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Evaluation of Physical and Economic Water-Saving Efficiency for Virtual Water Flows Related to Inter-Regional Crop Trade in China

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Abstract: If products were traded from regions with relatively high water productivity to regions with relatively low water productivity, water saving could be achieved. In this study, two indices—physical water-saving efficiency (volume of water savings per cubic meter of virtual water flows) and economic water-saving efficiency (value of water savings per cubic meter of virtual water flows considering water right trading)—were proposed to analyze the efficiency of inter-regional virtual water flows related to crop trade in China. Results indicated that the volume of inter-regional virtual water flows was 1.61×10^9 m^3, more than 90% of which was occupied by oil-bearing crops, cereals, and beans. In terms of physical efficiency, only cereals and vegetables presented negative values. All kinds of crop trades were economically efficient, while most crops' economic water-saving efficiency was less than 10×10^3 Yuan/m^3. The application of advanced water-saving technologies, the cultivation of new crop varieties, the adjustment of regional cropping patterns, or consumption and trade patterns, could contribute to more water savings and higher physical water-saving efficiency, while the possible social, economic, and environmental tradeoffs should be considered simultaneously. Water right trading and virtual water compensation could contribute to sustainable water consumption, and full-cost pricing should be adapted in the future.

Keywords: physical water-saving efficiency; economic water-saving efficiency; water saving; virtual water; crops; China

1. Introduction

As water shortages have become more and more severe due to the increasing population, changing climate, and other factors, the improvement of water efficiency has been promoted frequently and many different water efficiency indicators/indices have been introduced. In agricultural production systems, irrigation efficiency (classical irrigation efficiency [1], net or effective irrigation efficiency [2]) and water productivity (crop water productivity [3], water use efficiency [4], generalized water productivity [5], gross inflow water productivity [6], irrigation water productivity [7], and rain-fed water productivity [8]) are currently used to evaluate water use efficiency. In 2002, the concept of a water footprint was proposed. The water footprint of a product is the volume of freshwater used to produce the product, measured over the full supply chain, and the water footprint per mass of product is used to show the efficiency of water use for different sectors [9]. People can obtain products with greater diversity and quantity than before with the help of trades, and virtual water embedded in traded products flows among regions [10–12]. To evaluate the water efficiency associated with product trades, or the efficiency of virtual water flows, the concept of "water saving" was proposed. Water saving is calculated as the difference between the actual water consumption for imported products and the assumed water consumption if these imported products were produced locally [13]. Virtual water flows are efficient if products are traded from regions with relatively high water productivity to regions with relatively low water productivity, in which case a positive water saving can be achieved; otherwise, virtual water flows are inefficient and a negative water saving, i.e., a water loss, would result [9,13]. A large amount of research has been conducted on water savings on different scales, such as the global scale [14], inter-regional scale [15,16], country scale [17–19], and irrigation district scale [20]. Besides these studies, Zhao et al. assessed scarce water saving through interprovincial trade within China, for which water scarcity status was considered [21]. The value of water saving is usually affected by trade volume and virtual water efficiency for different scales, which is difficult to compare only with the water saving index. Thus, a physical water-saving efficiency was proposed to show the volume of water savings per cubic meter of virtual water flow. Recently, the role of economic factors in determining virtual water flows has been explored by scholars, while few studies have shown the economic efficiency of virtual water flows [22,23]. Only a combination of different perspectives can provide a complete picture of regional water efficiency evaluation.

In this study, two indices are proposed to analyze the physical and economic efficiency of water savings due to virtual water flows. Firstly, we estimated the virtual water flows related to crop trades in China and the related water savings. Then, the physical water-saving efficiency (the volume of water savings for per cubic meter of a virtual water flow) and economic water-saving efficiency (the value of water savings for per cubic meter of a virtual water flow when considering water right trading) were evaluated. This study could be beneficial for the analysis of regional water saving and contribute to the improvement of regional production and trade patterns.

