1 Study Area Overview This study examines major regional groupings worldwide based on World Bank classifications (<https://datatopics.worldbank.org/world-development-indicators/>), covering 189 countries and regions globally. To ensure temporal continuity of data across changing national boundaries, we matched data for countries before and after boundary changes according to their main periods of existence. The regional classification scheme follows previous research [Figure 1: see original paper].

1.2 Data Sources This study utilizes production data (1961-2019) from the Food and Agriculture Organization (FAO) Statistical Database (<https://www.fao.org/faostat/en/#data/QCL>), which includes production quantities for 35 selected crop types covering cereals, citrus fruits, and fiber crops. FAO also provides trade matrix data detailing actual trade interactions for major crops and their processed products. For example, for wheat, the trade matrix records not only wheat grain but also wheat flour, bran, and other derived products. Due to strict import tariff controls, the analysis primarily employs crop import data, with export data used to supplement missing import information [10,17]. To eliminate annual fluctuations, three-year moving averages were applied to both production and trade data for crops and their by-products.

Blue water footprint data reflecting crop irrigation were obtained from Scientific Data, providing country-level crop-specific irrigation water consumption at 5 arc-minute spatial resolution, accounting for annual climate variability and irrigation area expansion. Global water stress index data were sourced from AQUASTAT, with calculations referencing Sustainable Development Goal (SDG) 6.4.2, which incorporates environmental flow requirements into water resource carrying capacity assessments. Missing time series data were interpolated using spline interpolation methods.

1.3 Methods

1.3.1 Physical Trade Flow Analysis The Physical Trade Flow (PTF) method was employed to estimate water consumption in processed agricultural products based on actual trade flows between countries or regions [28]. This approach enables detailed analysis of agricultural trade flows at higher product resolution, directly and clearly linking consumption data to primary product sources. It tracks crop products through international supply chains from domestic production to bilateral trade and ultimately to end consumers, widely

used for consumption-based environmental impact accounting of agricultural products such as water use [10,17] and carbon emissions [21].

For each crop type c in year y , the following matrices were constructed:

$C_{irrigation}(c, y)$ represents the irrigation water consumption matrix for crop c at the country level; A denotes the share matrix of domestic material consumption in domestic material input; T represents the export share matrix by destination country derived from FAO trade data, including both crops and processed products; I is an identity matrix with the same dimensions as A ; $\hat{P}(c, y)$ is a diagonal matrix of crop production; and $u(c, y)$ is the water footprint consumption per ton of crop.

Actual irrigation water consumption (C_{wc}) and final consumption of crop irrigation water (P_{wc}) were calculated as:

$$C_{wc} = \sum J(c, y) \cdot C_{irrigation}(c, y)$$

$$P_{wc} = \sum i(c, y) \cdot C_{irrigation}(c, y)$$

Net import volume was calculated as the difference between crop irrigation water imports and exports for each country.

1.3.2 Virtual Water Sustainability Assessment Annual crop trade consumption blue water footprints were overlaid with global water stress index maps to calculate blue water scarcity [30]. When a region's blue water scarcity exceeds 1, its blue water footprint is considered unsustainable or exceeding environmental flow requirements, indicating that local blue water footprint exceeds available water (defined as natural runoff minus environmental flow). The proportion of blue virtual water exceeding environmental flow requirements for a specific product imported by a country can be calculated by combining that country's virtual water imports for the product with the environmental flow exceedance proportion.

Following Mekonnen and Hoekstra's blue water footprint scarcity classification [30], mild blue water scarcity (water scarcity index < 1) is defined as sustainable virtual water, while other categories are considered unsustainable (water scarcity index ≥ 1), i.e., not meeting environmental flow requirements. Considering a unified framework for all countries, this study adjusted water scarcity standards according to SDG 6.4.2 (freshwater withdrawal as a proportion of available freshwater resources), with a water scarcity index ≥ 0.25 at the national scale considered the boundary for water stress.

1.3.3 Spatial Autocorrelation Analysis Spatial autocorrelation refers to the potential interdependence of variables within the same region [32]. In crop virtual water trade analysis, spatial autocorrelation helps identify clustering effects of virtual water inputs or outputs within specific regions. Significant high-value clustering may reflect a region's high dependence on local water resources for crop trade, posing challenges for water resource management.

Global Moran' s I index was used to measure overall spatial autocorrelation of crop virtual water trade sustainability. The index ranges from [-1, 1]. Values significantly greater than 0 indicate positive spatial correlation (clustering of high-high or low-low values), while values less than 0 indicate negative correlation (spatial dispersion), and values near 0 suggest no spatial correlation. Although global analysis reveals overall clustering trends, it cannot capture spatial heterogeneity within regions [33]. Therefore, local spatial autocorrelation measures (Local Moran' s I) were introduced to identify statistically significant spatial clusters, such as high-value clusters (hotspots) and low-value clusters (coldspots).

