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Recent evolution of China's virtual water trade: analysis of selected crops and considerations for policy

J. Shi[1,2], J. Liu[2,3], and L. Pinter[1,4]

[1]Department of Environmental Sciences and Policy, Central European University, Budapest, Hungary
[2]School of Nature Conservation, Beijing Forestry University, Beijing, 100083, China
[3]Ecosystems Services and Management, International Institute for Applied Systems Analysis, Schlossplatz 1, 2361, Laxenburg, Austria
[4]International Institute for Sustainable Development, 161 Portage Avenue East, Winnipeg MB R3B 0Y7, Canada

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Correspondence to: J. Liu (water21water@yahoo.com, junguo.liu@gmail.com)

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Abstract

China has dramatically increased its virtual water import unconsciously for recent years. Many studies have focused on the quantity of traded virtual water but very few go into analysing geographic distribution and the properties of China's virtual water trade network. This paper provides a calculation and analysis of the crop-related virtual water trade network of China based on 27 major primary crops between 1986 and 2009. The results show that China is a net importer of virtual water from water-abundant areas of North and South America, and a net virtual water exporter to water-stressed areas of Asia, Africa, and Europe. Virtual water import is far larger than virtual water export and in both import and export a small number of trade partners control the supply chain. Grain crops are the major contributors to virtual water trade, and among grain crops soybeans, mostly imported from the US, Brazil and Argentina are the most significant. As crop yield and crop water productivity in North and South America are generally higher than those in Asia and Africa, the effect of China's crop-related virtual water trade positively contributes to optimizing crop water use efficiency at the global scale. In order to mitigate water scarcity and secure the food supply, virtual water should be actively incorporated into national water management strategies. From the national perspective, China should reduce the export and increase the import of water-intensive crops. But the sources of virtual water import need to be further diversified to reduce supply chain risks and increase resilience.

1 Introduction

The concept of virtual water (VW) was first defined by Allan (1998a) as "the water embodied in food crops that are traded internationally" to provide a new perspective as well as policy tool for addressing food security and water management strategy development. Transfer of VW between different regions takes place when crop commodities are traded on the global market. Economies that are trading commodities are essentially also exchanging water resources with each other (Allan, 1998a). The exchange of VW can be considered as an anthropogenically-driven hydrological process closely linked to the socioeconomic sphere. To mitigate water scarcity, it is usually not economically feasible to transport real water from water-rich to water-poor regions due to long distances and major costs, but trade of VW is realistic (Hoekstra and Hung, 2005) and has often been carried on unconsciously i.e. without an explicit recognition by business and government regarding the fact and implications of the water being transferred (Liu and Savenije, 2008). Therefore, VW trade (VWT) is believed by some to be a cost-effective and market-based approach to reducing water inequalities and raising global water productivity (Chapagain et al., 2005; Hoekstra and Hung, 2005; Yang and Zehnder, 2007).

Studies on VWT have been carried out at different scales. At a global level, Hoekstra and Hung (2005) calculated the volume of crop-related international VW flows from 1995 to 1999 and found that conservatively 13 % of the water used in crop production is for export in VW form. Chapagain et al. (2005) estimated that VWT has saved 6 % of global agricultural water use, which equals 28 % of the total amount of VW flows associated with international agricultural trade. Further research by Hoeskstra (2010) has also shown that current water use in agriculture is reduced by 5 % through international VWT. Dalin et al. (2012a) was the first to use a network approach to analyze the evolution of the global VW flows from 1986 to 2007. Their findings support the argument that global VWT associated with international food trade has increased global water use efficiency and thus contributing to global water resource saving, although both regional and national VWT patterns have changed a lot. Also, despite efficiency improvements global and in many cases regional water withdrawals continue to increase in absolute terms, due to the combined effect of population growth and increasing effluence (Ozkaynak et al., 2012).

Recent studies have also considered the contributions of “green water” (defined as soil water originating from rainfall) and “blue water” (defined as irrigation with water abstracted from ground or surface water systems) in VWT as there are much higher opportunity costs and more negative environmental externalities particularly in the use of "blue water" (Chapagain et al., 2006; Liu et al., 2008; Liu and Yang, 2009; Aldaya, 2010). Aldaya (2010) showed that the share of "green water" in exported VW associated with maize, soybeans, and wheat from main exporting countries is by far the largest over the period of 2000–2004. Liu et al. (2009) also showed the low opportunity cost "green water" accounts for the origin of around 94 % of the global crop-related VWT over the period of 1998–2002.

