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Embodied agricultural water use in China from 1997 to 2010

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Abstract

Water is an important element in agricultural production. The recent population growth, rapid urbanization, and fast industrialization present increasing challenges for China's agricultural water use. Embodied water has been promoted as a substantial indicator for the assessment of water consumption induced by human activities. However, few studies have investigated the dynamic change in embodied agricultural water use by time-series data. The findings of such studies may facilitate the development of comprehensive sustainable water-usage strategies. Thus, this study quantifies the embodied agricultural water trade, as well as production- and consumption-based agricultural water footprints in China by using an input–output model during 1997–2010. According to the results, China's average embodied agricultural water intensity shows a declining trend from 43.33 m^3/thousand Yuan in 1997 to 32.66 m^3/thousand Yuan in 2010. The average embodied agricultural water intensity of the primary industry is larger than those of the secondary and tertiary industries. China has always been a net exporter of agricultural water. At the industrial level, the primary industry is a net importer because of the increasing food demand in China, the secondary industry has consistently been a net exporter, and the tertiary industry has maintained a trade balance. The production- and consumption-based

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embodied agricultural water uses demonstrate similar changing trends: both decrease from 1997 to 2007 and then significantly increase in 2010. The embodied agricultural water consumed by the primary industry shows a downward trend, whereas those consumed by the secondary and tertiary industries demonstrate an opposite trend. Therefore, in addition to the improvement of agricultural water efficiency, adjustments in consumption and trade structure are highly instrumental to the conservation of local agricultural water resources.

Key Words: Agricultural water use, virtual water flow, input–output analysis, international trade, China

Highlights:

1. Introduction

China feeds 21% of the world's population with only 6.5% of the world's freshwater (UNOHCHR, 2010). The country's per capita natural freshwater availability is reduced to less than 2000 m^3/year and its available water resources are predicted to be fully exploited by 2030 (CWR, 2010). Owing to water scarcity, the effective use of water resources has significant importance in achieving sustainable development (Liu and Yang, 2010; Oki and Kanae, 2006). Water is a fundamental element in agricultural production. As the most water-intensive industry, agriculture accounts for 70% of the total freshwater consumption (Molden, 2007). Moreover, the agricultural water requirements of China will greatly increase with increasing food demand caused by the growing population, rapid urbanization, and fast industrialization. To protect China's agricultural water resources, the Chinese Government imposed in 2010 the "three red line" restriction policy to achieve efficient control of water quantity, efficiency, and quality. The irrigation water use efficiency of 60% is targeted by 2030

(State Council, 2012). The manner of implementing sustainable water use into the government's strategy to secure the future water supply of China has become a key scientific problem.

A comprehensive understanding of water use is the indispensable foundation for developing an effective water management strategy. Virtual water is a useful concept for understanding the total (including direct and indirect) water consumption (Allan, 1993). Interchangeable with "embodied water" and "exogenous water", this concept refers to the total water required for the whole production process of goods or services (Hoekstra, 2003; Wang et al., 2013). Input–output (IO) analysis (IOA), as a top-down method, has been widely applied in the field of virtual water accounting (Dietzenbacher and Velázquez, 2007; Wang et al., 2013). IOA provides a quantitative solution to represent the virtual water flows accompanied by monetary transactions for goods or services in an interconnected and interdependent economy (Costanza, 1980). Most studies on virtual water are related to food production due to its very large proportion of total water consumption (Spiess, 2014; Vanham, 2013; Wang et al., 2014a; Wang et al., 2014b; Wichelns, 2001). These findings provided a host of valuable policy recommendations to address issues of water scarcity and food security. Considering China's situation, virtual water studies have flourished recently and the research scope has been widely extended to various scales, that is , country (Guan and Hubacek, 2007; Zhang and Anadon, 2014), region (Wang et al., 2013), river (Chen et al., 2009; Feng et al., 2012), project (Meng et al., 2014; Shao and Chen, 2013) and product (Tian, 2013). As regards China's agricultural water utilization, the water footprints of various agricultural products in China, such as grain products (Huang et al., 2014) and milk products (Wang et al., 2014a), have been widely estimated. However, studies on the total embodied agricultural water use in China are still lacking. Few studies have investigated the dynamic changes in the embodied agricultural water use in China, an understanding of which may facilitate the development of a sustainable agricultural water-usage strategy in China.

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To fill the research gap, this study presents an embodiment analysis of China's virtual agricultural water use through time-series IO data during the period of 1997–2010. Temporal changes in agricultural water use efficiency, agricultural water trade pattern, and production- versus consumption-based agricultural water use are specifically calculated and analyzed in this study. The rest of the paper is organized as follows. Section 2 elaborates on the IOA method and the latest available economic and environmental data sources. Section 3 presents the analysis results on China's embodied agricultural water use during 1997–2010. Section 4 discusses some key issues associated with China's virtual agricultural water use. Finally, Section 5 concludes.

