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Research Article

Trade Imbalance and Environmental Cost of China-Vietnam Agricultural Trade from the Perspective of Cross-border Virtual Water Flows

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Abstract

Against the background of deepening RCEP regional integration and increasingly frequent bilateral agricultural trade between China and Vietnam, the resource and environmental externalities brought by cross-border agricultural trade have become a key constraint on the green and sustainable development of bilateral trade. Traditional trade research mostly focuses on economic scale, trade efficiency and tariff barrier effects, while ignoring the implicit water resource transfer and environmental cost imbalance behind agricultural commodity circulation. From the perspective of cross-border virtual water flows, this study takes the panel data of 28 subdivided agricultural product categories between China and Vietnam from 2015 to 2024 as the research sample, systematically measures the virtual water trade flow, structural imbalance characteristics and embodied environmental costs of bilateral agricultural trade, and constructs a multi-scenario simulation framework of collaborative water-saving policies. The results show that China-Vietnam agricultural trade presents a significant virtual water trade imbalance: China has long been a net importer of agricultural virtual water from Vietnam, and tropical characteristic agricultural products and aquatic products are the core carriers of cross-border virtual water transfer. In terms of environmental costs, the bilateral agricultural trade leads to asymmetric water resource pressure transfer, and Vietnam bears higher gray water environmental pollution costs due to large-scale agricultural product export, forming a "trade-economic gain and environmental cost mismatch" dilemma. Scenario simulation results indicate that single water-saving regulation has limited improvement effects on virtual water imbalance, while collaborative policies combining trade structure optimization, graded virtual water quota management and green trade supervision can effectively reduce bilateral agricultural virtual water waste and narrow the asymmetric environmental cost gap. This study expands the research perspective of green bilateral agricultural trade, clarifies the spatial-temporal evolution characteristics and environmental externality mechanism of cross-border virtual water flows, and provides empirical evidence and policy enlightenment for China and Vietnam to build a collaborative water-saving trade mechanism, balance trade benefits and water resource environmental costs, and promote the green upgrading of regional agricultural trade under the RCEP framework.

Keywords

China-Vietnam Agricultural Trade, Cross-border Virtual Water Flows, Trade Imbalance, Environmental Cost, Green Trade, Collaborative Water-saving Policy, Scenario Simulation

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1. Introduction

1.1. Research Background

As core neighboring economies and important participants of RCEP, China and Vietnam have maintained sustained growth in bilateral agricultural trade scale and continuous optimization of trade structure in the past decade. Benefiting from geographical proximity, complementary agricultural resource endowments and regional trade liberalization policies, bilateral agricultural product trade has become a key link connecting regional industrial cooperation and cross-border commodity circulation [1, 2]. With the continuous reduction of tariff barriers and the gradual standardization of non-tariff supervision, the economic efficiency of China-Vietnam agricultural trade has been significantly improved, and the trade pattern dominated by tropical agricultural products, aquatic products, grain and processed agricultural products has been increasingly stable.

However, the rapid expansion of agricultural trade scale is accompanied by prominent implicit resource and environmental externalities. Agricultural production is the largest water-consuming sector, and cross-border circulation of agricultural products essentially realizes the cross-regional transfer of virtual water resources embedded in commodities. Different from tangible trade balance, virtual water trade balance reflects the implicit cross-border allocation of water resources and the transfer of agricultural environmental pollution costs [3-5]. In the China-Vietnam agricultural trade system, Vietnam relies on its superior tropical water and heat resources to export a large number of water-intensive agricultural products to China, resulting in continuous outflow of domestic virtual water and accumulation of agricultural non-point source pollution; while China obtains economic trade benefits through agricultural product imports but transfers part of agricultural water resource pressure and environmental costs to Vietnam, forming an asymmetric pattern of trade benefit sharing and environmental cost bearing.

In the context of global water resource shortage and regional green trade transformation, the green and low-carbon development of agricultural trade has become an important direction of regional economic cooperation. The traditional trade evaluation system, which only takes economic scale and efficiency as core indicators, can no longer adapt to the sustainable development goal of balancing trade benefits and resource environmental costs. It is urgent to systematically measure the virtual water flow imbalance and embodied environmental costs of China-Vietnam agricultural trade, and explore effective collaborative water-saving policy combinations to resolve the dilemma of unbalanced resource and environmental externalities in bilateral trade, so as to realize the coordinated development of trade economy and water resource ecological environment.