At a national level, water-poor economies can mitigate scarcity by actively importing water-intensive commodities instead of producing them domestically, while water-rich countries can also benefit economically by exporting VW from their abundant water resources. Allan (1998b) pointed out that it is VW import which helps the Middle East avoid armed conflicts over its scarce water resources. He estimated that by 2000, the Middle East and North Africa were importing VW associated with 50 million tons of grains annually. Shuval (2007) showed that Israel imports 80 % of the national caloric intake from abroad while Palestinians import more than 65 % of their caloric intake. El-Sadek (2010) also showed that the share of net VW import of Egypt has amounted to 23.55 % of its water resources. Other study on Mediterranean countries such as Spain showed its VW import associated with grain trade is consistent with relative water scarcity, but the evolution of grain exports does not match the variations in resource scarcity, which suggests other factors including quality, product specification or the demand for a standardized product also influence VWT (Novo et al., 2009). Study on the inter-state VW flows in India showed similar results (Verma et al., 2009). They found that the existing VWT pattern is actually worsening water scarcities in water-short states, which is influenced by non-water factors such as "per capital gross cropped area" and "access to secure markets" rather than water endowments.

China is a water-poor country in terms of water resource per capita and faces a trend of exacerbating water inequalities between water-abundant South and water-stressed North in general (Jiang, 2009; Liu et al., 2013). Liu et al. (2007) showed that the VWT of China which is influenced by both micro- and macro-economic conditions and weather fluctuations has developed unconsciously and suggested that active VW strategy could play a more important role in food security and sustainable water use, as China's agricultural commodity markets are liberalized. Yang and Zehnder (2001) analyzed water scarcity in the North China Plain and pointed out that VW import should be taken as an additional measure in contrast with the conventional wisdom of "opening up new sources and economizing on the use of resources" to meet growing water demand. Some studies (Ma et al., 2004, 2006; Chen, 2011; Sun et al., 2011) have revealed that while the ongoing South-North Water Transfer Project (SNWTP) is carrying real water (40–50 $\mathrm{km}^3\,\mathrm{yr}^{-1}$ when fully developed) from water-abundant Southern China to water-stressed Northern China (particularly the North China Plain), a comparable amount of VW (52 $\mathrm{km}^3\,\mathrm{yr}^{-1}$) associated with agricultural products is flowing in the reverse direction. This is mainly because of more arable areas in the North and more developed economies with rapidly increasing demand in the South. It indicates that despite water resource endowments, other factors also contribute significantly to VW flow patterns. Guan and Hubacek (2007) incorporated water quality assessment and calculated the intra-regional VWT within China. They found that the water-scarce North is importing virtual wastewater, while water-abundant South is exporting virtual wastewater, based on the assumption that crop production impacts on water quality and that such impacts can contribute significantly to water scarcity within a country.

Wichelns (2004) pointed out that the metaphor of VW only addresses resource endowment and does not address production technologies or opportunity costs. In order to enhance the policy-relevance of the VW metaphor, the theory of comparative advantage could be applied to determine optimal production and trade strategies. His research found that optimal strategies cannot always be defined considering only resource endowments. In a working paper for the World Trade Organization (WTO), Hoeskstra (2010) warned about serious risk in international trade agreements lacking accounts for the sustainability of water use or products and called for combining the liberalization of agricultural products trade and promotion of sustainable agricultural water use through mechanisms such as water labelling, an International Water

Pricing Protocol and an International Water-Footprint System. These findings can also shed light on the further understanding of global VWT patterns and hint at better global water governance to optimize the reallocation of global water resource through trade agreements.

Literature is available on the amounts of VW traded between China and other countries, but there is a lack of research on the geographic distribution of China's VWT network (VWTN), how it has evolved over time, and what its implications for global and national water resources are. Also, the network properties of a China-centred VWTN have never been analysed. This study is aimed at reconstructing the evolution, geographic distribution and patterns of China's crop-related VWTN over the last two decades and drawing corresponding policy implications.