2. Method and Data Sources

Economic globalization has rendered international trade an important way to balance water resource deficit and surplus through resource transfer accompanied by the flows of commodities or services. IOA is a useful method to integrate agricultural water resources into the economic network to reveal water resource flows in/out the concerned economy (Costanza, 1980; Guo et al., 2014). Depending on the research scope, relevant studies can be categorized as single regional IOA (SRIO) and multi-regional IOA (MRIO). SRIO not only clarifies how water resources are assigned to final consumption but also determines the sources and destinations of virtual water flows. Currently, SRIO has been widely employed at national and regional levels (Chen and Chen, 2015; Duarte et al., 2002; Guo et al., 2012; Lenzen and Foran, 2001; Mubako et al., 2013). MRIO provides an analysis of virtual water flows not only in different sectors but also in various regions (Guo and Shen, 2014; Wiedmann, 2009). Studies focusing on interregional virtual water flows have been conducted by many researchers (Ewing et al., 2012; Wang et al., 2009; Zhang and

Anadon, 2014; Zhang et al., 2011a). In the time-series analysis of virtual water flows within a targeted region, SRIO is applicable for discussing the changing trend of virtual water flows. In this study, China's embodied agricultural water flows during 1997–2010 are estimated by using SRIO. The detailed algorithm and data sources are described in this section.

2.1 Algorithm

To calculate and compare the virtual water flows accompanied by various economic activities, such as production, consumption, and trade activities, an ecological IO table (Table 1) whose origin dates back to Odum's ecological and general systems theory (Odum, 1983, 2000) is established. This table is composed of two parts, namely, the traditional economic IO table and the direct sectoral agricultural water use table.

Table 1

Basic structure of the ecological IO table for agricultural water (revised from Chen et al. (2010)).

Output / Input		Intermediate use				Final consumption	Export	Total output
		Sector 1	Sector 2	…	Sector *n*			
Intermediate input	Sector 1	z_{11}	…		z_{1n}	f_1	e_{x1}	x_1
	Sector 2	⋮	…		⋮	⋮	⋮	⋮

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	…						
	Sector *n*	z_{n1}	…	z_{nn}	f_n	e_{xn}	x_n
Direct agricultural water use		w_1	…	w_n			

On the basis of the sectoral biophysical balance and IO model, the virtual water flow process within the economic network can be described as follows: water resources are directly incorporated into agricultural production activities and are then entered into the interconnected and interdependent economy in the form of virtual water flows hidden in agricultural products. To quantify virtual water flows in various economic activities, embodied agricultural water intensity is first proposed and defined as the sum of direct and indirect agricultural water use in the whole supply chain to produce the per unit monetary value of targeted commodities or services (Yang et al., 2013). Embodied agricultural water flows in economic activities are obtained as the product of economic values and corresponding embodied agricultural water intensities.

(1) Embodied agricultural water intensity

The sectoral biophysical balance for the embodied agricultural water flows can be formulated as follows:

$$\varepsilon_j x_j = \sum_{i=1}^{n} \varepsilon_j z_{ij} + w_j , \tag{1}$$

where

ε_j is the embodied agricultural water intensity of commodities or services from Sector j,

x_j represents the economic value of total output from Sector j,

z_{ij} is the economic value of intermediate inputs from Sector i to Sector j, and

w_j stands for the direct agricultural water use by Sector j.

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For all sectors in the whole economy, Eq. (1) can be deduced in matrix form as follows:

$$EX = EZ + W, \quad (2)$$

where

$W = [w_j]_{1\times n}$ is the direct agricultural water use matrix,

$E = [\varepsilon_j]_{1\times n}$, the embodied agricultural water intensity matrix,

$Z = [z_{ij}]_{n\times n}$, the intermediate input matrix, and

$X = [x_{ij}]_{n\times n}$ the total outputs matrix, where $i, j \in (1, 2, ..., n)$, $x_{ij} = x_j (i = j)$ and $x_{ij} = 0 (i \neq j)$.

Finally, the embodied agricultural water intensity matrix E can be expressed as follows:

$$E = W(X - Z)^{-1}. \quad (3)$$

(2) Embodied agricultural water flows

The transfer of agricultural water resource flows is driven by domestic and international trade, which has a significant function in redistributing water resources accompanied by commodity flows. In agricultural water management within modern commodity economy, the balance of regional water demand and supply, as well as water resource deficit and surplus, needs to be thoroughly understood. Embodied agricultural water in trade balance (EWB) is an important indicator to assess the regional water trading status.

EWB can be expressed as the difference between agricultural water embodied in exports and imports:

$$EWB_j = \varepsilon_j E_{xj} - \varepsilon_j I_{mj}, \tag{4}$$

where

E_x stands for the economic value of export to other regions, and

I_m denotes the imports from other regions.

To clarify environmental responsibility, this paper compares agricultural water use in production and consumption. The production-based accounting principle focuses on the actual water use for agricultural production within the targeted region. On the contrary, the consumption-based accounting principle is concerned with the agricultural water consumed as final demand within this targeted region. These two principles differ from the responsible subject, that is, whether the “producer” or “consumer” should be responsible for protecting the agricultural water resources within the targeted region.

Production-based agricultural water use (*EWP*) is equal to the direct agricultural water use (Chen and Zhang, 2010), which is expressed as follows:

$$EWP_j = L_j, \tag{5}$$

Consumption-based agricultural water use (*EWC*) is the agricultural water embodied in the whole supply chain of communities consumed as final demand within a country.

$$EWC_j = \varepsilon_j F_j , \tag{6}$$

where F_j is the final consumption from Sector *j*.

2.2 Data sources

To analyze the virtual agricultural water flows with the use of IOA, two types of data sources are needed, that is, environmental and economic data. Environmental data consist of the annual agricultural water-usage data, and economic data include the national economic IO data. These data can be obtained from official statistics in China.

