Optimization of domestic inter-regional virtual water trade of agriculture products in China

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Abstract. In the face of increasingly severe pressure on water resources, the theory of virtual water and virtual water trade provides feasible solutions for improving the efficiency of global water use for agricultural products and alleviating the pressure on water resources in water scarce countries or regions. Optimizing the domestic inter-regional trade of virtual water trade of agricultural products can provide information to help for the formulation of China’s water policy. In this study, we will establish scenarios from the two aspects of economy and water resources allocation and utilization, to study the impact of virtual water trade on water saving of agricultural products trade between regions in China. One scenario does not consider water conservation, only economic revenue - net social revenue maximization scenario. Another way to consider water saving is to maximize water saving. With the maximization of net social revenue, 9.6 billion m3 of virtual water had been exported to other regions in the severe drought regions, saving 18.6 billion m3 of water in China. The net social revenue is 9.1 billion RMB. In the scheme of water-saving maximization, virtual water is exported to water rich regions in severe, moderate and mild drought areas, and China had saved 21.5 billion m3 of water. China’s net social revenue is 4 billion RMB. The results show that the optimization of agriculture products domestic inter-regional trade can have a favorable impact on the allocation and utilization of water resources.

1. Introduction
At present, with the acceleration of globalization, high-speed economic development, population growth and urbanization process, as well as the consequent aggravation of human water use and water ecological environment damage, the problem of water shortage has increasingly become a major concern for all mankind. Water shortage is becoming a huge bottleneck restricting the development of global economy and society. Only 1% of the world’s water resources are available fresh water [1]. In the future, under the condition of climate change, this amount will decrease in many areas, such as more frequent and obvious drought and the decline of glacier flow [2]. According to the current trend of population growth and economic development, 60% of the world’s population will experience the crisis of water shortage by 2025.

The traditional ways to alleviate the water shortage are mainly through the construction of water conservancy projects and the development of water-saving technology. Although these two methods have made great contributions to alleviate the water shortage, they both have some disadvantages. For example, the construction cost of water conservancy project is too high and difficult to implement, and may cause certain ecological hidden dangers; the progress of water-saving technology is limited, the
more developed the technology, the more difficult it is, and the effect will be more and more limited. However, there are only a few cases to alleviate the pressure of water resources by means of economy, management and policy. Virtual water provides a new way to solve the problem of water shortage from the perspective of producers [3]. The concept of virtual water originated from Fisher's "embedded water" in agricultural production, but it did not attract the attention of water resource management departments and academia at that time. In 1993, Allan, a professor at the University of London, defined virtual water as water resources embedded in agricultural products in international trade for the first time [4]. After continuous research and improvement by scholars, the current definition of virtual water is more accurate: virtual water is the amount of water resources consumed in the production of products and services [5, 6].

The amount of water required for the production of products varies with the natural and technical conditions of the production site. The virtual water content of 1 kg maize produced in France is 0.6 m³, while that in Egypt is 1.12 m³. Therefore, if 1 t maize is exported from France to Egypt, 520 m³ of water can be saved globally, and 120 m³ of water can be saved for Egypt [4]. Oki et al. estimated the global water saving of $4.55 \times 10^{11}$ m³ per year due to the global grain trade. Considering that the global water consumption for crop production is 5.4 $\times 10^{12}$ m³ per year, the saving water accounts for 8% of the global total water consumption [7]. Zeitoun et al. (2010) calculated that from 1998 to 2004, the Nile Basin countries exported 14000 m³ of water resources through virtual water trade of agricultural products, and imported about 41000 m³ of water resources, which was equivalent to 1 / 3 of the Nile water resources [8].

Virtual water on agriculture is very important, but little researches are studied the optimization of virtual water on agriculture. Mohammad et al. used linear programming and genetic algorithm to calculate the cost and benefit of crop import and export, and then established the objective function - maximum benefit and minimum virtual water consumption to optimize the import and export of crops in Iran [9]. Pearson and McRoberts optimized the planting and trading volume of crops in Germany through three perspectives: maximizing trade revenue, self-sufficiency of crops and minimizing virtual water [10]. Abu-Sharar et al. used the income per unit of water resources and the virtual water content per unit of product to evaluate the feasibility of Jordan's crop cultivation and production of all crop water resources demand, and then identified profitable export crops with the income per unit of water resources and the virtual water content per unit of product [11]. These studies are focused on optimizing crop production and international trade. At present, there is no research on the optimization of crops virtual water domestic inter-regional trade.