2 Methods

2.1 Selection of crops studied

In order to portray the representative profile of crop-related VWTN of China, we selected 27 primary crops which constitute around 80 % of the total harvested area of the primary crops in China from 1986 to 2009 by average (FAOSTAT, 2012). They were categorized in four groups including 8 grain crops, 6 fruit crops, 6 vegetable crops and 7 cash crops. The categorization of selected crops followed Liu et al. (2007) to make the results comparable, which incorporated soybeans in grain crops as the traditional way of Chinese statistics and separated fruits and vegetables from cash crops.

2.2 Crop yields

Crop yields data were extracted from FAOSTAT (2012). Yields of all selected crops showed a general increasing trend over the study period of 1986–2009, with complicated oscillating patterns due to the mutual impacts from improvement of technologies, fluctuation of weather conditions, a warming trend possibly due to climate change, the associated growing concentration of atmospheric CO_2, and changes in relevant social and economic policies.

2.3 Virtual Water Content (VWC)

Virtual water content (VWC) here is defined as the volume of water used in order to produce a unit of a crop. For primary crops, it can be calculated by directly dividing the national average crop water requirement by corresponding crop yield in each year (Renault, 2003; Zimmer and Renault, 2003; Liu et al., 2007). Table 1 shows the crop category, crop water requirement, crop yield and VWC of selected crops between 1986 and 2009.

2.4 Virtual Water Trade (VWT)

VWT is associated with the international food trade of corresponding agricultural commodities, and consists of VW import (VWI) and VW export (VWE). Trade data were adopted from FAOSTAT's (2012) detailed trade matrix. VWI and VWE were calculated based by Eqs. (1) and (2) and VW balance (VWB) was calculated by subtracting VWE from VWI as in Eq. (3). If the volume of VWI is larger than that of VWE, VWB will be positive and the value is net VWI; if the volume of VWI is less than that of VWE, then VWB will be negative and the value is net VWE. VW flow is also referred to VWT in some literature. It better illustrates VWT as an important anthropogenic way of hydrological process in socioeconomic sphere. Total VWI, total VWE and total VWB of all the selected crops are the sums of VWI, VWE and VWB in each year as in Eqs. (4)–(6). For convenience, the countries which import/export VW from/to China are denominated as "VWI partners" (VWIPs) and "VWE partners" (VWEPs). Since some countries can be importers and exporters simultaneously, "net VWIPs" and "net VWEPs" are also introduced in this study.

$$\mathrm{VWI}_{\mathrm{c,n,j}} = \mathrm{VWC}_{\mathrm{c,j}} \times I_{\mathrm{c,n,j}} \tag{1}$$

$$\mathrm{VWE}_{c,n,j} = \mathrm{VWC}_{c,j} \times E_{c,n,j} \qquad (2)$$

$$\mathrm{VWB}_{c,n,j} = \mathrm{VWI}_{c,n,j} - \mathrm{VWE}_{c,n,j} \qquad (3)$$

$\mathrm{VWC}_{c,j}$ is VWC of crop "c" in year "j" for China. $I_{c,n,j}$ is the amount of crop "c" imported from country "n" in year "j" and $E_{c,n,j}$ is the amount of crop "c" exported to country "n" in year "j". $\mathrm{VWI}_{c,n,j}$ is the VWI of crop "c" from country "n" in year "j", $\mathrm{VWE}_{c,n,j}$ the VWE of crop "c" to country "n" in year "j", and $\mathrm{VWB}_{c,j}$ the VWB of crop "c" with country "n" in year "j".

$$\mathrm{TVWI}_j = \sum_c \sum_n \mathrm{VWI}_{c,n,j} \qquad (4)$$

$$\mathrm{TVWE}_j = \sum_c \sum_n \mathrm{VWE}_{c,n,j} \qquad (5)$$

$$\mathrm{TVWB}_j = \sum_c \sum_n \mathrm{VWB}_{c,n,j} \qquad (6)$$

TVWI_j is the total VWI in year "j", TVWE_j the total VWE in year "j", and TVWB_j the total VWB in year "j".