With regard to environmental data, China's Ministry of Water Resources has released the agricultural water use data yearly since 1997 in China's Water Resources Bulletin, and the latest version has been updated to 2012. According to the statistics, water resource utilization can be classified as agricultural water, industrial water, household and service water, and eco-environment water. The agricultural water use in China ranges from 378.03 billion m^3 to 304.61 billion m^3, accounting for 70.42%–61.26% of the total water use during 1997–2010.

As regards economic data, national IO tables are able to present the interdependencies and interconnection among different industries. In China, national standard IO tables have been compiled every five years since 1987, and the extended tables are published every five years starting from 1992. Thus, 10 IO tables, i.e., tables for 1987, 1990, 1992, 1995, 1997, 2000, 2002, 2005, 2007, and 2010, have been compiled up to the present.

Time-sequence studies are difficult in terms of collecting data because of the required large dataset. The year of agricultural water use data must match the year of economic IO data. Considering the availability of agricultural water use data and economic data, this study covers the period of 1997–2010. Prolonged time-series comparison is conducted in this study. GDP deflators (Table 2) are employed to adjust price levels on the basis of price inflation/deflation from the base year of 1997.

Table 2

GDP deflators during 1997–2010 (calculated from CSY (2012)).

Year	1997	2000	2002	2005	2007	2010
GDP deflator	100.00	125.83	148.67	200.43	257.82	340.95

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3. Results

3.1 Temporal change in agricultural water use efficiency

The trend of agricultural water use efficiency, expressed as the embodied agricultural water intensity, during 1997–2010 is illustrated in Fig. 1. The average embodied agricultural water intensity during 1997–2007 shows a downward trend, declining from 43.33 m^3/thousand Yuan to 32.50 m^3/thousand Yuan. Thereafter, the average embodied agricultural water intensity then experiences a smooth trend at 32.66 m^3/thousand Yuan. The exponential trend line is simulated with a high goodness of fit as represented by a high R^2 value of 0.9523. The fact that embodied agricultural water use per economic output continues to decrease shows China's effort and effectiveness in improving agricultural water use efficiency through various measures such as technical development, effective water policy making, and industrial and trade structure adjustments. The average annual decrement rate has been declining from 0.89 m^3/thousand Yuan to 1.36 m^3/thousand Yuan during 1997–2007, thus showing the great potential of increasing efficiency to conserve agricultural water. Therefore, China should devote effort into developing an integrated agricultural water use management mode to combine modern agricultural production or irrigation technology and optimal economic structure.

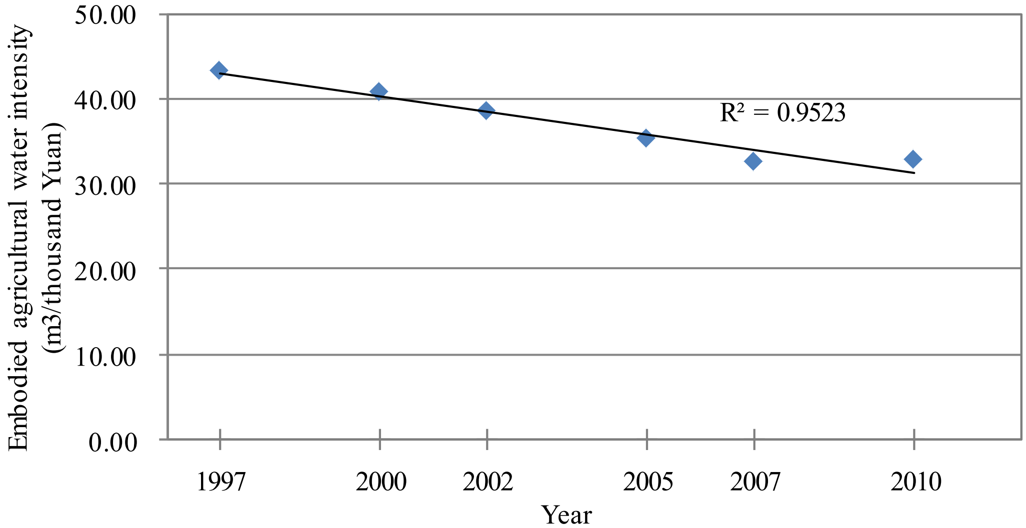

Fig. 1. Embodied agricultural water intensity, 1997-2010.

The industrial structure evolution, as an inevitable economic development outcome, has an extremely significant influence on regional water resource balance. Fig. 2 shows China's embodied agricultural water intensities from the perspective of industrial structure. By comparison, the embodied agricultural water intensities of three major industries all demonstrate a slight increase albeit a fluctuating trend. The average embodied agricultural water intensity of the primary industry increases from 200.65 m^3/thousand Yuan in 1997 to 241.23 m^3/thousand Yuan in 2002, and then decreases to 226.64 m^3/thousand Yuan in 2010. By contrast, the average embodied intensities of the secondary and tertiary industries over the years are quite small compared with that of the primary industry. The average embodied agricultural water intensity of the secondary industry decreases from 23.92 m^3/thousand Yuan in 1997 to 21.42 m^3/thousand Yuan in 2002, and finally increases to 23.90 m^3/thousand Yuan in 2010. For the tertiary industry, the embodied agricultural water intensity experiences a long-term fluctuation. The lowest intensity is 11.73 m^3/thousand Yuan in 2002, whereas the highest intensity is 13.86 m^3/thousand Yuan in 2010. In the inter-industry comparison, the embodied agricultural water intensity of the primary industry is

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higher than those of the secondary and tertiary industries, thus proving that industrial structure adjustment is important for the reasonable use of agricultural water resources.

