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Calculation and Sustainability Evaluation of Grain Virtual Water Flow Among Provinces in China

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Abstract

Under the spatial distribution of water resources, with more water resources in the southern regions and less in the northern regions, and the "north–south grain transport" pattern, calculating the virtual water flow in food trade between provinces in China and analyzing its sustainability is crucial for ensuring the country's water resources and food security. By considering various products and consumption types, the virtual water flow in inter-provincial grain trade is estimated using the Minimum Transport Cost Method and the Penman-Monteith formula. The sustainability of this virtual water flow is evaluated at the provincial level. (1) The results show that the top three provinces with the largest net virtual water outflow from inter-provincial grain trade are Heilongjiang, Henan, and Anhui, with net outflows of 43.166 billion m^3, 18.974 billion m^3, and 13.089 billion m^3, respectively. The top three provinces with the largest net virtual water inflows are Hebei, Guangxi, and Liaoning, with net inflows of 18.875 billion m^3, 10.076 billion m^3, and 8.795 billion m^3, respectively. (2) The largest inter-provincial virtual water flow occurs from Henan to Hebei (15.06 billion m^3), followed by Inner Mongolia to Hunan (9.57 billion m^3), and Heilongjiang to Hubei (9.04 billion m^3). (3) Overall, the current pattern of virtual water flow in China's grain trade is sustainable, though several exporting provinces are under greater stress. In the actual scenario, the average water resource pressure index across all provinces is 0.43, 17.31% lower than the average of 0.52 in the scenario without inter-provincial grain trade. Compared with the scenario without inter-provincial grain product trade, in the actual scenario, Heilongjiang, Jilin, and Inner Mongolia show a higher increase in water resource pressure index, with increases of 94.74%, 73.68%, and 48%, respectively; Beijing, Shanghai, and Qinghai show a greater decrease in water resource pressure index, with reductions of 94.64%, 79.41%, and 66.67%, individually. And then, efforts should be made to adjust and optimize the structure of grain production and circulation; provinces with virtual water net outflow (such as Heilongjiang, Henan, Anhui, etc.) need to adjust their grain cultivation types and grain export structures.; provinces with virtual water net inflow (such as Hebei, Guangxi, Liaoning, etc.) can appropriately expand the scale of grain cultivation, while adjusting their diets to reduce the demand for water-intensive grains.

Keywords: grain product trade; virtual water; sustainability evaluation; minimum transport cost method; water resource pressure index

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1. Introduction

With the accelerating process of industrialization and urbanization in the southern provinces and autonomous regions of China, there has been a reduction in local arable land

area and an increase in the opportunity cost of grain cultivation. As a result, China's grain production has gradually shifted and concentrated toward the economically underdeveloped central and western regions as well as northern regions [1], eventually forming the pattern of "Grain Transportation from the North to the South" [2]. The northern regions hold 60% of the country's total arable land, yet possess only 19% of China's total water resources [3]. Grain exports from these regions lead to virtual water outflow, which further exacerbates local water resource pressure. Virtual water refers to the total amount of water resources required in the production of various products and services [4]. Therefore, analyzing the pattern of virtual water flows in inter-provincial grain product trade in China and assessing the sustainability of such flows at the provincial level can provide a basis for provinces and autonomous regions to optimize water resource management in a targeted manner and ensure national food security.

Since there is no publicly available statistical data on inter-provincial grain product trade volumes in China, existing studies have proposed different quantification methods based on assumptions. An early quantification approach is the social equity method [5,6], which assumes that per capita grain consumption is uniform across all regions and does not consider the impact of factors such as transportation distance and mode on the trade pattern. Wang Xin [7] introduced a distance component and applied the gravity model to calculate the allocation coefficient between various provincial-level administrative regions. However, these calculations fail to account for either product types or consumption categories. Some studies have distinguished product types when measuring China's inter-provincial grain product trade volumes, but did not differentiate between consumption categories. Ma [8] et al. divided China's 31 provincial-level regions into two first-level regions (the North and the South) and eight second-level regions, constructed a grain proximity trade model, distinguished six product types (including grains, vegetables, fruits, and meat), and estimated the net grain product trade flow based on the principle of prioritizing regional demand satisfaction in grain product trade. Zhao Yong [9] et al. considered more than ten product types (such as grains, legumes, and tubers) in their measurement of China's inter-provincial grain product trade volumes. Other studies have distinguished consumption categories when calculating inter-provincial grain product trade volumes in China, but did not differentiate between product types. Qian [10] et al. constructed a multi-objective linear optimization model to estimate inter-provincial grain product trade volumes based on transportation costs (accounting for transportation mode and distance) and grain consumption structure. Qian Haiyang [11] considered both the dual impacts of distance and transportation mode on transportation costs, as well as the influence of consumption categories and consumption structure on inter-provincial grain product trade, and built a multi-objective optimization model to calculate inter-provincial grain product trade volumes. Yang Tingting [12] et al. took into account four consumption categories (including grain for human consumption and feed grain) to estimate grain circulation among provinces in China.

To date, no study has simultaneously considered both product types and consumption categories when measuring inter-provincial grain product trade volumes.Existing calculations of virtual water flows in inter-regional grain product trade have mainly been conducted at the national scale [13,14]. Sartori [15] et al. integrated stochastic models, fitness models, and gravity models to predict the pattern of virtual water flows in international grain product trade under different climate scenarios for 2020 and 2050; Dalin [16] et al. quantified the virtual water flow network of inter-country agricultural trade from 1986 to 2007; Hoekstra [17] et al. measured virtual water flows in grain product trade among more than 100 countries from 1995 to 1999.Studies on the calculation of virtual water flows in China's inter-provincial grain product trade have primarily been based on

the aforementioned estimates of China's inter-provincial grain product trade pattern or the multi-regional input-output (MRIO) method. Zhuo [18] used the MRIO method to measure virtual water flows in China's inter-provincial grain product trade and constructed four different scenarios to predict the impacts of five types of driving factors on the virtual water trade pattern of grain. Zhang Guangjie [19] built an inter-provincial virtual water trade network for grain using the 2012 multi-regional input-output table.

Based on the calculation of virtual water flow volumes in regional grain product trade, some studies have assessed the sustainability of virtual water flows. Lokendra [20] et al. evaluated the sustainability of virtual water flows associated with grain import and export trade by introducing the "unsustainable import share"; Tian Guiliang [21] et al. analyzed the impact of virtual water flows on food security in China's eight major regions using a fixed-effects regression model to assess the sustainability of virtual water flows in grain product trade; Li Xinsheng [22] quantified the impact of grain product trade on regional water resource pressure from both production and consumption perspectives, and based on this, conducted a sustainability assessment of virtual water flows in the Beijing-Tianjin-Hebei region; An [23] et al. analyzed the sustainability of inter-provincial virtual water flows in China's grain product trade using the Water Stress Index (WSI) and predicted the virtual water flow pattern of grain in 2030; Zhao Yidan [24] et al. used the water resource pressure index to assess the degree of impact of staple grain import and export trade on domestic water resource pressure and the sustainability of the current virtual water import and export trade pattern.

At present, no study has simultaneously considered both product types and consumption categories when measuring inter-provincial grain product trade volumes. This oversight of differences in consumption purposes among different product types undermines the accuracy of grain product trade volume accounting.

In this study, when measuring inter-provincial grain product trade volumes, we distinguish four types of grain (rice, wheat, corn, and soybeans) and identify five consumption categories (grain for human consumption, feed grain, industrial grain, seed grain, and grain loss). We also calculate the consumption volume of different grain types for different consumption purposes in different regions, aiming to improve the accuracy of the measurement. In addition, existing assessments of the sustainability of virtual water flows in China's grain product trade have mostly focused on changes in water resource pressure at the national level or across entire parts of river basins, comparing scenarios with and without virtual water flows from grain product trade. However, few studies have analyzed the sustainability of virtual water flows in China's grain product trade at the provincial scale, failing to reflect the differences in changes in water resource pressure among provinces regarding virtual water flows from grain product trade. This study calculates the water resource pressure index for each province and the whole country under scenarios with and without virtual water flows, analyzes the sustainability of virtual water flows in China's inter-provincial grain product trade, and aims to provide more detailed support for the sustainable development of provincial water resources and national food security.

In this study, the Minimum Transport Cost Method is employed to model inter-provincial grain product trade in China. A linear programming model is constructed with the total transportation cost of a specific grain type among all provinces as the objective function. The study uses the Penman-Monteith formula, incorporated through CROPWAT software 8.0, to calculate the virtual water flow associated with grain product trade. Additionally, the Water Resource Pressure Index (WRPI) is used to assess the sustainability of virtual water flows across the provinces under scenarios with and without inter-provincial grain product trade. The net trade flows of grain between provinces are solved using Matlab's R2024a's linprog function.