2.5 Virtual Water Trade Network (VWTN)

The VWT relationships between China and trade partners can be viewed collectively as a directed and weighted VWTN (Dalin et al., 2012a). Each trade partner forms a node in the trade network in a given year, and VW flows associated with corresponding agricultural commodities form the links between nodes with the direction pointing to China as net VWI and the direction pointing from China as net VWE, respectively. The volume of traded VW between each pair of trade partners is the weight of the link. The number of trade partners is described by the node degree k and the sum of weights is denoted by node strength s. This study reconstructed the VWTN centred at China for the period of 1986–2009. The data reported by China were solely used irrespective of any divergence from the data reported by the other trade partner. It is also assumed that no direct trade was taking place if no data were reported between China and a certain country in a given year.

3 Results

3.1 Crop-related VWT of China

China's crop-related VWTPs are from all 6 continents but most are located in Asia, Europe and Africa. The total number of VWTPs has increased significantly since 1986, though the geographic distribution of VWTPs by continent has remained unchanged. In 1986, there are 24 VWTPs from Asia, Europe and Africa while there are 10 from North and South America and Oceania. And in 2009, there are 125 VWTPs from Asia, Europe and Africa but there are only 34 from the Americas and Oceania. Note that generally, Asia, Europe and Africa are net VWEPs while the Americas and Oceania are net VWIPs, from whom China imported much larger volumes of VW than that exported to net VWEPs. However, the patterns of import-export relationships have changed significantly over recent years, as the number of net VWIPs keeps rather steady but the number of net VWEPs has drastically increased. Figure 1 shows the evolution of crop-related VWTPs of China over the period 1986–2009.

China has a positive crop-related total VWB with the total net VWI of 934 km^3 and yearly average of 39 km^3 over the period 1986–2009. The volume of the total VWI is about 1242 km^3 which is three times greater than that of the total VWE (308 km^3).

Figure 2 shows the crop-related VWT of China. From 1986 to 2000, the total VWB fluctuated below or around 20 km^3 yr^{-1} but since 2001 it began to increase dramatically mainly due to a major food trade policy shift and reached nearly 140 km^3 in 2009, which was six times higher. Note that the curves of the total VWB and the total VWI are very close to each other, which reflects that VWI dominated the overall VWT of China during the study period of time, while the total VWE is generally below 20 km^3 yr^{-1}.

Grain crops contribute the most in all total VWB, total VWI and total VWE. In total VWI, the VWI associated with grain crops is 1203 km^3 in total and 50 km^3 yr^{-1} on average, both of which take up to 97 % of all VWIs. In total VWE, VWE associated with grain crops is 163 km^3 in total and 7 km^3 yr^{-1} on average, accounting for 53 % of all. Despite the overwhelmingly dominant role of grain crops, cash crops also play an important role in total VWE as they contribute 141 km^3 VW in total and 6 km^3 yr^{-1} on average, corresponding to 46 % of grain crops. Furthermore, according to most recent trends, cash crops may replace grain crops as the largest contributor in total VWE. As shown in 2008 and 2009, they accounted for 80 and 84 %, respectively, a double jump from 48 % in 2007. However, since the volume of total VWI is much greater than that of total VWE, it can still be stated that for the study period VWI associated with grain crops dominated VWT of China.

3.2 Geographic distribution of VWTN of China

China mainly imported VW from North America before 2000 but added South America as another major source of VWI afterwards. In 1986, China imported 6.70 km^3 VW from North America and in 2009 this number increased to 78.7 km^3 but with another 64.95 km^3 from South America. Additionally, the accumulated amount of VWI from South America has been catching up with that of North America. The geographic distribution of VWE is more balanced, even if less significantly by volume. Asia has generally been the major destination of VWE over the study period of time, but Europe and Africa have also been important. The distribution of VWE among these three continents became more evenly since 2008 (See Fig. 3).

Figure 4 combines the numbers of VWTPs and geographic distribution of VWT to give a holistic view of the evolution of China's VWTN over 1986–2009.