China is a country with serious water shortage, and the situation of water resources security is very serious: the per capita available water resources of China is only 2300m³, less than 1/4 of the per capita share of the world, ranking 110th in the world, and one of the 13 most water-poor countries in the world. Agriculture is the largest water user in China, accounting for nearly 70% of total water withdrawals [12]. However, there isn’t any study on the optimization of agricultural products virtual water domestic inter-regional trade of China. The specific Spatial Equilibrium models are used to optimize the agricultural products virtual water trade of domestic inter-regional trade of China with two angles of net social revenue maximization and water saving maximization. 30 Chinese provinces, autonomous regions and municipalities (Chongqing is attributed into Sichuan Province) in 2009 are taken as research objects. Based on the investigation of the current situation of water resources, each region is defined as different regional water resources set. This can more directly describe the relief effect of water resource pressure in China. We hope our research results can provide a reference for China's water policy.

2. Methodology and data

2.1 Optimization of agricultural products trade volume
Spatial Equilibrium models are used to optimize the agricultural products domestic inter-regional trade. The agricultural product lack volume of N regions in 30 regions is seen as the demand for the other
N) regions. Then the agricultural product surplus volume of (30-N) regions is seen as the supply for the N regions. The specific Spatial Equilibrium models are shown:

**Net social revenue maximization objective function**

\[ MAX \ NSR = \sum_{i=1}^{N} \sum_{j=1}^{M-N} X_{ijk} \times P_{ijk} - \sum_{i=1}^{N} \sum_{j=1}^{M-N} X_{ijk} \times P_{ijk} - \sum_{i=1}^{N} \sum_{j=1}^{M-N} \sum_{k=1}^{N} X_{ijk} \times F \times d_{ij} \]  

(1)

Where NSR is the Net Social Revenue; \( i \) is the agricultural products lack regions; \( j \) is the agricultural products surplus regions; \( k \) is the kind of agricultural product; \( n \) is the number of kind of agricultural product; \( N_i \) is the number of regions lacking of agricultural product \( k \); \( M \) is the number of the agricultural product regions; \( M-N_k \) is the sum of the agricultural products surplus regions of agricultural product \( k \); \( X_{ij} \) is the trade volume of agricultural products from region \( j \) to region \( i \) (t); \( P_i \) is the retail agricultural products prices in region \( i \) (yuan/kg); \( P_j \) is the agricultural products prices in region \( j \) (yuan/kg); \( F \) is the transportation costs of per unit of agricultural products (yuan/kg·km); \( d_{ij} \) is the distance between region \( i \) and region \( j \) (km).

**Water saving maximization objective function**

\[ MAX \ WS = \sum_{i=1}^{N} \sum_{j=1}^{M-N} X_{ijk} \times VWC_{ik} - \sum_{i=1}^{N} \sum_{j=1}^{M-N} \sum_{k=1}^{N} X_{ijk} \times VWC_{jk} \]  

(2)

Where WS is the water saving (m³); \( VWC_{ik} \) is the virtual water content per unit weight of agricultural product \( k \) in region \( i \) (m³/t); \( VWC_{jk} \) is the virtual water content per unit weight of agricultural product \( k \) in region \( j \) (m³/t).

Constraints

\[ \sum_{j=1}^{M-N} X_{ijk} \leq \sum_{i=1}^{N} CL_{ijk} \]  

(1)

\[ \sum_{j=1}^{M-N} X_{ijk} \leq \sum_{j=1}^{M-N} CS_{jk} \]  

(2)

\[ \sum_{i=1}^{N} \sum_{j=1}^{M-N} X_{ijk} = \sum_{j=1}^{M-N} CL_{ijk} \]  

(3)

\[ \sum_{i=1}^{N} \sum_{j=1}^{M-N} X_{ijk} \geq \sum_{j=1}^{M-N} CS_{jk} \]  

(4)

Calculate \( X_{ijk} \) and \( X_{iak} \)

Where \( CL_{ik} \) is the lack volume of agricultural product \( k \) in region \( i \) (t); \( CS_{jk} \) is the surplus volume of agricultural product \( k \) in region \( j \) (t).