2. Materials and Methods

2.1. Methods

In this study, seven kinds of crops—cereals, beans, tubers, oil-bearing crops, sugar crops, vegetables, and fruits—were studied for the virtual water flows, which were the product of crop virtual water content and trade volume. The virtual water content refers to the water required for the production of commodities per unit of mass (m^3/kg), and was derived from the research of Mekonnen and Hoekstra [24]. The trade volume was calculated based on the surpluses and deficits method [25–27]:

$$\text{If } P_i \geq C_i, \quad \text{then} \begin{cases} E_i = P_i - C_i \\ I_i = 0 \end{cases} \tag{1}$$

$$\text{If } P_i < C_i, \quad \text{then} \begin{cases} E_i = 0 \\ I_i = C_i - P_i \end{cases} \tag{2}$$

where P_i and C_i are the production and consumption volumes for crop i (kg), respectively, and E_i and I_i are the export and import volumes for crop i (kg), respectively.

If crops are exported from a province with relatively low virtual water content to a province with relatively high virtual water content, a positive national water saving occurs, indicating that the trade was efficient from the perspective of water consumption. Otherwise, a negative water saving would result, showing that the trade was inefficient. The value of water saving can be calculated as follows [9]:

$$WS = \sum_{i=1}^{n} (VWC_i^{imp} - VWC_i^{exp}) \times T_i \tag{3}$$

where WS is the national water saving due to crop trade (m^3); VWC_i^{imp} and VWC_i^{exp} are virtual water contents (in m^3/kg) for crop i in crop importing and exporting regions, respectively; T_i is the trade volume for crop i (kg); and n is the number of crop types.

To compare the water efficiency for different regions from physical and economic perspectives, especially for those at different scales, two indices—physical water-saving efficiency and economic water-saving efficiency—were proposed. Physical water-saving efficiency can demonstrate the volume of water savings per cubic meter of a virtual water flow, which is similar to the definition of irrigation efficiency in agricultural production systems [1,28,29]. The physical water-saving efficiency was calculated as follows:

$$\mathrm{PWSE} = \frac{\mathrm{WS}}{\mathrm{VWF}} \quad (4)$$

where PWSE is the physical water-saving efficiency and VWF is the volume of inter-regional virtual water flows (m^3). A region with a relatively high physical water-saving efficiency can achieve more water saving than a region with a relatively low physical water-saving efficiency when the volumes of virtual water flows are the same.

The economic value of water in the agricultural sector was usually much lower than that of other sectors, especially the industrial sector. We assumed that if the water consumed in the production of traded crops was consumed by the industrial sector, the obtained economic value would be the ideal value of these water resources. In China, water right trading has been tried by the Yellow River rural farmers, in which case water saved from agriculture was used to meet industrial production demands; a similar case can also be found in Australia [22,23]. Thus, the economic water-saving efficiency was calculated as follows:

$$\mathrm{EWSE} = \frac{\sum_{i=1}^{n} \left(VWC_i^{imp} \times \mathrm{T_i} \times \mathrm{V^{imp}} - VWC_i^{exp} \times \mathrm{T_i} \times \mathrm{V^{exp}} \right)}{\mathrm{VWF}} \quad (5)$$

where EWSE is the economical water-saving efficiency (Yuan/m^3) and V^{imp} and V^{exp} are the economic value in industrial sectors per unit volume of water consumption in crop importing and exporting regions, respectively (Yuan/m^3). The economic water-saving efficiency could demonstrate the value of water savings, considering water right trading per cubic meter of virtual water flow. A region with a relatively high economic water-saving efficiency could generate more economic value than a region with a relatively low economic water-saving efficiency when the volumes of virtual water flows are the same.

The economic value in industrial sectors per unit volume of water consumption (V, Yuan/m^3) was calculated as follows:

$$\mathrm{V} = \frac{\mathrm{V_{tot}}}{\mathrm{WW} \times \alpha} \quad (6)$$

where V_{tot} is the total economic value in the industrial sector (Yuan), WW is the industrial water withdrawals (m^3), and α is the industrial water consumption ratio (the proportion of industrial water consumption to industrial water withdrawal) [30–32], which is mainly influenced by industry structure and applied water-saving technologies [9,33].

2.2. Data Sources

Data on crop output and consumption and total economic value in the industrial sector were obtained from the Statistical Yearbook of China and the Agricultural Statistical Data of China [34,35]. Data on water withdrawals and water consumption ratios were obtained from the China Water Resources Bulletin and the Water Resources Bulletin for provinces [36].