3.3 Properties of VWTN of China

Considering trade links and the total amount of VW traded, the number of VWTPs generally grew from 35 in 1986 to 160 in 2009, a four times increase, which mainly came from the increase of the number of net VWEPs from 18 in 1986 to 125 in 2009, most of which are located in Asia, Europe and Africa, as mentioned before. But the number of net VWIPs remained rather steady, growing from 17 in 1986 only to 35 in 2009, which are mainly located in North and South America and Oceania. In contrast to the relatively small number, net VWIPs contributed 81.15 % of the total net VW traded with a percentage of 28.14 % in number on yearly average. Also, the pattern of a small number (less than 30 %) of net VWIPs contributing to a large percentage (greater than 70 %) of total net VW traded has been unchanged over the study period.

If we take the number of China's VWTPs (trade links k) and the corresponding VW traded (node strength s) in each year as a pair and rearrange all the pairs in the k-s space during the study period of time, the relationship satisfies the power law $s(k) \propto k^{\alpha}(\alpha = 1.675)$, that characterizes the feature of "scale-free" degree distribution in VWTN of China (see Fig. 5) as power-laws have the property of having the same functional form at all scales. In fact, power-laws are the only unchanged functional form $f(x)$, apart from a multiplicative factor, of the solution to the equation $bf(x)=f(ax)$ when rescaling the independent variable x (Boccaletti et al., 2006). It's an intrinsic characterization which had remained unchanged during the study period of time.

Further network analysis shows that the VWTN of China is inhomogeneous and highly polarized. A few "big partners" (defined as trade partners who traded larger than average volumes of VW) dominated China's VWT (see Fig. 6a and b). In terms of net VWI, the number of "big partners" was relatively small and rather steady, with an average of 3.1 each year, 12.98 % of the total number of net VWIPs, and an absolute deviation of 0.45; but they traded 95.97 % of the total net VWI. "Other partners" contributed mostly to the increase in number of trade partners, with an average of 21 each year, 87.02 % of the total number of trade partners, and an absolute deviation of 3.5; but they only took up 4.03 % of the total net VW flow. The polarity is also prominent within net VWE. In net VWE, ‘big partners’, with an average of 11.7 each year, 18.97 % of the total VWEPs, and an absolute deviation of 3.6, took up 83.55 % of the total net VWE.

Node strength exceedance probability distribution of VWT reconfirmed the highly-polarized characteristics of China’s VWTN. The probability distribution shows the feature of a “super flat tail” in each net VWT network, net VWI network, and net VWE network, which highlights the fact that trade among a very small group of partners dominate the whole (see Fig. 6c). Therefore any change in the trade with these “big partners” would impact on the whole trade pattern fundamentally. This is a disadvantage in terms of food security and resilience.

3.4 A case in focus: soybeans

China is the place of origin for soybeans and has been a net exporter before 1996. However the situation changed and soybeans imports increased dramatically. Soybeans show a prominent role in China’s VWT especially after 2000. The import of soybeans in 2003 exceeded total domestic soybeans production in 2002. Increasing domestic demand and the shift of food trade policy since China’s accession to the WTO both contributed to the jump of soybeans import of China. The VWT associated with soybean imports also reflects this highly polarized pattern in that a very small number of trade partners dominated the entire trade (see Fig. 7). Before 1996, the US was the only major trade partner, but since 2000 Brazil and Argentina gradually became also major suppliers. These three countries altogether exported 886 km^3 of soybeans-related VW to China over the period of 1986–2009 while all the other countries imported 29 km^3 from China. The accumulated VWB associated with soybeans accounted for 56.97 % in the total VWB between 1986 and 2009, and 78.26 % between 2000 and 2009.

4 Discussion

4.1 Comparison and analysis

China has significantly raised its net VWI from 7.02 km^3 in 1986 to 137.14 km^3 in 2009. The pattern of historic trend of VWT are essentially the same and values of traded VW are slightly smaller but comparable with Liu et al. (2007), which could be expected as more types of crops were used to calculate China's VWT in their study. This dramatic rise in China's net VWI is mostly due to a major food trade policy shift in 2001 (Carter and Rozelle, 2001). China's VWI is far larger than VWE, and grain crops overwhelmingly dominate VWI, accounting for 97 % on yearly average, which is also comparable with the result of over 95 % from Liu et al. (2007). Grain crops are also important contributors in VWE with a share of 53 %, although not as dominant as in VWI. VWE of fruits and vegetables are minor but cash crops are significant, with a share of 46 %, among which, VWE of tea is the most important source. This finding, again, goes along with the study of Liu et al. (2007) on China's VWT between 1961 and 2004. The comparison suggests that the recent trend of China's VWT has been kept since the policy turning point in 2001 and there is no indication its direction observed after 2004 will shift in the near future.