The results show that China's grain product trade follows a pattern of virtual water flowing from north to south. The northern provinces, such as Heilongjiang, Henan, and Anhui, experience a net outflow of virtual water, while southern and eastern provinces, like Hebei, Guangxi, and Liaoning, have a net inflow. The study finds that inter-provincial grain product trade reduces China's overall water resource pressure by 17.31%, supporting the sustainability of the current trade pattern.

The contributions of this paper are mainly reflected in two aspects: First, addressing the gap in estimating inter-provincial grain product trade volumes, it provides a more realistic analytical approach by distinguishing between different grain types, identifying consumption categories, and considering regional consumption for various uses, thereby improving the accuracy of the calculations. Second, it fills the gap in the study of the sustainability of virtual water flows in inter-provincial grain product trade by calculating the Water Resource Pressure Index for each province, offering more detailed support for provincial water resource sustainability and national food security decision-making.

The structure of the paper is as follows: Section 2 presents the materials and methods used in the study, including the calculation models for inter-provincial grain product trade and virtual water flow. Section 3 outlines the results of the analysis, including the net virtual water flow between provinces and the sustainability evaluation based on the Water Resource Pressure Index. Section 4 integrates conclusions on the pattern of virtual water flow, discussions with existing literature, policy implications and research limitations.

2. Materials and Methods

The study object of this paper is 31 provinces, autonomous regions and municipalities directly under the Central Government in Mainland China (excluding Taiwan, Macao Special Administrative Region and Hong Kong Special Administrative Region). Water resource distribution in China is extremely uneven, generally presenting a pattern of "more in the south and less in the north" [25]. The southern regions, including the basins of the Yangtze River, Pearl River and Min River, have abundant rainfall and dense river networks, with relatively rich water resources. In contrast, the northern regions—especially the Yellow River Basin, Haihe River Basin and northwest inland areas—have scanty precipitation with uneven spatial and temporal distribution, resulting in relatively scarce water resources. Regions such as the Northeast China Plain, North China Plain, Middle-Lower Yangtze Plain and Sichuan Basin have become important bases for grain production in China, relying on their superior natural conditions, abundant arable land resources and long history of agricultural cultivation. Among them, the three northeastern provinces (Heilongjiang, Jilin, Liaoning) mainly focus on crops such as soybeans and corn; the North China Plain primarily centers on wheat and corn; and the Middle-Lower Yangtze Plain is dominated by rice. In general, China's grain production presents the characteristic of "water resources in the south and arable land in the north" [26].

2.1. Definition of Terms and Modeling Process

2.1.1. Definition of Terms

This study focuses on the inter-provincial virtual water flow and sustainability evaluation of grain product trade across the 31 provinces, autonomous regions, and municipalities of mainland China. It lies at the intersection of water resource utilization and grain product trade, where each key concept carries specific connotations within this research context. Therefore, this section provides standardized definitions of the core terms to unify conceptual understanding, establish a consistent foundation for measuring inter-provincial grain product trade volumes, calculating virtual water flows, and evaluating water resource

stress. These definitions ensure logical rigor throughout the analysis and help readers accurately grasp the study's conceptual framework and analytical logic.

(1) Local Water Resources

In this study, local water resources refer to the total amount of naturally formed water resources within the administrative boundaries of the 31 provinces, autonomous regions, and municipalities of mainland China that can be directly used for agricultural, domestic, and ecological purposes. They represent the intrinsic endowment of regional water resources and exclude externally supplied water such as inter-provincial virtual water inflows and inter-basin water transfers. Local water resources include natural surface water (e.g., tributaries of the Yangtze and Yellow Rivers, lakes, and reservoirs), shallow and confined groundwater, and effective soil moisture that supports crop growth. In this study, local water resources serve as the baseline for assessing each province's self-sufficiency in agricultural water use and for evaluating water stress in a scenario without inter-provincial grain product trade.

(2) Water Withdrawal

Water withdrawal denotes the total volume of water extracted from natural surface and groundwater sources within each province to meet agricultural demands such as irrigation for rice and wheat cultivation. It is a key indicator reflecting the intensity of human exploitation of regional water resources. In the context of this study, water withdrawal is closely related to the estimation of virtual water in grain production. The portion of withdrawn water that is consumed through crop evapotranspiration and soil absorption constitutes water consumption, which directly contributes to the virtual water content of grain. The remaining portion, which is not consumed, returns to water bodies as return flow. Hence, water withdrawal is generally greater than the corresponding consumptive water use for grain production.

(3) Net Virtual Water

Net virtual water refers to the difference between virtual water inflows and outflows resulting from inter-provincial grain product trade in mainland China. It quantifies the extent to which a region indirectly imports or exports water resources through grain product trade. Virtual water inflow represents the total volume of water embodied in grains (e.g., rice, wheat, maize, soybean) imported from other provinces, calculated as the product of traded grain volumes and the corresponding crop-specific virtual water content. Virtual water outflow represents the total volume of water embodied in grains exported to other provinces. Accordingly, net virtual water equals virtual water inflow minus virtual water outflow. A positive value indicates that a province indirectly imports water resources through grain product trade, thereby alleviating local water stress; a negative value indicates that a province indirectly exports water resources, implying potential risks of local water overexploitation.

(4) Return Flow

Return flow denotes the total volume of water that, after being withdrawn for agricultural, industrial, or domestic use, is not consumed through evapotranspiration or biological absorption and eventually returns—either directly or indirectly—to surface or groundwater systems. It represents a critical component of regional water recycling and sustainable utilization. Return flow can occur in two main forms: direct return, such as irrigation runoff discharging into rivers or treated industrial cooling water entering lakes; and indirect return, such as infiltration of irrigation water that replenishes groundwater and subsequently flows back into surface water bodies through subsurface runoff.

(5) Environmental Flow Requirement

Environmental flow requirement refers to the minimum amount or flow of water that must be reserved to maintain the ecological functionality and health of rivers, lakes, and wetlands within each of the 31 provinces, autonomous regions, and municipalities. It serves as a prerequisite for calculating the total available water resources and as an implicit ecological threshold in evaluating the sustainability of virtual water flows in grain product trade. In this study, the water resources available for agricultural production in each province are determined after accounting for ecological flow requirements, ensuring that water utilization remains within ecological boundaries and does not exceed the environmental red line.

2.1.2. Modeling Process

In this study, the Penman-Monteith equation was used to calculate the reference crop evapotranspiration (ET_0). Subsequently, with the help of the CROPWAT software, crop water requirements (CWR) were calculated based on ET_0, and further derivation was conducted to obtain the virtual water content per unit product (VWC). Next, a linear programming model was constructed based on the Minimum Transport Cost Method—taking the total inter-provincial grain transportation cost as the objective function and inter-provincial net grain product trade flows as the decision variables—and the inter-provincial grain product trade was optimized using Matlab's linprog function. Furthermore, combined with the inter-provincial grain product trade volume and the VWC of various grain types, the virtual water export volume (EVW) and import volume (IVW) of inter-provincial grain product trade were calculated. Subsequently, the calculation method of the Water Resource Pressure Index (WRPI) was introduced to compute the corresponding index. Finally, by comparing the water resource pressure index under the scenarios with and without inter-provincial grain product trade, a sustainability assessment was carried out. The modeling process of this study is shown in Figure 1.

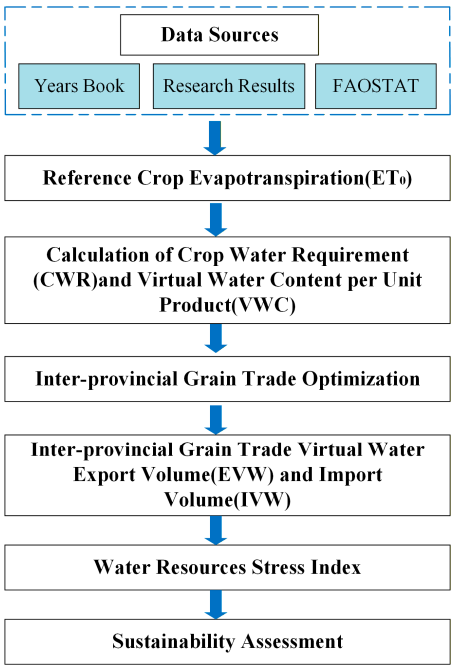


Figure 1. Modeling Process Flow Diagram.