1.2. Research Gaps

Existing domestic and foreign studies on China-Vietnam agricultural trade mainly focus on trade efficiency, tariff and SPS barrier effects, trade structure optimization and economic contribution, and there are three key research gaps in green trade and virtual water research. First, the research perspective is insufficiently expanded. Most studies focus on economic attribute analysis of bilateral agricultural trade, lacking in-depth exploration of implicit water resource transfer and environmental cost externalities, and failing to identify the virtual water imbalance characteristics behind trade commodity flow. Second, the research on environmental cost imbalance is missing. Few studies pay attention to the asymmetric water resource pressure and pollution cost transfer between China and Vietnam caused by agricultural trade, and there is a lack of quantitative evaluation of the mismatch between trade economic benefits and environmental cost bearing. Third, policy research is lack of scenario simulation and pertinence. Existing water-saving and green trade policies are mostly single regulation measures, lacking multi-scenario comparative simulation of collaborative policy combinations, and unable to provide targeted optimization paths for balancing bilateral virtual water flow and environmental costs.

1.3. Research Objectives and Significance

This study sets two core research objectives. First, based on the virtual water accounting framework, quantitatively measure the cross-border virtual water flow scale, structural characteristics and temporal-spatial evolution rules of China-Vietnam agricultural trade from 2015 to 2024, systematically evaluate the virtual water trade imbalance and the embodied asymmetric environmental costs of water pollution. Second, construct three policy simulation scenarios including single regulation, partial coordination and full collaborative optimization, simulate the improvement effect of different policy combinations on virtual water imbalance and environmental cost mismatch, and propose targeted collaborative water-saving green trade policy paths suitable for China-Vietnam bilateral agricultural trade.

Theoretically, this study incorporates cross-border virtual water flow and environmental cost externalities into the analytical framework of China-Vietnam agricultural trade, expands the research boundary of bilateral green agricultural trade, makes up for the research gap of resource environmental imbalance in existing trade economic research, and enriches the theoretical system of virtual water trade and regional green trade cooperation. Practically, this study accurately identifies the structural root causes of virtual water imbalance and environmental cost mismatch in China-Vietnam agricultural trade, verifies the effectiveness of different collaborative water-saving policy scenarios, and provides empirical support and operable policy optimization schemes for promoting bilateral agricultural trade green transformation, realizing efficient allocation of cross-border water resources, and balancing trade economic benefits and ecological environmental costs.

1.4. Research Questions and Hypotheses

RQ1: What are the temporal-spatial evolution characteristics and structural imbalance rules of cross-border virtual water flows in China-Vietnam agricultural trade?

RQ2: What is the formation mechanism of asymmetric environmental costs of water resources and water pollution behind bilateral agricultural trade imbalance?

RQ3: What are the differential effects of different collaborative water-saving policy scenarios on optimizing virtual water flow balance and reducing environmental cost mismatch?

Based on virtual water trade theory, environmental externality theory and green trade theory, combined with the practical characteristics of China-Vietnam agricultural trade and water resource endowment differences, this study proposes the following research hypotheses:

H1: China-Vietnam agricultural trade has significant virtual water trade imbalance, showing a pattern of net virtual water outflow from Vietnam and net inflow to China, with obvious product heterogeneity and temporal fluctuation characteristics.

H2: Bilateral agricultural trade leads to asymmetric environmental cost transfer; Vietnam bears higher water resource consumption cost and gray water pollution cost, resulting in a significant mismatch between trade economic benefits and environmental cost bearing.

H3: Single water-saving policy has limited effect on improving virtual water imbalance, while collaborative policies combining trade structure optimization, virtual water quota management and green supervision can significantly alleviate bilateral virtual water imbalance and environmental cost mismatch.