### 2.2 Crops virtual water trade volume

We use the virtual water volume of import crops in origin area minus virtual water volume of export crops in local area to calculate the virtual water trade volume (VWT) between two regions.

\[ VWT_{ab} = \sum_{k=1}^{n} (X_{abk} \times VWC_{bk} - X_{bak} \times VWC_{ak}) \]  

(3)

Where \( VWT_{ab} \) is the virtual water trade volume from region \( b \) to region \( a \) (m³); \( X_{abk} \) is the import volume of crop \( k \) from region \( b \) to region \( a \) (t); \( VWC_{bk} \) is the virtual water content per unit weight of crop \( k \) in the region \( b \) (m³/t); \( X_{bak} \) is the export volume of crop \( k \) from region \( a \) to region \( b \) (t); \( VWC_{ak} \) is the virtual water content per unit weight of crop \( k \) in region \( a \) (m³/t).

We also use the crops import volume minus the export volume, then multiplied by the corresponding crops virtual water content in local area to calculate the water saving volume.

\[ WS_a = \sum_{k=1}^{n} (\sum_{j=1}^{M-N} X_{ajk} - \sum_{i=1}^{N} X_{iak}) \times VWC_{ak} \]  

(4)
Where $W_{Sa}$ is the water saving of region $a$ (m$^3$); $X_{ajk}$ is the import volume of agricultural product $k$ from region $j$ to region $a$ (t); $X_{ak}$ is the export volume of agricultural product $k$ from region $a$ to region $i$ (t).

2.3 The regions set based on the quantity of water resources

Investigating the status of water resources of the Chinese provinces, autonomous regions and municipalities by querying the water resources bulletin, then all regions are defined as the severe drought regions (quantity of water resources per capita between 0-1000 m$^3$) (SDR), the moderate drought regions (quantity of water resources per capita between 1000-2000 m$^3$) (MDR$^a$), the mild drought regions (quantity of water resources per capita between 2000-3000 m$^3$) (MDR$^b$) and the water rich regions (quantity of water resources per capita above 3000 m$^3$) (WRR).

Table 1. The regions set based on the quantity of water resources

| SDR       | MDR$^a$           | MDR$^b$           | WRR          |
|-----------|-------------------|-------------------|--------------|
| Beijing, Tianjin, Hebei, Henan, Liaoning, Shaanxi, Shandong, Jiangsu, Shanghai, Ningxia | Heilongjiang, Hunan, Sichuan, Guizhou, Jilin, Anhui, Zhejiang | Fujian, Qinghai, Xizang, Xingjiang | Xiangjiang, Jiangxi, Yunnan, Guangxi, Hainan |

2.4 Data

Rice, wheat and maize are three major grain crops in China, accounting for more than 86% of the total grain output [13, 14]. Therefore, this paper takes these three crops as the research objects. The balance data of domestic agricultural products supply and demand is provided by China National Grain and Oil Information Center [15]. The data of agricultural products prices are collected from China price information center and China Price Yearbook [16]. The virtual water content of agricultural products is shown by Sun [17]. The average transportation costs of agricultural products by train is 0.051 yuan / km / t. The distance between regions is the railway distance between provincial capitals.

3. Result and discussion

3.1 Net social revenue maximization

The maximization of net social revenue is achieved by maximizing export earnings and minimizing import expenditures. This scenario reflects the country’s strong self-interest strategy in improving the country’s economic returns.

Based on the spatial equilibrium model, the virtual water flow of agricultural products trade in 2009 is calculated under the net social revenue maximization objective function. Under the net social revenue maximization scenario, the total amount of agricultural products virtual water trade between regions in China was 56.5 billion m$^3$, accounting for 15.2% of total agricultural water consumption in 2009. Through calculation, it’s found that under the net social revenue maximization scenario, China’s agricultural virtual water trade was not conducive to China’s water resource balance. The trade of 9.6 billion m$^3$ of virtual water from the severe drought regions to the moderate drought regions, the mild drought regions and the water rich regions further aggravated the pressure of water resources in the severe drought regions. In addition, through agricultural products inter-regional trade, the water rich regions imported the most virtual water of 8 billion m$^3$ from the severe drought regions, which further aggravated the uneven distribution of water resources in China (Table 2). Under the scenario of net social revenue maximization, the virtual water trade volume of maize was the largest, and the virtual water trade volume of wheat was slightly higher than that of rice.