2.2. Measurement Model of Inter-Provincial Grain Product Trade

This study employs the Minimum Transport Cost Method to measure inter-provincial grain product trade in China. Specifically, a linear programming model is constructed with the total transportation cost of a specific type of grain among all provinces in China as the

objective function, the net trade flow of this specific grain type between any two provinces as the decision variable, and the following constraint conditions: the outflow volume of this grain type transported from one province to other provinces shall be less than or equal to the surplus quantity of this grain type in that province, and the inflow volume of this grain type transported from other provinces to a given province shall be greater than or equal to the deficit quantity of this grain type in that given province. Subsequently, with the help of the Matlab platform, the linprog function is used to solve this model, and the net trade flows of various grain types among provinces are obtained. The specific formulation is shown in Equation (1):

$$minf = \sum_{i=1}^{31} \sum_{j=1}^{31} TC_{ij} \times Z_{ij}$$
$$s.t. \begin{cases} \sum_{j=1}^{31} Z_{ij} \leq S_i \\ \sum_{i=1}^{31} Z_{ij} \geq D_j \\ Z_{ij} \geq 0 \end{cases} \quad (1)$$

In the equation, TC_{ij} refers to the transportation cost per unit weight of grain sold from Province i to Province j; Z_{ij} represents the net trade flow of a specific type of grain sold from Province i to Province j; S_i denotes the surplus quantity of a specific type of grain in Province i; and D_j stands for the deficit quantity of a specific type of grain in Province j.

The estimation of the net outflow volume of various grain types among provinces is conducted as follows: first, the grain type-specific input method is adopted to classify grain consumption into five categories, namely grain consumption for human use, feed grain consumption, industrial grain consumption, seed grain consumption, and grain loss. Then, the net outflow volume of each type of grain in each province is obtained by subtracting the local consumption of that grain type, its net export volume, and the volume of imported grain transferred to other provinces from the total output of that grain type in the province. The consumption of various grain types for human use in each province is calculated by multiplying the per capita consumption of each grain type in the province by the province's population; the feed consumption of various grain types in each province is derived by multiplying the province's livestock product output by the feed conversion rate and the proportion of each grain type in the feed; the industrial consumption of various grain types in each province is the total amount obtained by first multiplying the output of three industrial products (beer, liquor, and edible oil) in the province by their respective grain conversion coefficients, and then performing weighted aggregation according to the proportion of the four grain types in the three industrial products; the seed consumption of various grain types in each province is calculated by multiplying the seed grain per unit area by the sown area of each grain type in the province; and the loss volume of various grain types in each province is obtained by multiplying the total output of each grain type in the province by the grain loss rate.

2.3. Measurement Model of Virtual Water Flow Volume in Inter-Provincial Grain Product Trade

This study utilizes the CROPWAT software to construct a virtual water trade network for grains. The CROPWAT model characterizes the water consumption during the crop growth process by calculating the actual evapotranspiration of the crop, with the specific calculation steps outlined Equation (2).

$$VMC_c^m = \frac{CWR_c^m}{Y_c^m} \quad (2)$$

Among them, VWC_c^m refers to the virtual water content of provincial-level grains (unit: m^3/kg), Y_c^m refers to the yield per unit sown area of grain type c in province m (unit: kg/hm^2), and CWR_c^m refers to the water requirement of grain type c in province m during the growth period (unit: m^3/hm^2), which can be calculated using Equation (3).

$$CWR_c^m = 10 \times \sum_{d=1}^{1p} ET_c^m \tag{3}$$

Among them, 10 refers to the unit conversion parameter, with the conversion standard being 1 mm = 10 m^3/hm^2; lp refers to the number of days in the crop growth period; ET_c^m refers to the evapotranspiration of grain type c in province m during the growth period (unit: mm), as shown in Equation (4):

$$ET_c^m = K_c \times ET_0^m \tag{4}$$

Among them, K_c refers to the crop coefficient of grain type c, which reflects the differences in evapotranspiration caused by different crop biological characteristics, different soil surface reflectivities, and different canopy resistances; ET_0^m refers to the reference crop evapotranspiration in province m (unit: mm/day), which can be calculated according to the modified standard Penman-Monteith formula recommended by the Food and Agriculture Organization (FAO) [27] of the United Nations, as shown in Equation (5):

$$ET_0^m = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2(e_s - e_d)}{\Delta + \gamma(1 + 0.34U_2)} \tag{5}$$

Among them, Δ refers to the slope of the saturation vapor pressure versus temperature curve (unit: kPa/°C); R_n refers to the net radiation at the reference crop surface (unit: $MJ/(M^2d)$); G refers to the soil heat flux (unit: $MJ/(M^2d)$); γ refers to the psychrometric constant (unit: kPa/°C); T refers to the mean daily temperature (unit: °C); U_2 refers to the wind speed at 2 m height (unit: m/s); e_s refers to the saturation vapor pressure (unit: kPa); e_d refers to the measured vapor pressure (unit: kPa).

On this basis, the inter-provincial grain virtual water trade volume is further calculated. Therefore, the virtual water outflow volume and inflow volume of inter-provincial grain product trade in Province i can be expressed as follows respectively:

$$EVW_i = \sum_{\substack{j=1 \\ i \neq j}}^{31} \sum_{c=1}^{4} E_c^{ij} \times VWC_c^i \tag{6}$$

Among them, EVM_i refers to the virtual water outflow volume of inter-provincial grain product trade in Province i, and E_c^{ij} refers to the volume of grain of type c (with a total of 4 types) flowing out from Province i to Province j.

$$IVW_i = \sum_{\substack{j=1 \\ i \neq j}}^{31} \sum_{c=1}^{4} I_c^{ij} \times VWC_c^j \tag{7}$$

Among them, IVM_i refers to the virtual water inflow volume of inter-provincial grain product trade in Province i, and I_c^{ij} denotes the volume of grain of type c flowing into Province i from Province j.

2.4. Sustainability Assessment of Virtual Water Flow in Inter-Provincial Grain Product Trade

This study evaluates the sustainability of virtual water flow in inter-provincial grain product trade in China by calculating and comparing the provincial water resource pressure index under two scenarios: the existence and the non-existence of such virtual water flow.

$$I_i = \frac{V_i}{L_i} \tag{8}$$

$$T_i = \frac{V_i + IVW_i - EVW_i}{L_i} \tag{9}$$

In the equation, V_i, L_i, and I_i respectively represent the virtual water volume corresponding to grain production, total available water resources, and water resource pressure index in Province i. Among them, V_i is obtained by multiplying the virtual water content of various grain types in each province by their corresponding grain output. T_i denotes the water resource pressure of each province under the assumption that there is no inter-provincial grain product trade. In the equation, IVM_i refers to the virtual water inflow volume of inter-provincial grain product trade in Province i, and EVM_i refers to the virtual water outflow volume of inter-provincial grain product trade in Province i. If T_i is greater than I_i, it indicates that under the scenario with grain flow, the water resource pressure index of Province i increases, and the provincial grain product trade pattern is unsustainable; otherwise, it is sustainable.

2.5. Data Sources

The data and their sources required for calculating the net inter-provincial trade flow of the four grain types include: First, the output of various grain types and population size of each province, which are from the China Statistical Yearbook 2022. Second, the import and export volumes of various grain types of each province, which are sourced from the official website of China Customs Import and Export Statistics. Third, the estimation data of grain consumption in each province: among them, the per capita consumption of various grain types and feed conversion rate in each province are from Chen Yongfu [28]; the output of livestock products, beer output, and sown area of various grain types in each province are from the China Statistical Yearbook 2022; the proportion of various grain types in different kinds of feed is from Wu Fang [29]; the liquor output and edible oil output of each province are from the CHOICE Financial Data Terminal; the industrial conversion coefficients of liquor, beer and edible oil, as well as the seed grain usage per unit area, are from Zhang Zhixin [30]. Fourth, the transportation cost per unit weight of grain between provinces is the transportation cost under the minimum cost condition calculated by Gao Shoujie [31].

The data and their sources required for calculating the grain virtual water content include: First, the meteorological data (such as temperature, humidity, air pressure, etc.) of each province, which are from CLIMWAT, a software of the Food and Agriculture Organization (FAO) of the United Nations. The meteorological data of the capital city of each province are selected to calculate the evapotranspiration of the four grain crops in each province; due to the lack of data for Xining City, the data of Dulan City (which is close to Xining City) are used as the reference for Qinghai Province. Second, data such as crop growth period days, crop coefficients and soil types, which are from the FAO Database. Third, the data of grain sown area in each province, which are from the China Statistical Yearbook 2022.