In terms of geographic distribution, there are many more VWTPs located in Asia, Europe and Africa than that in the Americas and Oceania. The numbers of VWTPs located in different regions have all seen a great rise since 1986 but apparently most of the increase comes from Asia, Europe and Africa. This is in accordance with the spike of the number of VWEPs, which accounts for most of the increase in China's VWTPs. Interestingly, the relationship between VWTPs and corresponding traded VW satisfies the power law and reflects the "scale-free" feature of China's VWTN, which is also observed in the global VWTN (Dalin et al., 2012a). This is important for the projection of the way China's VWT may continue to evolve. Despite of the increase in both VWTPs and traded VW, which is coherent with the general behaviour of the global VWTN (Dalin et al., 2012a), there is a consistency of the geographic distribution in import-export relationship of VWT: a net VWI from water-abundant areas of North and South America, and a net VWE towards water-stressed areas of Asia, Africa, and Europe. This pattern has remained unchanged over the study period. As crop water use efficiencies in North and South America are generally higher than those in Asia and Africa (Liu et al., 2009), and China shared 13 % of global VWT (Dalin et al., 2012a), China's crop-related VWT positively contributes to optimizing crop water use efficiency at the global level, although global water withdrawals continue to increase in absolute terms (Ozkaynak et al., 2012). This is in line with the conclusion of Dalin et al. (2012a) that on average at the global level i.e. not taking regional differences into account, VWT helps save the world water resources. But water endowment might not be the only factor affecting VW flow directions at a lower scale e.g. at the regional or national levels especially when considering commodities beyond food (D'Odorico et al., 2012; Tamea et al., 2013). The most prominent feature of China's VWTN is the high inhomogeneity i.e. within both import and export a small group of VWTPs control the entire trade. This is also coherent with the global VWTN characteristics that a small number of global actors control a significant portion of VWE, which reflects Pareto Principle in the context of VWTN (Carr et al., 2012, 2013a, b).

Notably, soybeans, nearly all imported from the US, Brazil and Argentina (in fact, the soybean-associated VWB of other countries is minor and negative), account for 91.7 % of China's VWT on yearly average. This is similar to 90 % calculated by Dalin et al. (2012a) and driven by growing economic growth and demand and changing preferences towards a more meat-based diet (Liu et al., 2008). Together with the lifting of food trade barriers, it explains the dramatic increase of China's VWI. The large demand for soybeans in China has not only changed China's VWTN but also has influenced the structure of agriculture in the Western Hemisphere. Despite its negative impact on worsening the deforestation in the Amazon Basin, this trend also has trade and water resource sustainability related advantages, since the Americas have comparative advantages due to higher yields and lower soybean production costs. In addition, crop water productivity of soybean is higher in the Americas than in China (Liu et al., 2009).

Hence, scale issues aside, China's soybean imports from the Americas help save water resources *at the global level*. Strictly speaking, they are also consistent with the goals of the General Agreement on Tariffs and Trade (GATT) to "take full advantage of the world's resources, and expand the production and circulation of goods".

4.2 Policy implications

As China is facing increasingly severe water scarcity (Jiang, 2009; Liu et al., 2013), intrinsically linked with food security, a more integrated water management strategy is required, including an active VW policy. The need for such an approach can only grow if current trends continue. On the demand side, the need for water resources in China will continue to grow, driven by population pressure, increasing affluence (e.g. increasing role of meat in the diet) and rapid growth of a resource-intensive economy. On the supply side, water resources in China are increasingly stressed. The uneven distribution of water resources between Northern and Southern China is projected to be worsening due to further climate change and water pollution (Piao et al., 2010; Mountford, 2011; Wang and Zhang, 2011). There are plans to tackle the problem of spatial distribution of water through major diversion projects, but these initiatives are fraught with challenges.