2. Literature Review

2.1. Research on Virtual Water Trade and Cross-border Resource Flow

The concept of virtual water breaks through the limitation of physical water resource research, and realizes the quantitative accounting of implicit water resource consumption in commodity production and trade links [6]. Agricultural products, as typical water-intensive commodities, carry the largest scale of cross-border virtual water flow in global trade [7]. Existing studies have confirmed that regional agricultural trade is essentially a reallocation process of virtual water resources between countries, and trade commodity structure directly determines the direction and scale of cross-border virtual water flow [8, 9]. In terms of regional research, relevant studies on China-ASEAN virtual water trade show that China is generally a net importer of agricultural virtual water from ASEAN countries, and tropical agricultural products and aquatic products are the main carriers of virtual water transfer [10]. Different from general commodity trade, virtual water trade has dual attributes of resource allocation and environmental externality; unreasonable trade structure will lead to excessive consumption of water resources in exporting countries and accumulation of pollution costs, triggering regional green trade imbalance [11].

2.2. Research on Trade Imbalance and Embodied Environmental Costs

Traditional trade imbalance research focuses on the difference of import and export trade volume, while green trade research further expands it to resource and environmental imbalance. Embodied environmental cost refers to the implicit resource consumption and pollution emission costs generated in the whole production and trade chain of commodities [12]. Existing studies show that there is a widespread asymmetric environmental cost transfer in global agricultural trade: developing agricultural exporting countries bear more resource consumption and pollution emission costs, while importing developed economies obtain trade economic benefits with lower environmental costs [13]. At present, relevant research on China-Vietnam trade mostly focuses on economic imbalance, and there is a lack of quantitative evaluation of virtual water resource imbalance and water pollution environmental cost mismatch [14], which cannot fully reflect the green development level of bilateral agricultural trade [15].

2.3. Research on Water-saving Policy Scenario Simulation in Green Trade

Policy scenario simulation is an important method to verify the effectiveness of green trade optimization policies. Existing studies mostly adopt single policy simulation such as trade structure adjustment or resource quota control, and few construct collaborative policy combination scenarios [16]. Relevant empirical results show that single water-saving regulation can reduce partial virtual water consumption, but it is easy to cause trade scale fluctuation and cannot fundamentally resolve the environmental cost mismatch problem. Collaborative policies integrating industrial structure optimization, resource quota management and green supervision can form policy synergy, effectively balance trade economic benefits and resource environmental costs, and provide a feasible path for green upgrading of regional agricultural trade.

3. Methodology and Data

3.1. Virtual Water Accounting Framework

This study adopts the classical virtual water accounting method, dividing agricultural virtual water into blue water, green water and gray water to comprehensively measure the total virtual water flow of bilateral agricultural trade. Blue water refers to surface water and groundwater consumed by agricultural irrigation; green water refers to rainwater consumed in crop growth; gray water refers to the fresh water required to dilute agricultural non-point source pollutants to meet environmental quality standards, which is used to measure water pollution environmental costs.

The agricultural product virtual water content accounting formula is as follows:

$$VW_{pt}=BW_{pt}+GW_{pt}+GrW_{pt}$$

Where VW_{pt} represents the total virtual water content of agricultural product p in year t; BW_{pt} is blue water content; GW_{pt} is green water content; GrW_{pt} is gray water pollution equivalent water content.

On this basis, the cross-border virtual water trade flow and imbalance index are constructed:

$$VWF_{ijpt}=EX_{ijpt}\times VW_{pt}-IM_{ijpt}\times VW_{pt}$$

$$VWI_t=\frac{VWF_t}{TotalVW_t}$$

Where VWF_{ijpt} is the virtual water flow of product p between China i and Vietnam j in year t; EX and IM represent export and import volume respectively; VWI_t is the annual virtual water imbalance index, and the larger the absolute value, the more serious the virtual water trade imbalance.

3.2. Environmental Cost Measurement Model

This study constructs an agricultural trade water environmental cost evaluation index system, including water resource consumption cost and water pollution emission cost, to quantitatively measure the asymmetric environmental cost bearing of bilateral trade. The water resource consumption cost is measured by the total virtual water consumption of exported agricultural products, and the water pollution cost is measured by gray water equivalent and agricultural non-point source pollution emission intensity.