3. Results

3.1. Measurement Results and Analysis of Virtual Water Flow in Inter-Provincial Grain Product Trade

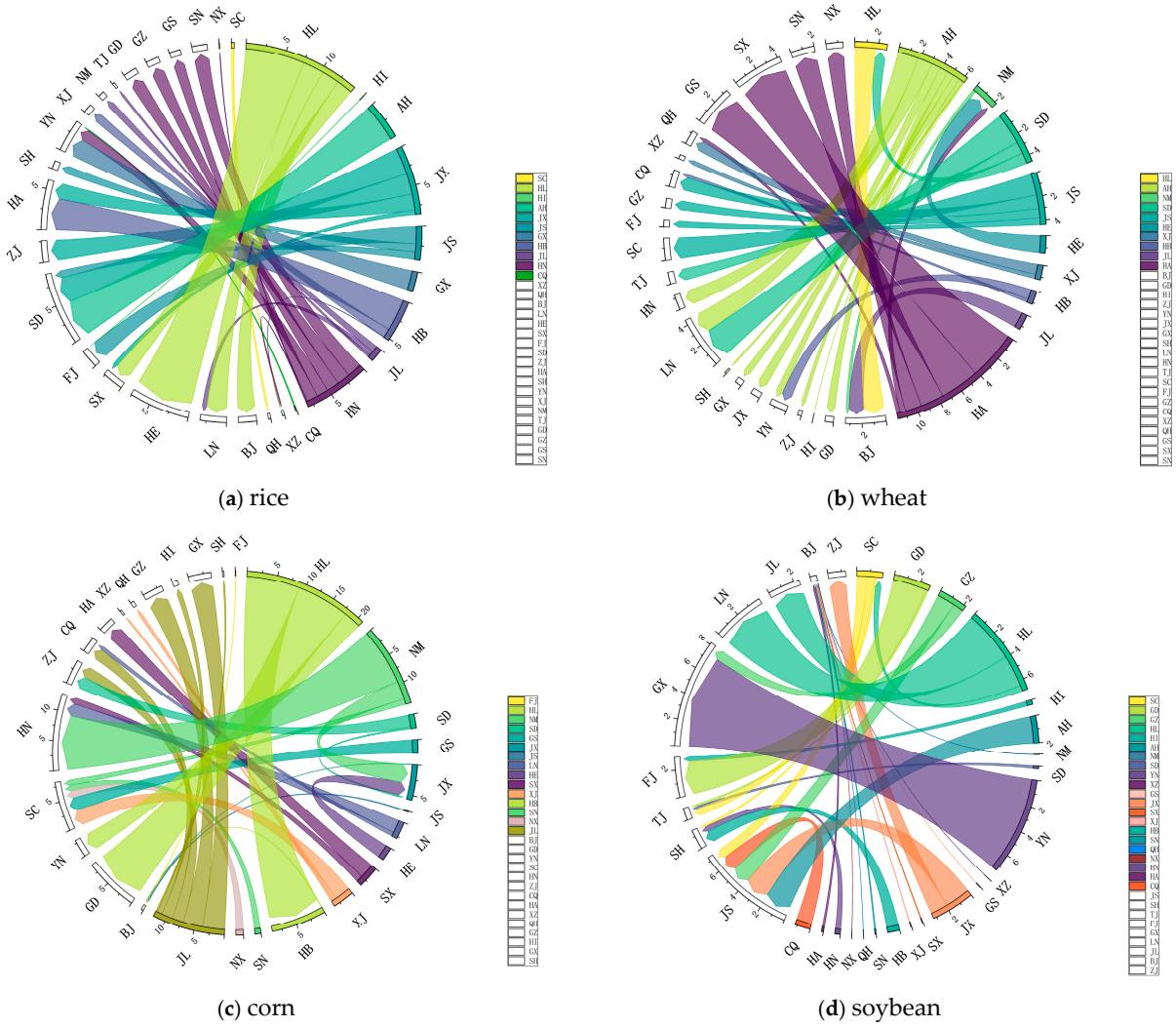
3.1.1. Measurement Results and Analysis of Product-Specific Inter-Provincial Virtual Water Flow

Based on the calculations of the aforementioned model, the inter-provincial virtual water flow patterns of rice, wheat, corn, and soybeans in China in 2021 are shown in Figure 2. The province with the largest inter-provincial virtual water inflow volume of rice is Shandong, with its rice virtual water inflow reaching 9.118 billion m^3. Although Shandong mainly consumes pasta, factors such as inter-provincial population mobility and the improvement of people's living standards have led to an increase in the number of households that take rice as their staple food [32]; moreover, most of Shandong's rice is imported from Anhui, and the virtual water content per unit of rice in this origin is relatively high, which results in Shandong having the highest virtual water inflow volume of rice. In terms of the virtual water outflow volume of rice, Heilongjiang, as an important rice-producing area [33], ranks first with a rice virtual water outflow of 14.525 billion m^3. This is due to Heilongjiang's superior climatic conditions and sufficient soil fertility, which contribute to high yield and quality of rice. Among the pairwise inter-provincial virtual water flows of rice, the flow from Heilongjiang to Hebei is the largest, at 7.567 billion m^3, which is related to Heilongjiang being a major grain-producing area and Hebei having an industrial structure with a large number of industrial enterprises; the flow from Anhui to Shandong ranks second, at 4.817 billion m^3, which is attributed to Shandong's large population (leading to high grain demand) and the short distance between the two provinces (resulting in low transportation costs).

In the inter-provincial virtual water flow of wheat, Liaoning has the highest virtual water inflow volume of wheat, reaching 4.434 billion m^3. Located in northern China, Liaoning has a predominantly pasta-based dietary structure; meanwhile, the accelerated urbanization process and the expansion of urban land have led to a reduction in wheat cultivation land, thus necessitating inter-provincial wheat trade to compensate for the shortage in local consumption. This result is consistent with the conclusion of Zhang Qianqian [34]. In addition, due to the high virtual water content per unit of wheat in Henan and the large volume of Henan's wheat outflow in inter-provincial grain product trade, Henan has the largest virtual water outflow volume of wheat, at 11.764 billion m^3. Among the pairwise inter-provincial virtual water flows of wheat, the flow from Henan to Shanxi is the largest, at 4.196 billion m^3; the flow from Henan to Gansu ranks second, at 3.372 billion m^3, which is related to Henan's role as a major wheat-producing area, the pasta-dominated dietary structures of residents in Shanxi and Gansu, and the short distance from Henan to the two provinces.

Hunan is the province with the largest inter-provincial virtual water inflow volume of corn (12.857 billion m^3), which mainly comes from Gansu and Inner Mongolia where the virtual water content per unit of corn product is relatively high. The province with the largest inter-provincial virtual water outflow volume of corn is Heilongjiang (20.978 billion m^3); this province boasts favorable natural and climatic conditions and is one of the world's three major "Golden Corn Belts" [35], but its local corn deep processing capacity is still relatively insufficient, which in turn leads to a large volume of inter-provincial corn outflow from the region. Among the pairwise inter-provincial virtual water flows of corn, the largest one is the flow from Inner Mongolia to Hunan (9.568 billion m^3), followed by the flow from Heilongjiang to Hubei (9.040 billion m^3). The largest virtual water outflow of corn from Inner Mongolia to Hunan is related to the large corn surplus in Inner Mongolia and Hunan being a major animal husbandry province in China [36] with high demand

for corn. The relatively high corn flow from Heilongjiang to Hubei is consistent with the advantages of Heilongjiang's natural conditions for corn cultivation and the high demand for corn driven by the development of industry and animal husbandry in Hubei.



(**a**) rice (**b**) wheat

(**c**) corn (**d**) soybean

Figure 2. Grain Virtual Water Flow among 31 Provinces of China in 2021. Note: In the chord diagram, the sector blocks represent the provincial-level administrative regions, and the connecting ribbons indicate the volume of inter-provincial virtual water flows associated with grain product trade. The colored legends denote the exporting provinces of virtual water in inter-provincial grain product trade (each color corresponds to a different province), while the white legends represent the importing provinces.

Guangxi has the largest inter-provincial virtual water inflow of soybeans, with its soybean virtual water inflow reaching 8.149 billion m^3. Guangxi has become the province with the largest inter-provincial virtual water inflow of soybeans, mainly due to the structural contradiction between soybean supply and demand and its industrial characteristics. From the perspective of agricultural production, Guangxi is dominated by mountainous and hilly terrain, and soybeans are mainly planted in scattered dryland areas, primarily through intercropping with corn and interplanting in orchards, resulting in a low level of large-scale cultivation. Guangxi has a diversified soybean consumption structure: in addition to soybean consumption for feed processing, traditional soybean product industries such as Huangyao fermented soybeans and yuba (dried bean curd sticks) also require large quantities of raw materials, and more than 60% of the raw materials for these processing enterprises are transferred from other regions. Among provinces, Yunnan has the largest

inter-provincial virtual water outflow of soybeans, with its soybean virtual water outflow reaching 7.355 billion m^3. Soybeans in Yunnan are widely distributed: except for alpine mountainous areas at altitudes above 2600 m where soybeans are rarely grown, soybeans are cultivated in all other regions of the province, and the province has a relatively high soybean yield [37]. Due to the large-scale outflow of its soybeans, Yunnan has also become the province with the largest virtual water outflow of soybeans, with a soybean virtual water outflow of 7.355 billion m^3. The largest bilateral inter-provincial virtual water flow of soybeans occurs from Yunnan to Guangxi, with a volume of 7.355 billion m^3. Yunnan and Guangxi are geographically adjacent, with a long inter-provincial border; moreover, the transportation distance between Yunnan's main soybean-producing areas and the regions in Guangxi with concentrated demand (such as for soybean product processing and feed production) is short. This spatial location advantage significantly reduces the logistics costs of cross-regional soybean transportation, which is consistent with the modeling logic of the Minimum Transport Cost Method used in the study to calculate inter-provincial grain product trade, thus verifying the logistical feasibility of the large-scale virtual water flow of soybeans between the two regions.