3. Results

3.1. Virtual Water Flows and Water Savings

Table 1 shows the virtual water flows related to the trade of different kinds of crops. As China is an important cereal-producing country, only five of its provinces imported virtual water due to cereal trade. The largest importer, Shanghai Province, accounted for 54.14% of the total virtual water imports, while the largest exporter, Heilongjiang Province, accounted for about 13.41% of virtual water exports. For beans, about two thirds of the provinces had a virtual water import, and the value imported by the largest importer, Guangdong Province, was 31.47 times that imported by the smallest importer (Ningxia). The virtual water imports related to oil-bearing crops were mainly dominated by Zhejiang, Guangdong, and Heilongjiang Provinces, and the virtual water exports were mainly dominated by Inner Mongolia, Henan, and Hubei Provinces. The fruit needs of nearly all regions could be met locally, excluding Shanghai, Beijing, Tianjin, Qinghai, and Tibet. Compared with the abovementioned crops, the values of virtual water flows related to tubers, sugar, and vegetables were much smaller. About two thirds of the provinces had a virtual water import related to inter-regional sugar crops, while Beijing was the only province with virtual water imports related to vegetables. Taking all kinds of crops together, about 60% of virtual water exports were due to the exports in Inner Mongolia, Henan, Anhui, and Xinjiang Provinces, while the imports in Shanghai, Beijing, and Guangdong Provinces accounted for 72.95% of the total virtual water imports.

Due to differences in crop water productivity, a positive or negative water saving could result, as shown in Table 2. Oil-bearing crops were the crops with the largest water saving, while the values for fruits and tubers were much smaller, amounting to 2.04% and 1.13% of the value for oil-bearing crops, respectively. Unlike other crops, the trades of cereals and vegetables resulted in a negative water saving, indicating that the trades were inefficient from the perspective of water productivity. Taking all kinds of crops together, a positive water saving of 1.37×10^9 m^3 was obtained.

Table 1. Virtual water flows related to crop trade in China.

Provinces	Cereals (10^6 m^3)	Beans (10^6 m^3)	Tubers (10^6 m^3)	Oil-Bearing Crops (10^6 m^3)	Sugar Crops (10^6 m^3)	Fruits (10^6 m^3)	Vegetables (10^6 m^3)	Virtual Water Exports Related to Crop Trade (10^6 m^3)	Virtual Water Imports Related to Crop Trade (10^6 m^3)
Anhui	32.23	50.13	0.01	68.66	−1.75	0.80	0.01	151.84	−1.75
Beijing	−167.33	−13.42	−0.22	−38.98	−0.45	−42.80	−0.73	0.00	−263.93
Chongqing	5.97	18.16	0.07	−22.36	−1.95	1.65	0.01	25.87	−24.31
Fujian	0.39	−6.14	0.01	−29.99	−0.23	0.20	0.00	0.59	−36.36
Gansu	9.75	13.62	0.04	0.34	−0.64	0.87	0.03	24.65	−0.64
Guangdong	−74.13	−66.08	0.00	−74.14	1.82	0.18	0.00	2.00	−214.35
Guangxi	7.31	−19.99	0.00	−5.94	4.35	0.26	0.00	11.92	−25.93
Guizhou	3.13	0.54	0.00	8.14	1.54	0.08	0.00	13.43	0.00
Hainan	1.36	−4.04	0.00	−1.27	0.34	0.04	0.00	1.74	−5.31
Hebei	43.49	−33.92	0.10	−5.27	0.08	6.64	0.12	50.44	−39.20
Heilongjiang	74.03	85.11	0.05	−74.04	−1.35	0.20	0.00	159.39	−75.39
Henan	53.46	−20.24	0.03	128.33	−2.18	4.96	0.03	186.81	−22.42
Hubei	25.57	−16.36	0.01	77.23	−0.37	0.01	0.00	102.82	−16.72
Hunan	13.01	−30.11	0.01	58.92	−1.11	0.14	0.01	72.09	−31.22
Inner Mongolia	29.68	85.63	0.10	142.71	0.79	3.78	0.06	262.75	0.00
Jiangsu	49.19	13.54	0.02	−58.59	−1.97	0.69	0.02	63.45	−60.56
Jiangxi	7.84	−8.58	0.02	−1.39	0.18	0.54	0.00	8.59	−9.97
Jilin	23.38	18.23	0.04	17.42	−0.74	0.39	0.00	59.46	−0.74
Liaoning	19.39	−9.14	0.02	−48.11	−1.31	0.93	0.01	20.36	−58.56
Ningxia	7.11	−2.10	0.02	1.30	−0.21	3.11	0.02	11.55	−2.31
Qinghai	−6.37	3.22	0.02	9.53	−0.20	−10.05	0.00	12.78	−16.63
Shaanxi	5.16	−9.99	0.01	−21.65	−0.88	0.50	0.00	5.67	−32.52
Shandong	56.57	−42.47	0.10	54.28	−2.28	7.03	0.06	118.03	−44.75
Shanghai	−298.88	−16.99	−0.31	−38.04	−0.85	−45.09	0.00	0.00	−400.16
Shanxi	6.24	2.08	0.01	−37.46	−0.68	1.56	0.01	9.90	−38.14
Sichuan	19.57	6.77	0.00	4.33	−2.13	0.04	0.00	30.71	−2.13
Tianjin	−5.33	−12.79	−0.23	−28.59	−0.52	−35.19	0.00	0.00	−82.64
Tibet	0.07	−4.01	−0.07	−0.61	−0.27	−0.27	0.00	0.07	−5.22
Xinjiang	50.08	−5.12	0.09	−7.24	1.66	97.73	0.33	149.88	−12.36
Yunnan	8.06	32.15	0.01	0.13	11.35	1.04	0.00	52.74	0.00
Zhejiang	0.04	−7.69	0.01	−77.65	−0.07	0.04	0.00	0.10	−85.42
National virtual water exports	552.05	329.19	0.83	571.30	22.12	133.40	0.73	1609.62	
National virtual water imports	−552.05	−329.19	−0.83	−571.30	−22.12	−133.40	−0.73		−1609.62