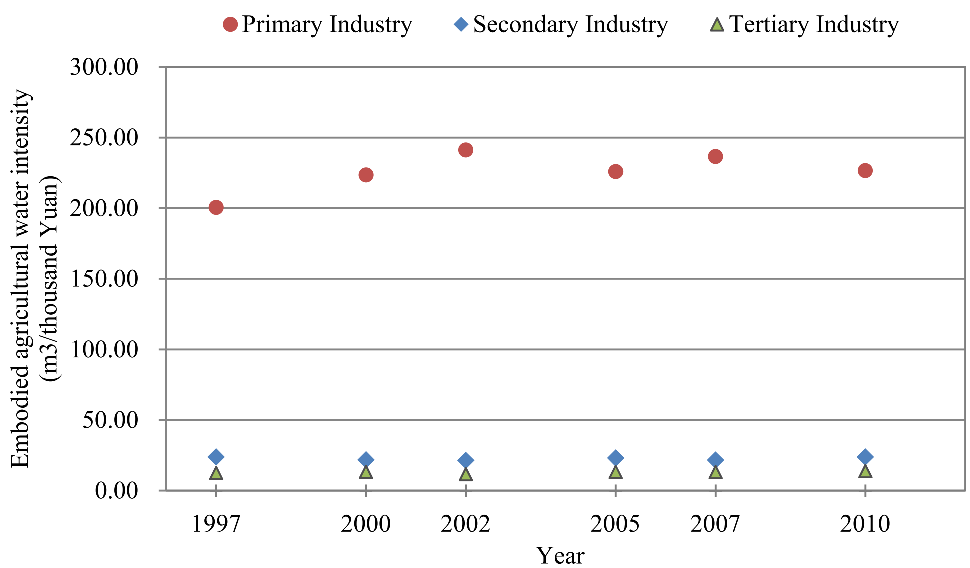

Fig. 2. Embodied agricultural water intensity of three major industries, 1997–2010.

3.2 Temporal change in agricultural water trade pattern

China has always been a net exporter of agricultural water during the study period (Fig. 3), thus demonstrating that China significantly contributes to the global agricultural water use. At the country level, the United States, China, India, Brazil, and Argentina are the largest virtual water exporters in the world (Hoekstra and Mekonnen, 2012). Currently, the extent of water scarcity and the degree dependence on other regions for water resources have not been considered in the imposition and reform of water price. However, production and trade patterns have a considerable effect on the regional water utilization in the modern economy. The embodied agricultural water in net export is approximately 15 million m^3, which has a relatively stable state during 1997–2005. The maximum EWB, 23.69 million m^3, is in 2007, whereas the minimum EWB is 3.45 million m^3 in 2010. The continuing decline of

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EWB can be attributed to changes in trade policy and adjustments in economic structures. In recent decades, the export product structure has changed from traditional light industry and textiles to high-tech products. As the embodied agricultural water intensity of the light industry is higher than that of the high-tech industry, the trading policy prevents substantial water transfer in the form of water-intensive products to other trading partners. Such a policy supports the protection of local water resources.

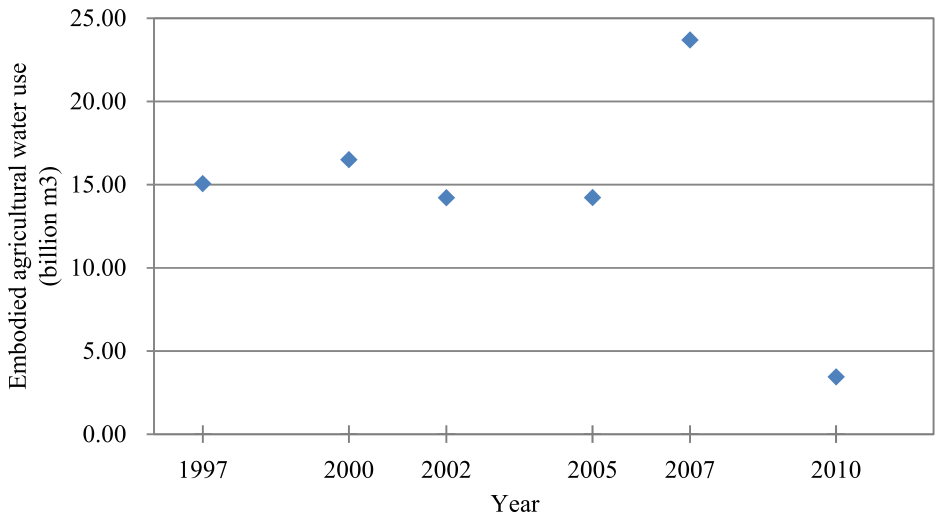

Fig. 3. Embodied agricultural water use in trade balance, 1997-2010.