3.1.2. Measurement Results and Analysis of Virtual Water Flow Volume in Inter-Provincial Grain Product Trade

The pattern of virtual water flow volume in inter-provincial grain product trade is shown in Figure 3. The provinces with the largest virtual water net inflow volume in inter-provincial grain product trade are Hebei, Guangxi, and Liaoning, with corresponding total net inflow volumes of 18.875 billion m^3, 10.076 billion m^3, and 8.795 billion m^3 respectively. The relatively high virtual water net inflow volumes in Liaoning and Guangxi are related to the large purchase volumes of wheat and soybeans in the two provinces, as well as the high virtual water content of these two crop types. Although Hebei is a major grain-producing province, its large local population leads to high grain demand, resulting in a large virtual water net inflow of grain. The top 10 provinces ranked by the net inflow of virtual water from inter-provincial grain product trade, along with their corresponding specific values of virtual water net inflow, are shown in Table 1.

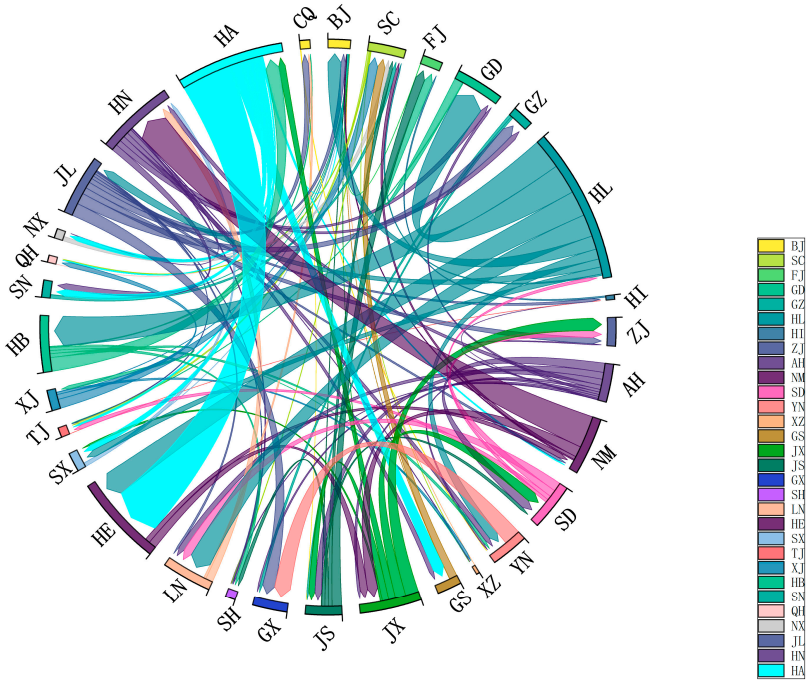


Figure 3. Total Virtual Water Flow of Grain in China in 2021.

Table 1. Top 10 Provinces of China by Net Inflow/Outflow of Virtual Water and Main Inter-provincial Bilateral Virtual Water Flow Paths in Grain Product Trade.

Provinces with Net Inflow of Virtual Water from Inter-Provincial Grain Product Trade	Net Inflow Volume (Billion m^3)	Provinces with Net Outflow of Virtual Water from Inter-Provincial Grain Product Trade	Net Outflow Volume (Billion m^3)	Inter-Provincial Bilateral Flow Path	Flow Volume (Billion m^3)
Hebei	18.875	Heilongjiang	43.166	Henan→Hebei	15.062
Guangxi	10.075	Henan	18.974	Inner Mongolia→Hunan	9.568
Liaoning	8.795	Anhui	13.089	Heilongjiang→Hubei	9.040
Sichuan	8.665	Jilin	12.675	Heilongjiang→Guangdong	8.939
Guangdong	8.555	Inner Mongolia	11.270	Heilongjiang→Hebei	7.567
Beijing	6.501	Jiangxi	5.360	Heilongjiang→Liaoning	6.596
Zhejiang	6.196	Xinjiang	3.772	Yunnan→Guangxi	4.915
Fujian	5.758	Jiangsu	1.478	Anhui→Shandong	4.817
Hunan	5.492	Ningxia	−0.225	Hubei→Henan	4.075
Guizhou	3.557	Hainan	−0.484	Heilongjiang→Beijing	4.033

The provinces with the largest virtual water net outflow volume in inter-provincial grain product trade are Heilongjiang, Henan, and Anhui, with corresponding total net outflow volumes of 43.166 billion m^3, 18.974 billion m^3, and 13.089 billion m^3 respectively. All three provinces are major grain-producing areas in China, undertaking the main responsibility of grain production in the country, and exporting large quantities of grain to other provinces after meeting their own needs. The top 10 provinces ranked by the net outflow of virtual water from inter-provincial grain product trade, along with their corresponding specific values of virtual water net inflow, are shown in Table 1.

Among the pairwise inter-provincial virtual water flows in grain product trade, the flow from Henan to Hebei is the largest (15.062 billion m^3), followed by the flow from Inner Mongolia to Hunan (9.568 billion m^3), and the third is the flow from Heilongjiang to Hubei (9.040 billion m^3). As a core grain-producing area in China, Henan is the second-largest province with net virtual water outflow, and its virtual water outflow of wheat ranks first in the country. Henan's total grain output, especially wheat output, still has a large surplus after meeting local consumption, which provides a solid supply foundation for large-scale grain export. Hebei is the province with the largest net virtual water inflow in China. Due to its large local population, the demand for grain is strong; moreover, the residents' dietary structure is dominated by pasta, leading to a prominent demand for wheat. Hebei's own grain production capacity cannot fully meet its consumption demand, resulting in a significant grain gap, which matches the wheat supply from Henan. Both provinces are adjacent to each other in the North China region, so the transportation distance between core grain-producing areas and major consumer areas is short. In addition, relying on the dense railway network, large-scale and low-cost grain transportation is realized, which conforms to the modeling logic of the Minimum Transport Cost Method and has sufficient logistical feasibility. The relatively large flows from Inner Mongolia to Hunan and from Heilongjiang to Hubei are mainly due to the large virtual water flow of corn between them. It can be seen that the results of this study further verify China's grain circulation pattern of "grain transportation from north to south". The top 10 groups of bilateral flows with relatively high virtual water flow volumes from inter-provincial grain product trade

between pairs of provinces, along with their corresponding specific values of virtual water flow, are shown in Table 1.

3.2. Sustainability Evaluation and Analysis of Virtual Water Flow in Inter-Provincial Grain Product Trade

The water resource pressure index and its variation range of each province in 2021 under the scenarios with and without inter-provincial grain product trade are shown in Table 2. It can be seen that under the scenario where there is no inter-provincial grain product trade in each province, Ningxia has the greatest water resource pressure index(3.92): Ningxia is located in an area with extremely scarce water resources, its ecological environment is relatively harsh, and the investment in farmland water conservancy infrastructure is insufficient [38], so local agricultural production has intensified Ningxia's water resource pressure; Hebei ranks second in terms of water resource pressure index (1.41), which is related to the limited potential for surface water development, severe over-exploitation of groundwater, and obvious shortage of water supply for grain production in the region [39]; Tianjin ranks third in water resource pressure index (1.21), which is attributed to its scarce local water resources, rapid economic development, and high external dependence on grains with high virtual water content such as wheat and soybeans. Tibet, Qinghai, and Hainan have the lowest water resource pressure indices, which are 0, 0.03, and 0.06, respectively. In the absence of inter-provincial grain flow, 10 provinces across the country have water resource pressure indices higher than the national average level, mainly concentrated in major grain-producing areas such as Hebei, Shandong, and Jiangsu. Overall, the water resource pressure in northern regions is generally higher than the national average level, while that in southern regions is generally lower than the national average level due to abundant physical water resources.