Note: the negative values mean virtual water import, while the positive values mean virtual water export.

Table 2. Water savings related to crop trade in China, physical water-saving efficiency, and economic water-saving efficiency.

Crops	Water Savings (10^6 m^3)	Physical Water-Saving Efficiency (m^3/ m^3)	Economic Water-Saving Efficiency (10^3 Yuan/m^3)
Cereals	−43.58	−0.08	0.92
Beans	553.76	1.68	6.93
Tubers	7.83	9.48	44.78
Oil-bearing crops	691.86	1.21	3.75
Sugar crops	146.25	6.61	13.42
Fruits	14.11	0.11	3.50
Vegetables	−0.10	−0.13	2.11
All kinds of crops	**1370.13**	**0.85**	**3.56**

3.2. Physical Water-Saving Efficiency

As can be seen from Table 2, the physical water-saving efficiency of tubers was the highest, with a value of 9.48 m^3/m^3, indicating that 9.48 m^3 of water resources could be saved per cubic meter due to the inter-regional virtual water flows related to the tuber trade. Sugar crops occupied second place. Compared with these two kinds of crops, the physical water-saving efficiency for beans, oil-bearing crops, and fruits was much lower, with the value for fruits being less than 10% of that for tubers. For cereals and vegetables, the situations were different. Considering that inter-regional virtual water flows occur due to all kinds of crop trades, 0.85 m^3 of water resources could be saved per cubic meter.

3.3. Economic Water-Saving Efficiency

All kinds of crops presented a positive economic water-saving efficiency value, which means that the water saving due to the inter-regional virtual water flows of China was efficient in terms of economic values (Table 2). As with the physical water-saving efficiency, the value of the economic water-saving efficiency for tubers was the largest, and sugar crops took second place. For the rest of the crops, no more than 10×10^3 Yuan of economic value could be obtained per cubic meter inter-regional virtual water flows. The economic water-saving efficiency of cereals was the lowest, amounting to only 2% of the value for tubers. Considering all kinds of crops, the economic water-saving efficiency was 3.56×10^3 Yuan/ m^3.

4. Discussion

Virtual water adds a new dimension to product trade, while the meaning of virtual water flows is scale-dependent [20]. For a certain region, more water consumption and severe water scarcity can be seen when it exports virtual water, while less water consumption occurs if it is a virtual water importer [13,25,27,37]. Wang et al. showed the role of virtual water trades on China's water security [38]. On a larger scale, including both exporting and importing regions, the concept of "water saving" can show the differences in water productivity among regions, indicate whether water is used efficiently, and give a more comprehensive picture for water management [13,25,39]. Physical water efficiency is the focus of many scholars, and economic values have played an increasingly significant role in water management [8,22,23]; thus, the water efficiency for water savings from both the physical and economic perspective were analyzed in this study.