As shown in Fig. 4, the embodied agricultural water uses in trade balance by the three major industries undergo different changing trends during the study period. The primary industry imports embodied agricultural water as much as it exports. Thus, the primary industry stays in a trade balance during 1997–2000. Thereafter, the primary industry becomes a net importer because of the increasing food demand in China. The net import of the primary industry continues to grow during 2002–2010 and reaches 21.66 million m^3 in 2010. Although the secondary industry has always been a net exporter, the trade deficit is stably maintained during 1997–2002but sharply increases to 36.32 million m^3 in 2007 and finally decreases to 23.21 million m^3 in 2010. The tertiary industry maintains a trade balance from 1997 to 2010. Following the accession of China to the World Trade Organization in 2002, manufacturing industries dominates the exportation of China's products. The secondary industry contributes the largest share of embodied agricultural water in China's net exports, which has obviously been increasing since 2002. Overall, China's industrial structure tends to be reasonable and leads to a comprehensive utilization and optimization of water resources.

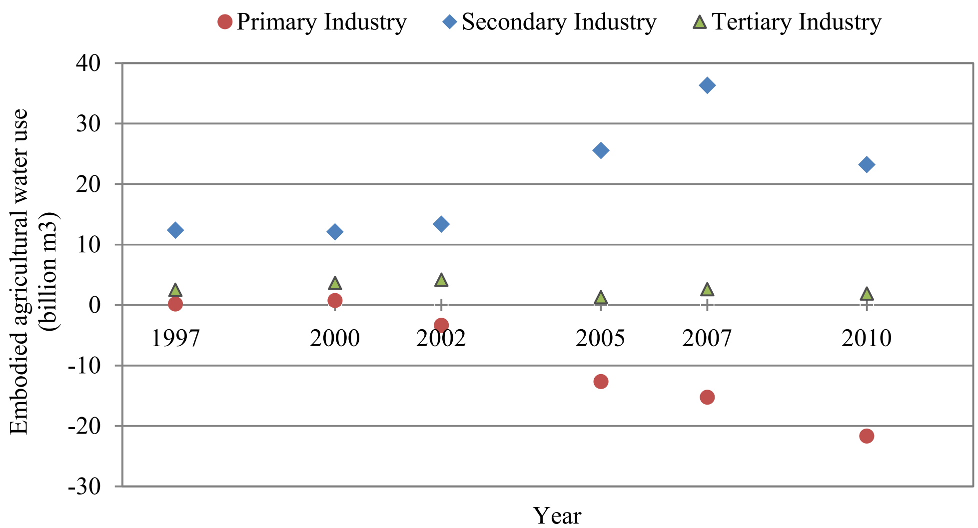

Fig. 4. Embodied agricultural water uses in trade balance by the three major industries, 1997–2010.

3.3 Production- versus consumption-based agricultural water use

To compare the actual and virtual agricultural water uses in China, production- and consumption-based embodied agricultural water uses during 1997–2010 are compared in Fig. 5. The total actual agricultural water use in China falls slightly from 391.97 billion m^3 in 1997 to 358.00 billion m^3 in 2005 and then increases to 368.91 billion m^3 in 2010. Despite a slight decrease in agricultural water use, the proportion of agricultural water decreases steadily from 70.42% in 1997 to 61.26% in 2010, which may be attributed to the decline in agriculture's share in the economy. The Chinese Government has limited the "red line" for total water use to 670.00 billion m^3 in 2020 (Ben Piper et al., 2012). Agricultural water is important to food safety, and establishing the "red line" for agricultural water use (the minimum agricultural water use) has been proposed to realize agricultural sustainable development (Wenlai, 2012).

The consumption-based embodied agricultural water use demonstrates a similar changing trend: it decreases from 378.03 billion m^3 in 1997 to 304.61 billion m^3 in 2007 with a declining rate of 2.41% and then remarkably increases to 340.60 billion m^3 in 2010. However, the agricultural water use embodied in consumption is always less than the direct agricultural water use in China during 1997–2010. This result shows that China sacrificed its own water resources to contribute to the external consumption of other countries. Thus, both production policies (focused on the improvement of agricultural water use efficiency) and consumption policies (focused on the optimization of consumption pattern) should be attended to by China to protect the agricultural water resources to the greatest extent. Furthermore, the shared responsibility of both the "producer" and "consumer" should be considered by the Chinese Government.

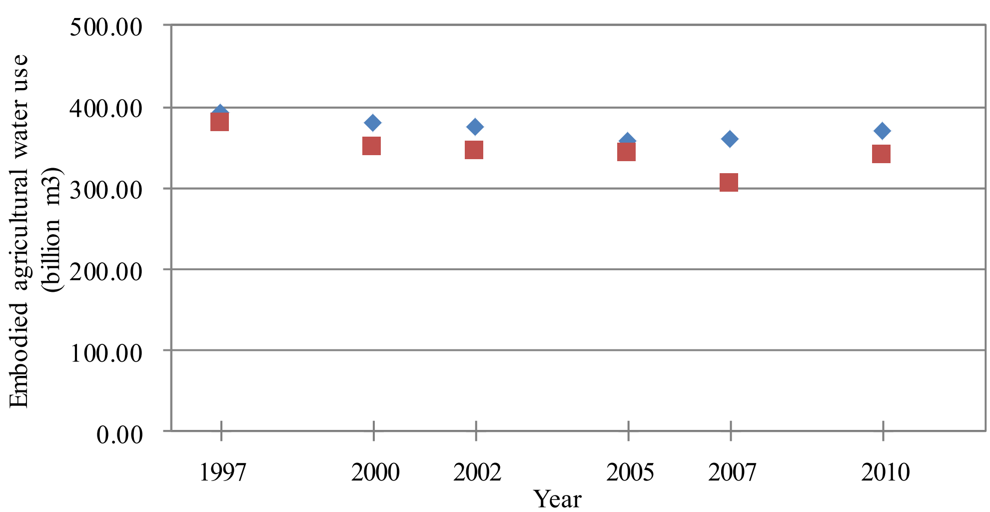

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Fig. 5. Production- versus consumption-based embodied agricultural water use, 1997–2010.