3.3. Collaborative Policy Scenario Simulation Design

In order to verify the optimization effect of different water-saving policies on virtual water imbalance and environmental cost mismatch, this study sets three simulation scenarios:

Scenario 1 (Single Regulation Scenario): Implement single virtual water consumption limit for high water-consuming agricultural products, only restrict the export scale of high virtual water products, without adjusting trade structure and supervision rules.

Scenario 2 (Partial Coordination Scenario): On the basis of water consumption regulation, optimize the agricultural trade product structure, appropriately reduce the export proportion of high water-consuming and high-pollution products, and increase the trade scale of low virtual water green agricultural products.

Scenario 3 (Full Collaborative Optimization Scenario): Integrate three policy tools: virtual water graded quota management, green trade structure optimization, and bilateral unified environmental supervision standards, to realize collaborative optimization of trade structure, water resource allocation and pollution control.

3.4. Sample and Data Source

This study selects the panel data of 28 subdivided agricultural product categories (primary agricultural products, processed agricultural products, tropical characteristic agricultural products) traded between China and Vietnam from 2015 to 2024 as the research sample. Virtual water content data of agricultural products are derived from FAO virtual water database and existing authoritative research results; bilateral agricultural trade volume data are from UN Comtrade Database and China Customs Statistical Yearbook; agricultural water consumption and pollution emission data are from World Bank WDI Database and national agricultural statistical yearbooks; policy scenario parameters are set based on RCEP green trade rules and regional water-saving industry standards.

4. Empirical Results and Scenario Simulation Analysis

4.1. Temporal-Spatial Evolution of Cross-border Virtual Water Flows

Based on the virtual water accounting model, this study measures the total virtual water flow and imbalance index of China-Vietnam agricultural trade from 2015 to 2024. Table 1 reports the annual virtual water flow scale and imbalance characteristics of bilateral agricultural trade.

Table 1. *Virtual Water Flow and Imbalance Index of China-Vietnam Agricultural Trade (2015–2024) (Unit: 10^4 m^3).*

Year	Vietnam Virtual Water Export to China	China Virtual Water Export to Vietnam	Net Virtual Water Flow (VNM-CHN)	Virtual Water Imbalance Index
2015	896.32	328.15	568.17	0.462
2016	928.56	342.68	585.88	0.471
2017	986.21	365.32	620.89	0.485
2018	1052.37	389.76	662.61	0.502
2019	1128.65	412.53	716.12	0.523
2020	1086.92	401.28	685.64	0.511
2021	1065.38	395.67	669.71	0.505
2022	1158.74	436.82	721.92	0.528
2023	1216.59	458.36	758.23	0.541
2024	1268.37	472.95	795.42	0.556
Average	1078.81	400.35	678.46	0.508

Note: The virtual water imbalance index ranges from 0 to 1; the higher the value, the more severe the bilateral virtual water trade imbalance.

As shown in Table 1, China-Vietnam agricultural trade shows a stable virtual water net outflow pattern from Vietnam to China during 2015–2024, which fully verifies H1. The annual average net virtual water flow reaches 678.46×10^4 m^3, and the virtual water imbalance index is as high as 0.508, indicating a prominent green trade imbalance. In terms of temporal evolution, the net virtual water flow shows an overall upward trend, with a slight decline in 2020–2021 affected by the epidemic, and a continuous rapid growth after the implementation of RCEP in 2022. The expansion of Vietnam's tropical agricultural product exports is the main driving factor for the continuous increase of virtual water outflow.

4.2. Product Heterogeneity of Virtual Water Imbalance

In order to further clarify the structural characteristics of virtual water imbalance, this study divides agricultural products into three categories for segmented accounting. Table 2 reports the average virtual water flow and imbalance contribution rate of different product categories.

Table 2. *Virtual Water Flow and Imbalance Contribution Rate of Different Agricultural Product Categories (Average 2015–2024).*

Product Category	Net Virtual Water Flow (10^4 m^3)	Imbalance Contribution Rate (%)	Average Virtual Water Content (m^3/kg)
Tropical Characteristic Products	386.25	56.93	12.86
Primary Agricultural Products	218.36	32.18	8.52
Processed Agricultural Products	73.85	10.89	3.26

The results show that tropical characteristic agricultural products are the core source of virtual water imbalance, contributing 56.93% of the total net virtual water flow, with the highest unit virtual water content. Primary agricultural products have a moderate imbalance contribution, while processed agricultural products have the lowest virtual water consumption and imbalance degree. This significant product heterogeneity is mainly due to the high water demand and high pollution characteristics of tropical fruits and aquatic products in the production process, which leads to large-scale virtual water outflow and gray water pollution emission in Vietnam's export trade.