The volume of inter-regional virtual water flows related to crop trade in China was 1.61×10^9 m^3, more than 90% of which was occupied by oil-bearing crops, cereals, and beans. The adjustment of crop-producing and crop-exporting provinces from regions with relatively low water productivity to those with relatively high water productivity, especially for the three kinds of crop mentioned above, could provide a way to achieve higher national water savings and a higher physical water-saving efficiency. Taking oil-bearing crops as an example, if all the oil-bearing crops exported from Henan (the largest producing and exporting region) were supplied by Guizhou, where water productivity was 1.70 times higher than in Henan, then the water savings related to the oil-bearing crop trade and physical water-saving efficiency would be 744.70×10^6 m^3 and 1.43 m^3/m^3, respectively, indicating an increase of 7.64% and 18.08% compared with the actual situation. However, water consumption in Guizhou could result in more environmental impacts compared with Henan [40]. For instance, the impact of water consumption on human health and on ecosystem quality in Guizhou would be 2.17 times and 2.91 times the current values, respectively, considering the adjustment for the producing regions of oil-bearing crops mentioned above. Furthermore, the application of advanced water-saving technologies, the cultivation of new crop varieties which require less water for their growth, and the adjustment of regional cropping patterns or consumption patterns from water-intensive crops to less water-intensive ones could contribute to more water savings and a higher physical water-saving efficiency. However, the possible social, economic, and environmental tradeoffs should be considered simultaneously before adjustment measures are taken [41–44].

Virtual water flows related to product trade were not only influenced by regional water resources but also affected by other factors, especially economic factors, due to the fact that the virtual water flows were the result of regional product trade [45–47]. Thus not only the physical perspective but also the economic perspective should be included for the analysis of regional water resource use. Tradable water rights help farmers in water-scarce regions to act flexibly when facing high fluctuations in water availability and to use water in a sustainable and environmentally friendly manner [22,23]. Compensation for virtual water exports related to crop trade was also promoted for sustainable water consumption [23,44,48]. According to the results of this study, crop trade was economically efficient, while most crops' economic water-saving efficiency was less than 10×10^3 Yuan/m^3. In the future, more efforts to reflect water value, such as full-cost pricing (including operation and maintenance costs, capital costs, opportunity costs, scarcity rents, and external costs of water use), which has received worldwide acknowledgment, and the adjustment of regional production, consumption, and trade patterns mentioned above, should be encouraged [49–51].

Climate change could influence regional virtual water flows and water savings. For example, Konar et al. found that the staple food trade is projected to save more water across most climate change scenarios for the year 2030, largely because the wheat trade reorganizes into a structure where large quantities of wheat are traded from relatively water-efficient exporters to less efficient importers [52]. Konar et al. evaluated the direct impacts of climate change and trade liberalization together and in isolation [53]. In our future research, the impacts of climate change should be included. Only crops were considered in this study, which was mainly due to the data availability; however, more kinds of products should be studied in the future to obtain a more complete picture for regional water management. Additionally, the efficiency of virtual water flows should be measured from many different perspectives in the future, and not restricted to the physical and economic fields we mentioned.

5. Conclusions

In this study, two indices (physical water-saving efficiency and economic water-saving efficiency) were proposed to analyze the efficiency of water savings due to inter-regional virtual water flows related to crop trade in China. The following conclusions could be drawn:

The volume of inter-regional virtual water flows related to crop trade in China was 1.61×10^9 m^3, more than 90% of which was occupied by oil-bearing crops, cereals, and beans. Only the inter-regional trades for cereals and vegetables resulted in negative water savings, indicating that their trade pattern is inefficient in terms of water productivity. The application of advanced water-saving technologies, the cultivation of new crop varieties, the adjustment of regional cropping patterns, or consumption and trade patterns could contribute to more water savings and a higher physical water-saving efficiency; however, the possible social, economic, and environmental tradeoffs should be considered simultaneously.

In terms of physical efficiency, only cereals and vegetables presented negative values, which were consistent with the situation for water savings. The trade of all kinds of crops was economically efficient, while most crops' economic water-saving efficiency was less than 10×10^3 Yuan/m^3. Water right trading and compensation for virtual water exports could contribute to sustainable water consumption. In the future, more efforts to reflect water value, such as full-cost pricing and the adjustment of regional production, consumption, and trade patterns, should be adapted.

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