The industrial structure evolution significantly influences the consumption-based agricultural water use but has no effect on the production-based agricultural water use. This influence stems from the fact that agricultural water resources are all used by the agricultural sector in production, whereas water resources are assigned to all economic sectors for consumption. The changing trends of industrial embodied agricultural water for consumption are clarified in Fig. 6. Given that the agricultural sector is the main user of water, the embodied agricultural water used for consumption by the primary industry accounts for a large share and generally declines linearly from 229.22 billion m^3 in 1997 to 109.34 billion m^3 in 2010. Embodied agricultural water consumed by the secondary industry has shown a general increasing trend from 125.38 billion m^3 to 182.24 billion m^3 during the study period and has surpassed the primary industry since 2005 because of the rapid development of industrialization. Owing to the low embodied agricultural water intensity of the tertiary industry, embodied agricultural water use for consumption by the tertiary industry shows a slow growth and always uses the smallest amount of water resources compared with the other two industries.

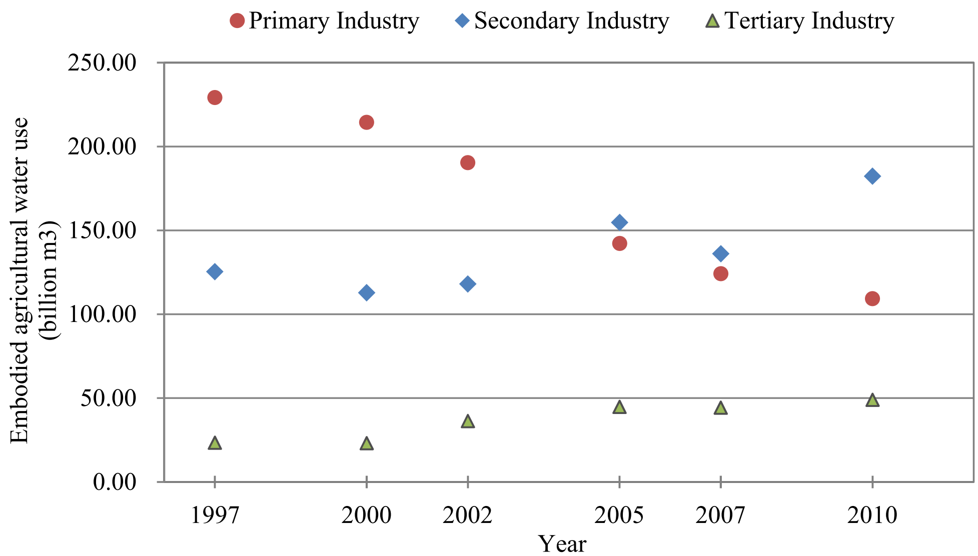

Fig. 6. Consumption-based embodied agricultural water use by three major industries, 1997-2010.

4. Discussions

4.1 Comparison with existing studies

China's water footprint has a considerable influence on the global water resources because of the country's huge water demand stemming from its growing population, rapid urbanization, and fast industrialization. China's water footprint is 489 billion m^3, which ranks third after those of India and the United States, which have water footprints of 610 and 549 billion m^3, respectively (Chen and Chen, 2013).

Agricultural water accounts for approximately 70% of the total global water use. As the main water use mode, agricultural water should be paid significant attention to achieve the effective utilization of water resources. However, current studies are mainly focused on the total water footprints at different scales, including global (Ercin and Hoekstra, 2014), national (Dong et al., 2014; Zhang and Anadon, 2014), regional

(Dong et al., 2013), industrial (Duarte et al., 2014), and products (García Morillo et al., 2015; Wang et al., 2015) scales. Studies are insufficient on embodied agricultural water use in China.

Therefore, China's total embodied water footprints in some studies are listed in Table 3 to compare China's embodied agricultural water use. Two conclusions can be obtained from the results: first, agricultural water footprint accounts for a major part of total national water consumption; second, the differences in the figures can be attributed to the applied methods (i.e., SRIO and MRIO). Such differences also reveal the significance of this study to assess China's agricultural water on a temporal scale by using a consistent and feasible method.

Table 3

Comparison of China's water footprint

Sources	Research objective	WF (billion m^3)	Year	Method
This study	Agricultural water consumption	304.61–378.03	1997–2010	SRIO
Zhang and Anadon (2014)	National total water consumption	264.26	2007	MRIO
Zhang et al. (2011b)	National total water consumption	400.03	2002	SRIO (Provincial IO table)
Zhao et al. (2009)	National total water consumption	489.21	2002	SRIO (National IO table)

4.2 Comparison of the water consumption of major agricultural products

As regards agricultural water use, all water resources are directly obtained by the agriculture sector but agricultural consumption contributes to less than 70% of the total virtual water requirement. According to the accounting results, the share of agricultural water consumed by the agricultural sector has been decreasing during 1997–2010, ranging from 60.64% to 32.10%. This result can be explained by the booming secondary and tertiary industries in China, which plays the role of the "world's factory" and provides a promising consumer market as the third largest economy in the world.