Table 2. Matrix of virtual water flows of inter-regional agricultural products trade of China in 2009 under net social revenue maximization scenario (10$^7$ m$^3$)

| Region | SDR | MDR$^a$ | MDR$^b$ | WRR | Total | Net Export |
|--------|-----|---------|---------|-----|-------|------------|
|        | SDR | <538.4/-| 9.6/-310.9| 447/-14.2| <37.8/-| 456.6/576.2/325.1 | 957.8 |
|        | MDR$^a$ | <487.5/88.2 | </-372.2 | 330.2/-| <15.8/6/34.8 | 330.0/646.1/495.2 | -156.3 |
Under the net social revenue maximization scenario, this paper analyzes whether there was water-saving benefit in virtual water flow brought by agricultural products trade between regions from the national perspective. Results as shown in Table 3, through regional trade in rice, wheat and maize, 2.8 billion m³, 7.5 billion m³ and 8.3 billion m³ of water were saved at the national scale. To sum up, China's agricultural products virtual water trade among regions, saved 18.6 billion m³ of water in 2009.

The severe drought regions had lost 6.5 billion m³ of water resources, which was the only net export area of water resources in the process of agricultural products virtual water trade between regions in China. The most water-saving regions was water rich regions, with a total water saving of 13.7 billion m³, accounting for 73.5% of the total water-saving in 2009.

Table 3. The water saving by inter-regional agricultural products trade of China in 2009 under net social revenue maximization scenario (10³ m³)

| Region | Import | Export | Water Saving | Total Water Saving |
|--------|--------|--------|--------------|--------------------|
| SDR    | 498.2/779.9/390.9 | -134.7/971.0 | 498.2/565.7/581.0 | -648.5            |
| MDR²   | 339.1/987.6/736.0 | 348.8/188.7/777.5 | -9.7/798.9/41.5 | 747.7            |
| MDR³   | 598.6/472.0/1041.4 | 1385.3/-332.1 | -786.7/472.0/709.5 | 394.6            |
| WRR    | 587.9/280.0/861.7 | -238.3/122.6 | 587.9/417.7/393.1 | 1368.7           |
| China  | 2023.8/2519.5/3003.0 | 1734.1/1771.7/2203.2 | 288.6/746.9/826.0 | 1862.5           |

Through the agricultural products inter-regional trade under the scenario of net social revenue maximization, the net social revenue was 9.1 billion RMB in 2009. Among them, 3.3 billion RMB and 7.7 billion RMB were achieved through inter-regional trade of rice and maize. However, China lost 1.9 billion RMB through inter-regional trade in wheat.

3.2 Water saving maximization

One of the main objectives of virtual water and virtual water trade research is to achieve national water conservation [17, 18]. Under the scenario of water saving maximization, in 2009, the total amount of agricultural products virtual water trade between regions in China was 54.4 billion m³, accounting for 14.6% of China's agricultural water consumption. The severe drought regions, the moderate drought regions and the mild drought regions all traded virtual water to the water rich regions. Compared with the social revenue maximization scenario, the virtual water export in the severe drought regions decreased by 7.7 billion m³, that in the moderate drought regions increased by 5.4 billion m³, and that in the mild drought regions increased by 1.8 billion m³. Water rich regions imported 7.5 billion m³ of virtual water from other regions, reducing imports by 500 million m³. Under the scenario of water saving maximization, the virtual water imported by the water rich regions through the agricultural products inter-regional trade is not conducive to the balance of water resources in China, but it is slightly better than the scenario of net social revenue maximization. Under the scenario of water saving maximization, the virtual water trade volume of Maize in China was the largest in 2009, and the virtual water trade volume of wheat was slightly higher than that of rice.

Table 4. Matrix of virtual water flows of inter-regional agricultural products trade of China in 2009 under water saving maximization scenario (10³ m³)