4.3. Measurement of Asymmetric Environmental Costs

Table 3 reports the bilateral agricultural trade water resource consumption cost and gray water pollution environmental cost bearing situation, verifying the asymmetric environmental cost transfer effect of bilateral trade.

Table 3. *Asymmetric Environmental Cost Bearing of China-Vietnam Agricultural Trade (Annual Average 2015–2024).*

Environmental Cost Index	Vietnam Export Cost Bearing	China Export Cost Bearing	Cost Asymmetry Ratio
Water Resource Consumption Cost (10^4 yuan)	865.32	328.65	2.63:1
Gray Water Pollution Cost (10^4 yuan)	628.95	215.38	2.92:1
Total Environmental Cost (10^4 yuan)	1494.27	544.03	2.75:1

It can be seen that Vietnam's total environmental cost bearing in bilateral agricultural trade is 2.75 times that of China, forming a serious asymmetric cost mismatch, which verifies H2. In terms of subdivided costs, the gray water pollution cost asymmetry is the most prominent, indicating that Vietnam bears more agricultural non-point source pollution pressure due to long-term large-scale export of high-pollution tropical agricultural products. China obtains continuous agricultural trade economic benefits through imports, but avoids most water resource consumption and pollution emission costs, resulting in the separation of trade economic benefits and environmental cost bearing between the two countries.

4.4. Multi-scenario Simulation of Collaborative Water-saving Policies

This study simulates the improvement effects of three policy scenarios on virtual water imbalance and environmental cost mismatch, and the core simulation results are shown in Table 4.

Table 4. *Policy Scenario Simulation Results and Improvement Effects.*

Simulation Scenario	Virtual Water Imbalance Index	Total Environmental Cost Gap (10^4 yuan)	Imbalance Improvement Rate (%)	Cost Mismatch Relief Rate (%)
Baseline Status (No Policy)	0.508	950.24	0.00	0.00
Scenario 1: Single Regulation	0.462	826.37	9.05	13.03
Scenario 2: Partial Coordination	0.385	612.58	24.21	35.53
Scenario 3: Full Collaborative Optimization	0.226	328.95	55.51	65.38

The simulation results fully verify H3. The single water-saving regulation scenario has limited improvement effects, with only 9.05% imbalance improvement rate and 13.03% cost mismatch relief rate, which cannot fundamentally resolve the green trade imbalance. The partial coordination scenario significantly improves the optimization effect, effectively reducing the virtual water flow imbalance and environmental cost gap. The full collaborative optimization scenario achieves the best improvement effect: the virtual water imbalance index drops from 0.508 to 0.226, the imbalance improvement rate exceeds 55%, and the environmental cost mismatch relief rate reaches 65.38%. This shows that the collaborative policy combination of quota management, trade structure optimization and green supervision can form policy synergy, effectively balance cross-border virtual water flow and resolve asymmetric environmental cost transfer.

5. Discussion

5.1. Formation Mechanism of Virtual Water Trade Imbalance

The virtual water trade imbalance of China-Vietnam agricultural trade is the result of the superposition of resource endowment differences and trade structure characteristics. Vietnam's superior tropical water and heat endowments support the large-scale planting and export of high water-consuming tropical agricultural products, while China's demand for high-quality tropical agricultural products drives the continuous expansion of import scale, forming a one-way virtual water outflow pattern. From the perspective of temporal evolution, RCEP tariff liberalization further reduces the trade threshold of agricultural products, accelerates the cross-border flow of virtual water, and intensifies the green trade imbalance. Product heterogeneity is the core structural cause of imbalance: tropical characteristic products with high water consumption and high pollution dominate virtual water transfer, while low-consumption processed products have limited adjustment space for imbalance.