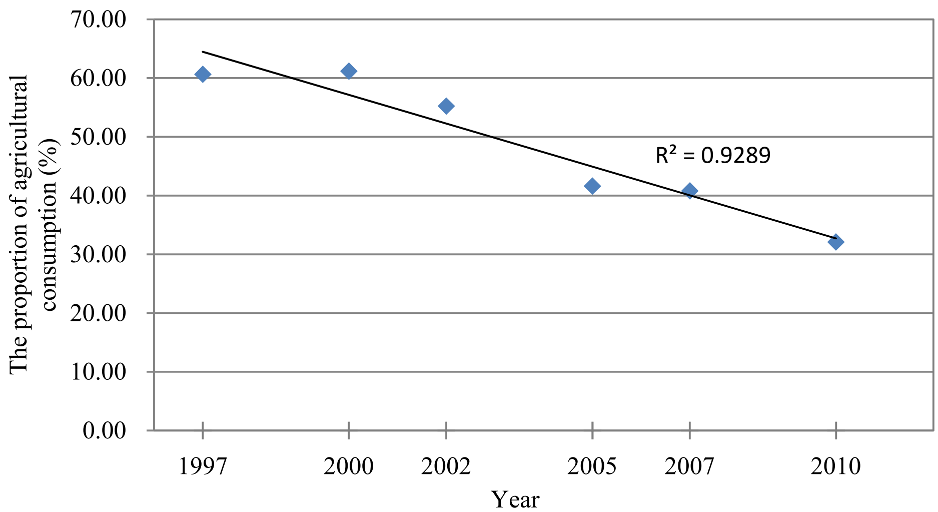

Fig. 7. Proportion of embodied water consumption in the agricultural industry.

As the main agricultural water consumers, the water consumption of different crop categories' need to be determined in tackling the food security problems. Fig. 7 describes the water consumption of major agricultural products during 1998–2007. The water use data of major agricultural products during 1998–2007 are available from the China Agricultural Water Report (Li and Peng, 2009). The changing trend can be clearly illustrated by the 10-year dataset. Among the four major agricultural products, rice consumes the largest share of water, ranging from 56.85% (in 1999) to 48.01% (in 2003). The proportions consumed by wheat and corn are equally weighted at 20%. The water consumption of soybean remains roughly 6% of the total. The shares of different crops fall in a tight range.

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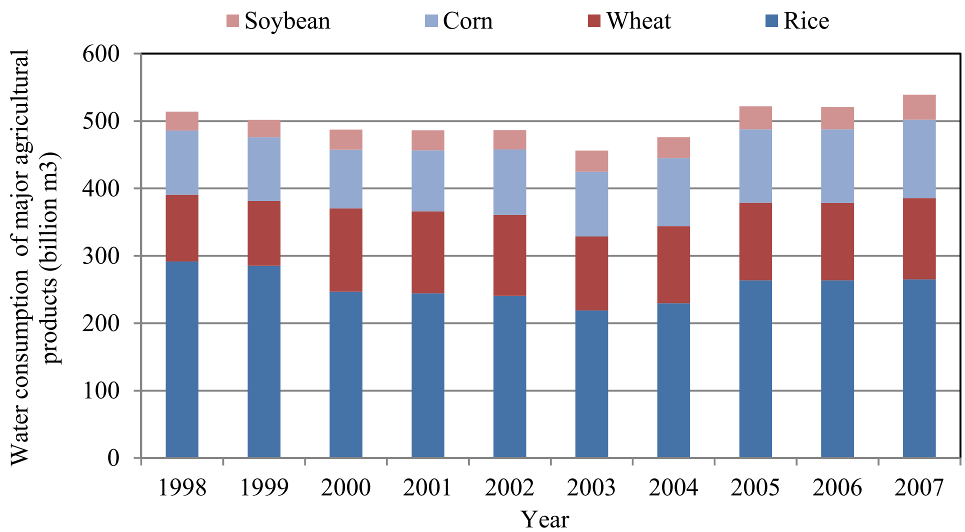

Fig. 8. Water consumption of major agricultural products, 1998-2007.

4.3 Key influencing factors on China's water footprint

Population growth and rapid urbanization have posed new challenges to the agricultural water demand in China. From 1997 to 2010, the population in China increased from 1.24 billion to 1.34 billion. China's urbanization rate improved from 31.91% in 1997 to 49.95% in 2010 (Chen et al., 2013). Increased population and rapid urbanization accompanied by the active economic activities result in large water demand. However, the agricultural water supply is limited because of the concomitant remarkable phenomena in the process of urbanization, such as a lack of cultivated land and rural labor force. During the study period, the cultivated land area was reduced from 129.90 million hectares to 122.01 million hectares and the rural population decreased from 0.84 billion to 0.67 billion (NBS, 2011). The increased demand and limited supply makes the improvement of water use efficiency in China imperative.