Under the scenario with inter-provincial grain product trade, consistent with the scenario without trade, Ningxia and Hebei still rank among the top three in terms of water resource pressure index, with values of 3.67 and 0.91, respectively. The reason why the two provinces still have relatively high water resource pressure index rankings lies in the large outflow of corn in Ningxia's inter-provincial trade; Hebei, while facing its own water scarcity, also transports large quantities of grain to other provinces, resulting in a large amount of virtual water outflow. Henan has a water resource pressure index of 1.12, ranking second, which is mainly due to the fact that Henan has the largest outflow of wheat in inter-provincial grain product trade, leading to virtual water outflow. The top three provinces with the lowest water resource pressure index are Tibet (0), Qinghai (0.01), and Zhejiang (0.03), respectively. The low water resource pressure indices of Tibet and Qinghai are mainly because their natural conditions are not suitable for grain growth [40]. Zhejiang's relatively low water resource pressure index is related to its location in southern China, where it has sufficient water resources and abundant precipitation, so grain production exerts little pressure on its water resources.

When comparing the changes in water resource pressure index of each province/municipality under the scenarios with and without inter-provincial grain product trade, inter-provincial grain product trade in Heilongjiang has led to a 94.74% increase in its water resource pressure index, making it the province with the largest increase in water resource pressure index among all provinces; Jilin's water resource pressure index increased by 73.68%, ranking second; Inner Mongolia's water resource pressure index rose by 48%, ranking third. As major grain-producing areas in China, Heilongjiang and Jilin assume the responsibility of large-scale grain outflow; in particular, Heilongjiang has a large outflow of rice, wheat, corn, and soybeans. Jilin also has a large outflow of corn, which has a relatively high virtual water content, thus leading to an increase in water resource pressure. The top three provinces/municipalities with the largest decrease in water resource pressure index

are Beijing, Shanghai, and Qinghai, with corresponding decreases of 94.64%, 79.41%, and 66.67%, respectively. The development of industry and tertiary industry in Beijing and Shanghai has occupied a large amount of agricultural land, resulting in high dependence on external grain; the inflow of grain, accompanied by the inflow of virtual water, has objectively alleviated the local water resource pressure. Qinghai's water resource pressure index is relatively low both with and without inter-provincial grain product trade, which is because its local natural environment is not suitable for grain cultivation and its grain output is low; when inter-provincial grain product trade exists, the inflow of grain (and the accompanying inflow of virtual water) further reduces the local water resource pressure.

Table 2. Water resource pressure index and its change range of various provinces of China under the scenarios of with and without inter-provincial grain product trade in 2021.

Province	Water Resource Pressure Index Under the Scenario of Trade Existence	Water Resource Pressure Index Under the Scenario of No Trade	Change Range (%)
BJ	0.06	1.12	−94.64
SC	0.07	0.10	−30.00
FJ	0.05	0.12	−58.33
GD	0.09	0.16	−43.75
GZ	0.07	0.10	−30.00
HL	0.74	0.38	94.74
HI	0.05	0.06	−16.67
ZJ	0.03	0.08	−62.50
AH	0.48	0.40	20.00
NM	0.37	0.25	48.00
SD	0.90	0.93	−3.23
YN	0.10	0.10	0.00
XZ	0.00	0.00	0.00
GS	0.40	0.49	−18.37
JX	0.15	0.11	36.36
JS	0.59	0.57	3.51
GX	0.10	0.17	−41.18
SH	0.14	0.68	−79.41
LN	0.39	0.56	−30.36
HE	0.91	1.41	−35.46
SX	0.77	0.92	−16.30
TJ	0.51	1.21	−57.85
XJ	0.23	0.18	27.78
HB	0.24	0.26	−7.69
SN	0.18	0.21	−14.29
QH	0.01	0.03	−66.67
NX	3.67	3.92	−6.38
JL	0.66	0.38	73.68
HN	0.14	0.17	−17.65
HA	1.12	0.84	33.33
CQ	0.08	0.12	−33.33
National	0.43	0.52	−17.31

Note: In the table, a positive value of the change range indicates the increase in the water resource pressure index in the scenario where inter-provincial grain product trade exists compared to the scenario where it does not exist; a negative value indicates the decrease in the water resource pressure index. The underlined values represent the top three largest increases and decreases in the water resource pressure index.

From a national perspective, the current inter-provincial virtual water flow in China's grain product trade is sustainable, but this sustainability is primarily reflected in the reduction in the national average water resource pressure. By exporting virtual water from major grain-producing areas, water-intensive crops are transferred to water-scarce

regions, resulting in a 17.31% reduction in the national average water resource pressure index (0.43) compared to the scenario without inter-provincial grain product trade (0.52). This has led to increased water use efficiency at the national level. However, this macro-level sustainability effect shows significant spatial disparities. Provinces with net virtual water outflows (such as Heilongjiang, Jilin, and Inner Mongolia) experience increased local water resource pressure due to the large export of virtual water. Studies show that although virtual water trade can save water at the national level, it often exacerbates water scarcity in the exporting regions [41]. Our analysis also reveals that provinces such as Inner Mongolia and Heilongjiang, which are major exporters of virtual water, have long maintained relatively high water resource pressure index(WSI). Large-scale virtual water exports may further exacerbate water pressure in these regions.

Thus, it is evident that the current virtual water flow model in China exhibits a clear trade-off and uneven distribution between national and regional scales. In other words, the reduction of national average water resource pressure comes at the cost of increasing water pressure in some exporting provinces. Based on the background of China's grain production functional zones and key agricultural product protection zones, it can be seen that major grain-producing provinces like Heilongjiang, Henan, and Jilin are experiencing significant increases in water resource pressure due to grain product trade, and these regions highly overlap with China's grain production functional zones. In contrast, water-scarce regions such as Beijing and Shanghai have alleviated their local water resource pressures through grain product trade. While this virtual water flow pattern helps ease local water scarcity, it is important to remain cautious of the ecological risks caused by over-exploitation in grain production functional zones in the long term.

4. Conclusions and Recommendations

4.1. Conclusions

This study used the Minimum Transport Cost Method to calculate the inter-provincial net grain product trade flow for four grain types, namely rice, wheat, corn, and soybeans. Subsequently, by combining with the Penman-Monteith formula, it measured the virtual water flow volume of each type of grain in each province, and compared the water resource pressure index of each province under the scenarios with and without inter-provincial grain product trade. It should be noted that the inter-provincial corn trade flow pattern calculated in this study is generally consistent with the research results of Li Fuzhong et al. [42]; moreover, the overall trend of China's grain product trade pattern has not changed significantly over the 18-year period. However, over these 18 years, affected by the increase in per capita disposable income, the adjustment of residents' dietary structures, and the change in industrial spatial layout, China's corn flow pattern has undergone minor changes, which has also led to slight differences between this study and the research of Li Fuzhong et al. [41] in terms of the specific ranking of trade volumes between pairs of provinces. Based on the above analysis, the main conclusions of this study are as follows:

(1) In 2021, the inter-provincial virtual water flow in China's grain product trade exhibited the characteristic of "virtual water transportation from north to south". The three provinces with the largest virtual water net outflow volume in inter-provincial grain product trade were Heilongjiang (43.166 billion m^3), Henan (18.974 billion m^3), and Anhui (13.089 billion m^3); while the three provinces with the largest virtual water net inflow volume in inter-provincial grain product trade were Hebei (18.875 billion m^3), Guangxi (10.076 billion m^3), and Liaoning (8.795 billion m^3).

(2) Among the pairwise inter-provincial virtual water flows in China's grain product trade, the flow from Henan to Hebei was the largest (15.062 billion m^3), followed by the flow from Inner Mongolia to Hunan (9.568 billion m^3) and the flow from

Heilongjiang to Hubei (9.040 billion m^3). By grain product type: among the pairwise inter-provincial virtual water flows of rice, the flow from Heilongjiang to Hebei was the largest (7.567 billion m^3), followed by the flow from Anhui to Shandong (4.817 billion m^3); among the inter-provincial virtual water net flows of wheat, the flow from Henan to Shanxi was the largest (4.196 billion m^3), followed by the flow from Henan to Gansu (3.372 billion m^3); among the inter-provincial virtual water flows of corn, the flow from Inner Mongolia to Hunan was the largest (9.568 billion m^3), followed by the flow from Heilongjiang to Hubei (9.040 billion m^3); among the inter-provincial virtual water flows of soybeans, the flow from Yunnan to Guangxi was the largest (7.355 billion m^3), followed by the flow from Heilongjiang to Liaoning (3.948 billion m^3).

(3) In 2021, the provinces with the largest increase in water resource pressure index due to inter-provincial grain product trade were Heilongjiang, Jilin, and Inner Mongolia, with increases of 94.74%, 73.68%, and 48%, respectively; the top three regions with the largest decrease in water resource pressure index were Beijing, Shanghai, and Qinghai, with decreases of 94.64%, 79.41%, and 66.67%, respectively. Under the scenario with inter-provincial grain product trade, the national average water resource pressure index decreased by 17.31% compared with that under the scenario without inter-provincial grain product trade. Overall, China's current virtual water flow pattern of grain is sustainable.