1.3.4 Multiscale Geographically Weighted Regression Multiscale Geographically Weighted Regression (MGWR) was employed to analyze how socioeconomic and natural variables (TABLE:2) influence multi-regional crop virtual water trade. This method is particularly suitable for spatial and geographic research as it allows regression parameters to vary across spatial units, accommodating spatial variability and revealing geographic dynamics more nuancedly than traditional regression models that assume constant relationships.

The model formula is:

$$y_i = \beta_0(u_i, v_i) + \sum_{k=1}^n \beta_k(u_i, v_i)x_{ik} + \epsilon_i$$

where y_i is the dependent variable value at observation point i ; $\beta_0(u_i, v_i)$ is the intercept at location i with geographic coordinates (u_i, v_i) ; $\beta_k(u_i, v_i)$ is the regression coefficient for independent variable x_k at location i , reflecting varying impacts across geographic locations; x_{ik} is the value of the k -th independent variable at observation i ; and ϵ_i is the random error term.

Before MGWR modeling, linear regression was used for global fitting. Variables with high multicollinearity were removed using stepwise elimination. The final MGWR model showed an adjusted R^2 of 0.342, significantly higher than the linear regression model' s 0.225, with a lower corrected Akaike Information Criterion (AICc), indicating better fit.

2. Results

2.1 Sustainability of Net Exported Virtual Water in Global Crop Trade From 2000 to 2019, the spatiotemporal distribution patterns of sustainable and unsustainable net exported virtual water related to crop trade showed that sustainable net exported virtual water volumes increased with annual fluctuations, rising from 28.07 Gm³ to 32.06 Gm³. China, Japan, and Vietnam ranked highest in sustainable net exported virtual water volumes, reaching 2.25 Gm³, 2.17 Gm³, and 2.17 Gm³ respectively. Unsustainable net exported virtual water footprints increased by 66.50% during the study period, from 20.59 Gm³ to 32.22 Gm³, averaging 0.20 Gm³ per year. However, the proportion of unsustainable net exported virtual water footprints in total virtual water footprints decreased slightly from 42.31% to 41.40%.

From a crop perspective, cotton accounted for the largest share of unsustainable net exported virtual water in 2000 (15.48 Gm³, 27.13% of the total), followed by sugarcane (1.63 Gm³, 12.06%) and sugar beet (0.78 Gm³, 5.58%). By 2019, cotton remained the largest contributor to unsustainable net exported virtual water consumption, accounting for 37.93% of the total (25.72%), with wheat (12.06%) also significant.

2.2 Spatial Characteristics of Sustainability in Global Crop Trade

Global spatial autocorrelation analysis of net exported virtual water in crop trade revealed that sustainable virtual water showed random spatial distribution without clustering from 2000 to 2019. In contrast, unsustainable net exported virtual water exhibited strong positive spatial autocorrelation throughout the study period (TABLE:3). Moran' s I values were positive and significant from 2000 to 2009, indicating pronounced spatial clustering. However, the clustering effect gradually weakened, with Moran' s I decreasing from 0.213 ($Z = 7.892$, $p < 0.01$) in 2000 to 0.112 ($Z = 4.215$, $p < 0.01$) in 2019.

Local spatial autocorrelation analysis identified significant hotspot and coldspot distributions [Figure 3: see original paper]. From 2000 to 2009, hotspots were concentrated in the United States, Brazil, and Pakistan, reflecting prominent unsustainability in crop trade net exports and high dependence on external water resources. Coldspots appeared in more sustainable countries like Russia, Canada, and parts of Eastern Europe, which demonstrated high water self-sufficiency. The analysis also revealed that sustainable crop trade net export clusters in Eastern Europe gradually decreased, while Sub-Saharan Africa and parts of South Asia consistently faced water scarcity challenges with low sustainability in virtual water trade.

2.3 Driving Factors of Net Exported Virtual Water in Global Crop Trade

MGWR model results identified significant drivers including GDP, cultivated land area, net export volume, number of neighboring countries, and agricultural value-added. GDP coefficients ranged from -0.236 to -0.215, with high-value clusters in East and South Asia and low-value clusters in North America and Western Europe. The number of neighboring countries showed coefficients from -0.109 to -0.027, with the lowest values in New Zealand. Agricultural value-added coefficients ranged from -0.678 to -0.629, with high-impact areas in South Asia and Central America and low-impact areas in Eastern Europe and parts of Africa.