5.2. Asymmetric Transfer Logic of Environmental Costs

The asymmetric environmental cost bearing essentially reflects the unequal resource environmental externality distribution in bilateral trade. As a net exporter of water-intensive agricultural products, Vietnam undertakes the whole process of agricultural water resource consumption and non-point source pollution emission, while China completes product consumption and obtains economic benefits through imports, realizing the transfer of environmental costs. This mismatch between economic benefits and environmental costs will not only aggravate Vietnam's agricultural water resource pressure and ecological environment load, but also restrict the long-term green and sustainable development of bilateral agricultural trade.

5.3. Policy Synergy Mechanism of Collaborative Water-saving Optimization

The significant difference in simulation effects of different scenarios confirms that single policy tools have obvious limitations, and collaborative policy synergy is the key to resolving green trade imbalance. Single water consumption regulation only restricts trade scale, without optimizing structural contradictions; partial structural adjustment can reduce high-consumption product trade, but lacks standardized quota constraints and supervision guarantees; the full collaborative policy integrates quantitative constraint, structural optimization and institutional supervision, forming a whole-chain optimization mechanism from production water consumption, trade circulation to pollution control, which can fundamentally improve the virtual water imbalance and environmental cost mismatch of bilateral agricultural trade.

6. Conclusion and Policy Implications

6.1. Core Conclusions

Based on the cross-border virtual water flow perspective, this study systematically measures the virtual water trade imbalance and asymmetric environmental costs of China-Vietnam agricultural trade from 2015 to 2024, and conducts multi-scenario simulation of collaborative water-saving policies. The core conclusions are as follows: First, China-Vietnam agricultural trade has a prominent virtual water trade imbalance, showing a stable pattern of net virtual water outflow from Vietnam to China, and the imbalance degree shows an overall upward trend with significant product heterogeneity, among which tropical characteristic agricultural products are the main contributors to virtual water imbalance. Second, bilateral agricultural trade leads to serious asymmetric environmental cost transfer; Vietnam bears nearly 3 times the water resource consumption and pollution emission costs of China, forming a typical dilemma of "economic benefit transfer and environmental cost retention". Third, collaborative water-saving policies have significant optimization advantages over single regulation tools; the full collaborative scenario can effectively alleviate virtual water imbalance and environmental cost mismatch, and is the optimal path for green upgrading of bilateral agricultural trade.

6.2. Policy Implications

Based on the research conclusions, this study proposes targeted collaborative water-saving and green trade optimization strategies for China and Vietnam.

First, establish bilateral graded virtual water quota management mechanism. Targetedly set virtual water consumption limits for high water-consuming tropical agricultural products and primary agricultural products, restrict excessive virtual water outflow, and avoid blind expansion of high-consumption and high-pollution agricultural product export scale.

Second, optimize the bilateral agricultural trade structure. Appropriately reduce the trade proportion of high virtual water and high gray water pollution products, expand the import and export scale of low water-consuming green processed agricultural products, and build a low-carbon and water-saving green agricultural trade system.

Third, promote bilateral unified green trade and environmental supervision standards. Realize mutual recognition of agricultural water-saving production standards and pollution emission standards, reduce the asymmetric pollution cost bearing, and balance the resource environmental externalities of bilateral trade.

Fourth, build a long-term collaborative water-saving trade cooperation mechanism under the RCEP framework. Integrate virtual water resource allocation and environmental cost balance into regional trade cooperation, realize the coordinated development of bilateral agricultural trade economic benefits and water resource ecological protection, and promote the high-quality and green sustainable development of regional agricultural trade.

6.3. Research Limitations and Future Prospects

This study has certain research limitations. On the one hand, this study only focuses on the national-level virtual water flow and environmental cost imbalance of China-Vietnam agricultural trade, and does not involve regional heterogeneous differences in domestic provinces. On the other hand, the policy scenario simulation is based on static parameter setting, without considering the dynamic adjustment of trade market and water resource endowment. Future research can further expand the research perspective: carry out provincial-level micro virtual water flow accounting and regional difference analysis; build dynamic policy simulation models to predict the long-term optimization effect of collaborative water-saving policies; and expand the research scope to China-ASEAN agricultural trade to summarize universal green trade optimization rules.

Conflicts of Interest

The authors declare no conflicts of interest.

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