4.2. Recommendations

(1) Guide the flow of virtual water through the optimization and adjustment of grain production and circulation. The government should strengthen macro-level regulation over grain production and circulation to adjust the main channels of virtual water flows and enhance policy support for major exporting provinces. The results reveal a distinct "north-to-south water transfer" pattern in China's virtual water flows embedded in interprovincial grain product trade. The top three provinces in terms of net virtual water outflow are Heilongjiang (43.166 billion m^3), Henan (18.974 billion m^3), and Jilin (12.675 billion m^3). These major grain-exporting provinces export substantial volumes of virtual water through grain product trade, which significantly increases local water stress. For example, Heilongjiang's water stress index rises by 94.74% due to grain exports. Although interprovincial grain product trade reduces the national average water stress index from 0.52 to 0.43 (a decrease of about 17.31%), indicating an overall mitigation effect and a relatively sustainable pattern, it simultaneously leads to spatial imbalance—some major exporting provinces experience aggravated water stress. Therefore, the government should fully exercise its regulatory capacity to rationally guide the main channels of virtual water transfer. For the largest interprovincial virtual water flows (e.g., Henan→Hebei, Inner Mongolia→Hunan, Heilongjiang→Hubei), targeted policy measures should be implemented to standardize grain circulation, lower logistics costs, and ensure the efficiency of major grain transportation routes. Meanwhile, stronger policy support—through direct subsidies, tax reductions, and low-interest loans—should be provided to key net-exporting provinces such as Henan and Inner Mongolia. By ensuring both food and water security, such measures would incentivize stable and increased grain production while alleviating local water stress, thereby enhancing the sustainability of interprovincial virtual water flows.

(2) Optimization of Cropping Structures in Major Producing Areas and Land-Use Control in Major Consuming Areas. Heilongjiang, Henan, and Jilin, the three provinces with the highest net virtual water outflows (43.166 billion, 18.974 billion, and

12.675 billion m^3, respectively), export enormous quantities of virtual water through grain product trade, causing notable increases in their local water stress indices (by 94.74%, 73.68%, and 48%, respectively). Accordingly, these major grain-producing regions should adjust their cropping structures by expanding the share of drought- and cold-tolerant, high-yield, and high-quality varieties while reducing the planting area of water-intensive crops. The adoption of water-saving irrigation technologies should be promoted to improve on-farm water-use efficiency [43]. Conversely, major grain-consuming areas should rationally control urbanization and strictly safeguard arable land to maintain a basic level of grain self-sufficiency. Provinces such as Hebei, Guangxi, and Liaoning are currently major net recipients of virtual water (with net inflows of 18.875 billion, 10.076 billion, and 8.795 billion m^3, respectively). Moreover, highly urbanized cities like Beijing and Shanghai have reduced their local water stress indices by 94.64% and 79.41%, respectively, through substantial grain imports. Hence, these net-importing regions should curb excessive urban expansion, preserve farmland and local production capacity, and thereby reduce over-dependence on external virtual water inputs.

(3) Expanding Grain Production in Water-Abundant Regions and Promoting Water-Saving Lifestyles. Empirical results indicate that southern provinces such as Zhejiang and Fujian possess abundant water resources, and grain production imposes minimal water stress (e.g., Zhejiang's water stress index is only ≈0.03). These water-abundant regions could leverage their resource advantages by moderately expanding grain cultivation to help relieve water stress in major producing areas. Meanwhile, populous provinces such as Sichuan and Guangdong should encourage residents to adjust their dietary structures—shifting toward food items with lower virtual water content and reducing consumption of water-intensive grains—to lower demand for high-virtual-water agricultural products. Some grain-importing regions, such as Qinghai, have already alleviated local water stress through virtual water inflows (its water stress index decreased by 66.67% due to imported grain). However, excessive dependence on external water resources is unsustainable. It is thus crucial to enhance public awareness of water conservation and foster a culture of sustainable consumption. At the national level, large-scale inter-basin water transfer projects should be accelerated to strengthen coordination between physical water redistribution and virtual water flows, thereby enhancing overall regional water and food security.

4.3. Limitations

Despite the fact that this study has carried out systematic analyses in aspects such as the construction of the measurement framework for virtual water flows in inter-provincial grain product trade and sustainability evaluation, this study still has the following limitations.

The data on the unit weight transportation costs of grain between provinces in this paper is sourced from Gao Shoujie (2014) [31]. This study used network analysis tools to analyze transportation paths and cost data under two conditions: minimum cost and shortest transportation distance. The minimum cost condition mainly considers railway and waterway transportation; under the shortest distance condition, highway transportation, which tends to have higher freight costs on certain segments, may be used, resulting in relatively higher transportation costs. Due to the lower cost advantages of waterway and railway transportation, they dominate inter-provincial grain transport, while highway transportation is mainly concentrated in intra-provincial or short-distance transport. This study believes that the unit weight transportation costs calculated under the minimum cost condition are more representative of the actual situation. Given that the data involves many

factors and is difficult to update, this study directly uses the data calculated in Gao Shoujie's research [31]. Additionally, since the primary fuel for China's rail, road, and waterway transportation is diesel, we have conducted a robustness test on the model to account for the potential impact of rising energy prices. Specifically, the freight cost matrix was adjusted by ±10% and ±20%, and the net inter-provincial grain product trade flows and virtual water flow patterns were recalculated. The results show that the model maintains basic robustness.

This study only uses the Water Resource Pressure Index as the sole indicator to measure the sustainability of inter-provincial grain product trade, and does not incorporate the multiple core dimensions of sustainability assessment. Specifically, the study does not cover the dimensions of economic feasibility, ecological risks, and social equity. While this single-dimensional assessment can accurately focus on the core research question of "the impact of virtual water flows in grain product trade on regional water resources" and avoid the dispersion of research focus due to an excessive number of dimensions, it also causes the study to fail to fully present the complete picture of the sustainability of inter-provincial grain product trade. It cannot comprehensively reveal the synergies and conflicts of trade activities at the economic, ecological, and social levels, which to a certain extent limits the comprehensive guiding value of the research conclusions for grain product trade policy formulation.

This study covers four types of grain—rice, wheat, corn, and soybeans—when measuring inter-provincial grain product trade volumes. The core consideration is that these four crops are the main components of China's grain production and consumption, and they also dominate inter-provincial trade. Therefore, the virtual water flow analysis based on these four types of grain is highly representative of the actual situation and can reflect the core patterns of China's grain product trade and virtual water flow. However, we are also aware that this choice introduces a limitation at the level of the research object: since other grain types, such as tubers, are not included, it may not fully assess the trade patterns of all grain crops and the sustainability of their virtual water flow. This limitation, along with the modeling methods and data scope, constitutes an area for improvement in this study.

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References

1. Deng, H.Y.; Li, C.M.; Cao, J.; Song, Y.L.; Liu, J. Spatial-temporal Pattern and Distribution Evolution of Grain Production in China. *J. Agric. Sci. Technol. China* **2024**, *26*, 1–11. [CrossRef]
2. Liu, J.; Wang, Y.; Yu, Z.; Cao, X.; Tian, L.; Sun, S.; Wu, P. A comprehensive analysis of blue water scarcity from the production, consumption, and water transfer perspectives. *Ecol. Indic.* **2017**, *72*, 870–880. [CrossRef]