Cultivated land area coefficients were all positive (0.225–1.122), showing significant spatial heterogeneity, with Europe as a low-value area and East and Southeast Asia as high-value clusters. Net export volume coefficients varied widely (-1.798 to 5.100), with high-value regions mainly in North America and low-value regions in Africa, the Middle East, and parts of Eastern Europe [Figure 4: see original paper].

3. Discussion

3.1 Attribution of Net Exported Virtual Water Changes The results show that sustainable net exported virtual water volumes increased with annual fluctuations over the past two decades, with China, Japan, and Vietnam ranking highest globally. Studies indicate that agricultural technological progress and optimized water resource management in these countries have significantly improved water use efficiency [34,35]. The promotion of efficient irrigation technologies and advanced agricultural management has reduced dependence on unsustainable water resources, enabling more virtual water exports to meet sustainability standards [36,37].

Although total unsustainable net exported virtual water footprints increased, their proportion in total virtual water footprints slightly decreased. This trend reflects expanding global agricultural demand driving virtual water trade growth [38], while increasing emphasis on sustainable development has led many countries (e.g., ASEAN nations like Malaysia) to promote sustainable agricultural policies and even impose trade restrictions on unsustainable production methods [39,40]. Meanwhile, growing consumer demand for environmentally friendly agricultural products has encouraged exporting countries to increase the proportion of sustainable virtual water footprints [41].

3.2 Impacts of Spatial Clustering Characteristics Correspondingly, unsustainable net exported virtual water showed significant spatial clustering from 2000 to 2009, which gradually weakened and dispersed by 2019. Research indicates that rapid global agricultural trade growth in the early 2000s led some regions (e.g., Sub-Saharan Africa and parts of South Asia) to rely on high-water-consumption, low-efficiency traditional irrigation methods, causing unsustainable water use to cluster in specific areas [42,43]. Market demand drove production and export of these water-intensive crops, creating pronounced spatial clustering.

Since 2010, growing global attention to water resource protection and sustainable development has prompted many countries to adopt more efficient and water-saving agricultural technologies and management practices. Russia, Canada, and parts of Eastern Europe have played positive roles in promoting virtual water trade sustainability [44]. Increased international attention and policy interventions in water-scarce regions, particularly regarding sustainable agriculture in trade policies and international agreements [45], have gradually dispersed the spatial concentration of unsustainability in virtual water trade.

3.3 Uncertainty Analysis and Future Outlook This study provides quantitative evidence for the continued growth of unsustainable virtual water volumes in global crop trade and identifies key driving factors. However, several limitations should be acknowledged. First, the accounting boundary focuses on crop irrigation water trade consumption, covering only crop-related trade. While the PTF method captures more trade chains and provides detailed data,

it lacks comprehensive consideration of energy crop utilization and crop storage compared to MRIO methods. Future research could combine advantages of both methods to reveal greater complexity in crop trade networks.

Second, the study is limited to crop trade and local accounting, excluding livestock feed consumption. This is because most feed crops (e.g., alfalfa) are primarily consumed locally, and long-term reliable data for accurate accounting or conversion of livestock feed consumption are lacking. Third, while authoritative FAO data were used for import-export comparisons with calculations based on more accurate import data, some discrepancies between import and export data may exist.

Future research plans include introducing additional datasets to strengthen analysis of environmental impacts related to water footprints in specific trade supply chains, focusing on how different consumption demands drive water footprint consumption. Furthermore, when examining regional differences in water footprints, other agricultural inputs (e.g., machinery use and fertilization) should be considered to more comprehensively assess the sustainability of crop trade.

4. Conclusion

This study quantifies the dynamic evolution of sustainability in global crop virtual water trade from 2000 to 2019, revealing spatial correlation characteristics and identifying key drivers of net exported virtual water volumes. The main conclusions are: (1) Global crop sustainable net exported virtual water volumes showed a fluctuating upward trend, led by China, Japan, and Vietnam. Additionally, unsustainable net exported virtual water volumes for global crops (especially cotton) continued to increase, though their proportion in total virtual water trade slightly decreased. (2) Spatially, unsustainable net exported virtual water volumes exhibited significant clustering from 2000 to 2009, but this clustering gradually weakened and dispersed in recent years. Hotspots were concentrated in the United States, Brazil, and Pakistan, while coldspots appeared in more sustainable countries like Russia, Canada, and parts of Eastern Europe. (3) The increase in net exported virtual water was primarily driven by cultivated land area changes, with agricultural value-added showing significant negative impacts. To support sustainable crop trade development, policymakers should prioritize improving water resource allocation efficiency to address challenges of uneven water distribution and environmental pressure, thereby advancing virtual water sustainability in crop trade.

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