The improvement of direct water use efficiency has an important influence on China's water footprint. The application of agricultural water-saving technology can greatly improve water use efficiency. Currently, mainstream agricultural water-saving technologies include supplementary irrigation, plastic film mulching, water-saving irrigation, and economic plant hedge. (Xu et al., 2015). Plantation structure adjustment directly affects the water use efficiency. The planting scale of water-intensive crops, such as cotton, may be constrained. By contrast, crops with low-level water usage, such as maize, vegetables, and melons, may be considered for planting on a large scale (Xu et al., 2015). Rain-fed farming, such as rain-fed maize farming, which mainly uses green water, is also recommended as an effective water-saving measure.

Internal industrial structure adjustments and external trade structure changes are directly correlated with the embodied agricultural water intensity and further influence China's total water footprint. China has become the second largest economy and the largest trading nation in the world. China's annual GDP growth rate has been 9.91% since the reform and opening-up (Wikipedia, 2015). The total imports and exports of China increased from 2696.72 billion in 1997 to 20172.21 billion in 2010 (NBS, 2011). The volume expanded 7.48 times during this period. Trade structural change shifting from traditional industries with high intensities to high-tech industries with low intensities is significant. This change is highly in instrumental in preventing excessive water loss from trading products with high embodied agricultural water intensity.

4.4 Policy implications for China's water management

Currently, policy-makers at all levels simply consider the water resource problems within their jurisdiction. They develop water-saving technologies, formulate water management policies, or adjust the water market on a local scale. However, with the arrival of globalization and international division, sharing common but differentiated responsibilities with different governments and authorities are more cost effective. Both the joint consumption- and production-based responsibility should be shared by considering the allocated burdens and the capacity of the regions. For example, China has sacrificed a great deal of agricultural water resources within its jurisdiction to satisfy other regions' consumption outside its boundary. In terms of consumption, regions that import agricultural water resources from China have transferred their resource burdens and should contribute to China's conservation of resources on the basis of their respective capabilities, such as transferring advanced water-saving technology or providing financial support. Thus, China should enforce industrial and trade structure adjustments to avoid resource leakage. In terms of production, strict measures should be conducted to protect the water resources in China during the exploitation and utilization of these resources. Only by implementing these mixed policies, which consider China both as a "producer" and a "consumer," can the most cost-effective measures to conserve water resources be achieved.

4.5 Limitations of this study

This study exhibits some limitations in evaluating China's virtual agricultural water use. These limitations need further improvements in future research. The first limitation results from the method used; a strong assumption was made that "imported goods/services have the same embodied water intensities as domestic ones because of the limitation of IO economic data although the imported commodities show a substantial difference from domestic ones" (Weber et al., 2008). The second limitation arises from the restricted amount of available data. Although this paper was able to study China's virtual agricultural water during 1997–2010 by combining the limited agricultural water data (1997–2012) and IO data (1987–2010) in China, a full analysis and observation remains to be conducted by using a long time series.

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5. Conclusions

Water is a crucial element in agricultural production. Given the increasing demand and competition for water resources from nonagricultural sectors in the process of urbanization and industrialization, China's ever-increasing agricultural water problem has attracted considerable attention. To determine how agricultural water meets China's consumption requirements and how trade policies in China prevent sacrificing water resources for economic benefits, this study quantitatively evaluates China's embodied agricultural water use in production, consumption, and trade activities during 1997–2010 by using the latest available economic and environmental data. The detailed results are as follows:

(1) Temporal change in agricultural water use efficiency

China's average embodied agricultural water intensity shows a decreasing trend during 1997–2007, dropping from 43.33 m^3/thousand Yuan to 32.50 m^3/thousand Yuan and then slightly increasing to 32.66 m^3/thousand Yuan in 2010. This downward trend demonstrates China's effort and effectiveness in improving agricultural water use efficiency. In the industry, the embodied intensities of three major industries all experience a long-term fluctuation. The average embodied agricultural water intensity of the primary industry increases from 200.65 m^3/thousand Yuan in 1997 to 241.23 m^3/thousand Yuan in 2002 and then drops to 226.64 m^3/thousand Yuan in 2010. By contrast, the average embodied water intensities of the secondary and tertiary industries over the years are quite small compared with that of the primary industry.

(2) Temporal change in agricultural water trade pattern

China was a net exporter of agricultural water during 1997–2010, thus demonstrating that China significantly contributed water resources to the development of other regions. During the study period, the maximum EWB was 23.69 million m^3 in 2007, whereas the minimum EWB was 3.45 million m^3 in 2010. The continuing decline of EWB can be attributed to trade policy changes and economic structure adjustments. At the industrial level, the primary industry maintains a trade balance during 1997–2000 and then becomes a net importer because of the increasing food demand in China, the secondary industry has consistently been a net exporter, and the tertiary industry has maintained a trade balance.

(3) Production- versus consumption-based embodied agricultural water uses

The production- and consumption-based embodied agricultural water uses demonstrate similar changing trends: they decrease from 1997 to 2007 and then significantly increase in 2010. The consumption-based agricultural water use is always less than the production-based water use in China during 1997–2010, thus showing that China sacrificed its own water resources to significantly contribute to the external consumption in other countries. Given that the agricultural sector is the main user of water, embodied agricultural water use in net export by the primary industry accounts for a considerable share. The embodied agricultural water consumed by the primary industry shows a downward trend, whereas those consumed by the secondary and tertiary industries demonstrate an opposite trend.

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