3. Sun, S.K.; Wu, P.T.; Wang, Y.B.; Zhao, X.N. The virtual water content of major grain crops and virtual water flows between regions in China. *J. Sci. Food Agric.* **2013**, *93*, 1427–1437. [CrossRef]
4. Allan, J.A. Fortunately there are substitutes for water otherwise our hydro-political futures would be impossible. *Priorities Water Resour. Alloc. Manag.* **1993**, *13*, 26.
5. Wang, Y.B.; Wu, P.T.; Zhao, X.N.; Engel, B.A. Virtual water flows of grain within China and its impact on water resource and grain security in 2010. *Ecol. Eng.* **2014**, *69*, 255–264. [CrossRef]
6. Tong, J.J.; Sun, S.K.; Ma, J.L.; Yin, Y.L.; Wang, Y.B.; Shen, X.; Xu, J.Y. Analysis of Socio-economic Driving Effect of Regional Grain Virtual Water Flow. *Trans. Chin. Soc. Agric. Mach.* **2024**, *27*, 1–26. [CrossRef]
7. Wang, X. Study on Grain Virtual Water Flow Between Regions in China and Its Impact on Water Resources. Master's Thesis, Northwest A&F University, Xianyang, China, 2016.
8. Jing, M.; Hoekstra, A.Y.; Hao, W.; Chapagain, A.K.; Dangxian, W. Virtual versus real water transfers within China. *Philos. Trans. R. Soc. London Ser. B Biol. Sci.* **2006**, *361*, 835–842. [CrossRef]
9. Zhao, Y.; Huang, K.J.; Gao, X.R.; An, T.L.; He, G.H.; Jiang, S. Evaluation of grain production water footprint and influence of grain virtual water flow in the Yellow River Basin. *Water Resour. Prot.* **2022**, *38*, 39–47. [CrossRef]
10. Qian, H.; Engel, B.A.; Tian, X.; Sun, S.; Wu, P.; Wang, Y. Evaluating drivers and flow patterns of inter-provincial grain virtual water trade in China. *Sci. Total. Environ.* **2020**, *732*, 139251. [CrossRef]
11. Qian, H.Y. Quantitative Method of Inter-Provincial Grain Trade and Evaluation of Virtual Water Flow Pattern in China. Master's Thesis, Northwest A&F University, Xianyang, China, 2020. [CrossRef]
12. Yang, T.T.; Zhang, X.N.; Gao, X.; Hu, Q.Y.; Wang, Q.H.; Lun, F.; Chen, X.L. Study on inter-provincial grain trade and its impacts on virtual water and soil resources in China. *Pratacultural Sci.* **2022**, *39*, 1686–1697.
13. Chapagain, A.K.; Hoekstra, A.Y.; Savenije, H.H.G. Water saving through international trade of agricultural products. *Hydrol. Earth Syst. Sci.* **2006**, *10*, 455–468. [CrossRef]
14. Masud, M.B.; Wada, Y.; Goss, G.; Faramarzi, M. Global implications of regional grain production through virtual water trade. *Sci. Total. Environ.* **2019**, *659*, 807–820. [CrossRef]
15. Martina, S.; Stefano, S.; Andrea, F.; Massimo, R. Modeling the future evolution of the virtual water trade network: A combination of network and gravity models. *Adv. Water Resour.* **2017**, *110*, 538–548. [CrossRef]
16. Dalin, C.; Konar, M.; Hanasaki, N.; Rinaldo, A.; Rodriguez-Iturbe, I. Evolution of the global virtual water trade network. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 5989–5994. [CrossRef]
17. Hoekstra, A.Y.; Hung, P.Q. Globalisation of water resources: International virtual water flows in relation to crop trade. *Glob. Environ. Chang.* **2005**, *15*, 45–56. [CrossRef]
18. Zhuo, L.; Mekonnen, M.M.; Hoekstra, A.Y. Consumptive water footprint and virtual water trade scenarios for China—With a focus on crop production, consumption and trade. *Environ. Int.* **2016**, *94*, 211–223. [CrossRef] [PubMed]
19. Zhang, G.J. Study on the Calculation Method of Water Resource Savings in Inter-Provincial Grain Trade in China. Master's Thesis, Hunan Normal University, Changsha, China, 2021. [CrossRef]
20. Rathore, L.S.; Aziz, D.; Demeke, B.W.; Mekonnen, M.M. Sustainability assessment of virtual water flows through cereal and milled grain trade among US counties. *Environ. Res. Infrastruct. Sustain.* **2023**, *3*, 025001. [CrossRef]
21. Tian, G.L.; Li, S.W.; Chen, S.F.; Wu, Z.; Xia, Q. The impact of virtual water flow on regional food security under the new development pattern. *J. Econ. Water Resour.* **2023**, *41*, 11–17. [CrossRef]
22. Li, X.S. Study on Coordination Degree and Regulation of Agricultural Water Footprint in Beijing-Tianjin-Hebei Region. Master's Thesis, North China University of Water Resources and Electric Power, Zhengzhou, China, 2020. [CrossRef]
23. An, T.; Wang, L.; Gao, X.; Han, X.; Zhao, Y.; Lin, L.; Wu, P. Simulation of the virtual water flow pattern associated with interprovincial grain trade and its impact on water resources stress in China. *J. Clean. Prod.* **2021**, *288*, 125670. [CrossRef]
24. Zhao, Y.D.; Chen, H. Impact of China's Staple Food Trade on Water Resource Pressure from the Perspective of Virtual Water. *J. Anhui Agric. Sci.* **2022**, *50*, 69–73+78. [CrossRef]
25. Jia, Z.F.; Liu, P.C.; Ma, Y.; Zheng, F.M. Analysis of the Current Situation and Trends of Water Resources Development and Utilization in China. *Water Resour. Power* **2023**, *41*, 27–30. [CrossRef]
26. Mu, Y.Y. Research on the Path and Mechanism Toward Effective Utilization of Water Resources to Ensure Food Security. *Theory J.* **2022**, *304*, 110–118. [CrossRef]
27. Wu, Z.D.; Ding, X.Q.; Chen, Q.Y.; Li, T. Influence of grain virtual water flow on the spatial equilibrium of water resources in the Yellow River Basin. *J. Econ. Water Resour.* **2023**, *41*, 62–71+102+105. [CrossRef]
28. Chen, Y.F. *Food Supply and Demand and Forecast in China*; China Agricultural Press: Beijing, China, 2004.
29. Wu, F.; Wang, H.; Yang, C.; Cui, X.F.; Meng, X.Y. Study on spatial-temporal change and flow pattern of agricultural water footprint in China. *Yangtze River* **2019**, *50*, 104–110+218. [CrossRef]
30. Zhang, Z.X.; Wang, D.; Tang, H.Y. China's Grain Security Guarantee: An Analysis Based on the Change of Grain Consumption Structure. *Consum. Econ.* **2022**, *38*, 38–49.

31. Gao, S.J.; Guo, G.Y.; Dai, X.B. Research of Inter-provincial Grain Transport Costs Based on GIS Network Analyst. *Logist. Sci-Tech.* **2014**, *37*, 135–139. [CrossRef]
32. Wang, N.N.; Zhou, X.B.; Li, X.H.; Liu, Y.Z.; Li, J.L. Analysis on Willingness of Urban Residents Consuming Shandong Rice Based on 1 936 Survey Data of 16 Cities in Shandong Province for Three Years. *Shandong Agric. Sci.* **2022**, *54*, 161–165. [CrossRef]
33. Wang, S.Y.; Gu, Y.N.; Wang, J.Y.; Qi, X.Y. Development Situation and Strategic Countermeasures of Rice Industry in Heilongjiang Province. *Agric. Outlook* **2024**, *20*, 98–104. [CrossRef]
34. Zhang, Q.Q.; Jin, H. Causes and Countermeasures of Wheat Foreign Trade Deficit in Liaoning Province. *Coop. Econ. Sci.* **2018**, *577*, 42–44. [CrossRef]
35. Sun, B.Y. Exploration on the High-Quality Development Path of Corn Industry in Heilongjiang Province. *South China Agric.* **2022**, *16*, 160–162. [CrossRef]
36. Deng, W.J.; Huang, S.; Zou, P.; Zhan, T.Y.; Song, B.B. Brief Discussion on the Path to Achieve Carbon Neutrality in Agriculture in Major Grain-Producing Areas of China—Taking Hunan Province as an Example. *China Eng. Consult.* **2023**, *10*, 93–96.
37. Wang, Y.L. Present situation and developing potentiality of soybean product and scientific research of Yun nan province. *Soybean Bull.* **2003**, *2*, 3–4. [CrossRef]
38. Zhou, J. Maintenance and management strategies of irrigation channels for farmland water conservancy in Ningxia. *South China Agric.* **2023**, *17*, 242–244. [CrossRef]
39. Huang, F.; Yang, X.L.; Fang, Y.; Wang, S.F.; Kang, S.Z. Exploring Water-and-Land-Adapted Spatial Layout of Crop Planting in North China. *Eng. Sci.* **2022**, *24*, 89–96. [CrossRef]
40. Liu, J.; Wang, J.N. Analysis of Tibet's Agricultural Industrial Structure Based on Shift-Share Analysis Method. *Shanxi Agric. Econ.* **2024**, *12*, 40–42. [CrossRef]
41. Zhou, B.; Li, Y.; Ali, T. Sector-level inter-provincial virtual water trade in China: Implications for regional water stress. *Sustain.* **2024**, *16*, 3666. [CrossRef]
42. Li, F.Z.; Zhang, X.J. Analysis of China's Regional Transportation of Corn and Its Direction of Flow. *China Bus. Mark.* **2005**, *5*, 50–53. [CrossRef]
43. Hassan, T.; Khan, Y.; Safi, A.; Chaolin, H.; Wahab, S.; Daud, A.; Tufail, M. Green financing strategy for low-carbon economy: The role of high-technology imports and institutional strengths in China. *J. Clean. Prod.* **2023**, *415*, 137859. [CrossRef]

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