| Region | SDR 112.8/287.6/44.2 | MDR² 138.3/217.2/144.2 | MDR³ 177.6/-141.3 | MDR³ 75.5/23.4 | WRR 428.7/580.3/353.1 | Total 487.5/682.4/522.4 | Net Export 387.6 |
|--------|----------------------|-------------------------|------------------|---------------|------------------------|--------------------------|----------------|
| MDR²   | 73.9/343.0/64.0      | 90.0/205.9/211.5        | 146.2/-216.7     | -79.5/30.2    | 310.1/628.4/522.4      | 443.6/319.5/742.0        | 177.3          |
| MDR³   | 131.7/156.1/58.5     | 117.8/108.5/248.1       | 194.1/-403.7     | -54.9/31.7    | 443.6/319.5/742.0      | 443.6/319.5/742.0        | 177.3          |
| WRR    | 118.6/79.4/78.0      | 141.9/51.5/173.6        | 202.3/-200.5     | -31.8/37.3    | 462.8/162.7/489.4      | 462.8/162.7/489.4        | -750.6         |
| Total  | 437.0/866.1/244.7    | 488.0/583.1/777.4       | 720.2/-362.2     | -241.7/122.6  | 1645.2/1690.9/2106.9   | 1645.2/1690.9/2106.9     | -1163.9        |

As shown in Table 5, through inter-regional trade in rice, wheat and maize, 4 billion m³, 8.3 billion m³ and 9.2 billion m³ of water were saved at the national scale respectively. Therefore, the virtual water trade of rice, wheat and maize saved 21.5 billion m³ of water for China.

China's agricultural products inter-regional trade under the scenario of water saving maximization saved 2.9 billion m³ more water than that under the scenario of social revenue maximization. Although
the severe drought regions, the moderate drought regions and the mild drought regions all exported virtual water from the perspective of producers. Due to the difference of virtual water content of agricultural products, the four water resource regions all saved water resources. Compared with the scenario of social revenue maximization, the severe drought regions has changed from the net export regions of water resources to the water saving regions, which 7.7 billion m$^3$ of water had been saved. Under the scenario of water saving maximization, 5.1 billion m$^3$ of water had been saved in the moderate drought regions, and 500 million m$^3$ of virtual water had been added in the mild drought regions. The most water-saving regions was water rich area, accounting for 63.1% of the total water-saving in 2009. However, compared with the scenario of social revenue maximization, the water rich regions had lost 100 million m$^3$ of virtual water.

Table 5. The water saving by inter-regional agricultural products trade of China in 2009 under water saving maximization scenario (10$^7$ m$^3$)

| Region | Import | Export | Water Saving | Total Water Saving |
|--------|--------|--------|--------------|--------------------|
| SDR    | 498.2/779.9/390.9 | 437.0/866.1/244.7 | 61.2/86.2/146.2 | 121.2 |
| MDR    | 339.1/987.6/736.0 | 488.0/583.1/777.4 | -148.9/404.5/-41.4 | 241.2 |
| MDR    | 598.6/472.0/1041.4 | 702.2/-962.2 | -103.6/472.0/79.2 | 447.6 |
| WRR    | 587.9/280.0/861.7 | -241.7/122.6 | 587.9/38.3/739.1 | 1356.3 |
| China  | 2023.8/2519.5/3030 | 1627.2/1690.9/2106.9 | 396.6/828.6/923.1 | 2148.3 |

Through the agricultural products inter-regional trade under the scenario of water saving maximization, China’s net social revenue in 2009 was 4 billion RMB. Among them, China achieved a net social revenue of 2 billion RMB and 6.6 billion RMB respectively through inter-regional trade of rice and maize. However, China had a trade deficit of 4.6 billion RMB through inter-regional trade of wheat. Compared with the scenario of net social revenue maximization, under the scenario of the water saving maximization, China’s net social revenue were reduced by 1.3 billion RMB, 2.7 billion RMB and 1.1 billion RMB respectively through rice, wheat and maize trade, with a total of 5.1 billion RMB of net social benefits reduced.

4. Conclusions

Optimizing the trade of agricultural products among regions with the focus on water saving will have a favorable impact on the allocation and utilization of water resources in China. For water resource balance, compared with the scenario of the net social revenue maximization, under the scenario of maximizing water saving, the water loss regions sets changed from only the severe drought regions to the severe drought regions, the moderate drought regions and the mild drought regions. The pressure on water resources in severe drought regions had been greatly reduced. In the case of water saving, under the water saving maximization scenario, China had saved 21.5 billion m$^3$ of water through agricultural products inter-regional trade, accounting for 116% of the net social revenue maximization scenario. But it also brings us other problems. For example, for the net social revenue, under the scenario of social revenue maximization scenario through agricultural products inter-regional trade, the net social revenue was 9.1 billion RMB in 2009. However, under the water saving maximization scenario, the net social revenue was only 5.1 billion RMB under the net social revenue maximization scenario.

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