The "super-project", the South-North Water Transfer Project (SNWTP), aims to transfer real water from the water-rich South to water-stressed North, particularly the drying North China Plain that currently produces half of China's wheat (Berkoff, 2003). However, the quantity of transferred water is projected to be limited compared to the growth in demand. Furthermore, agriculture in the North is not likely to be compensated as the price industry is able to pay for water is unaffordable for agriculture that uses more water but works with lower margins. Due to these and many other concerns related to water quality, as well as potential negative impacts on ecosystems, the western route of the SNWTP project has been halted.

In response to these trends a series of policy measures have been taken by the Government of China. The most recent of these policies include Central Document No. 1 of 2011, which introduced stringent water resources management in China with three "red lines" to control national water use, water use efficiency and water pollution (Liu et al., 2013).

An active VWT policy could be a wise additional option to complement integrated measures that focus on addressing water supply and demand issues at the national level. This is not without precedent, as policy measures to mitigate the water scarcity through VWT policy have been successfully implemented in other water-stressed countries, especially in the Middle East and North Africa (Allan, 1998b; Shuval, 2007; El-Sadek, 2010).

There has been a long-standing concern about the food sovereignty and security of China with a widely held view that China need to maintain a relatively high level of self-sufficiency of grain crops (about 95 %). While the accelerating integration of China into the world economy, especially China's accession to the WTO, has resulted in a loosening of policies on food trade, maintaining a high rate of self-sufficiency in grains is becoming more and more unnecessary and unfeasible, neither economically nor environmentally. So it is reasonable to incorporate VWT as a carefully considered active policy instrument into the national integrated water management strategy. To reduce the risk of volatile international food market, the sources of VWI should be diversified. This study has shown the high inhomogeneity of VWI in China via the tight coupling of the supply chain with a small group of countries. Therefore, more efforts should be aimed at diversifying imports to reduce risks and increase resilience. However, considering the fact that most of the VW resources available for export tend to remain concentrated in a small set of countries (Carr et al., 2013a) and the projection that the future structure of global VWTN will become increasingly heterogeneous (Dalin et al., 2012b), it is not sufficient to diversify VWIPs as an element of an improved VWT strategy. The structure of agriculture also need be adjusted. As discussed by Huang and Rozelle (2002), the structure of agricultural adjustment includes structural changes in the agricultural commodity mix, quality improvement of major commodities and the promotion of regional specialization. Liu et al. (2007) also pointed out that the goal of the structural adjustment of agriculture is to achieve a so-called "three-high" agriculture: high output, high quality, and high efficiency. They showed that most crops that turn water into high economic value such as fruits and vegetables, are low on water-intensity and they are more suited to water-saving irrigation; thus, shifting to high water value crops can increase farmers' incomes without increasing agricultural water consumption (Liu et al., 2007). Therefore, there also should be financial incentives to reduce exporting highly water-intensive but low economic-value agricultural products, and to increase exporting characterized by low water intensity but high economic-value. It is crucial to strive for a more efficient agricultural use of water as an element of a VWT strategy.

4.3 Further study

Due to data and time limitations for this study, there remains much scope for further research. More attentions should be paid to the reallocation of external VWI and the internal VWT between provinces since there have been a few studies on the VWT of China at the international level, but studies at the intra-regional level are lacking. In order to increase policy relevance, calculations and analyses could be scaled down to the regional and water-basin levels in order to directly assist policy-making at that scale. Therefore, a provincial-level VWTN analysis, accounting for the external VWT could be quite interesting and provide insights into a higher resolution picture of China's internal VWTN as well as enhancing policy relevance. The sources of VW ("blue" and "green" water) and its effect on water quality could also be integrated into a network analysis of VWT.

Apart from agricultural products, VWT associated with industrial commodities of China is also important, as the country has become "the world manufacturer". Some studies have suggested that China is net VW importer if only accounting for agricultural products but net VW exporter when combining industrial commodities (Zhang et al., 2011). This would provide a broader cross-sector perspective into the VWT of China.

Finally, in the interest of increasing their policy relevance, VW studies should be combined with economic analyses building on comparative advantage theory that has actually been well applied since China's economic reform and opening-up policy. This could include more systematically accounting for the monetary value of water are more effective ways to promote VWT as an option in the sphere of economic policy-making.

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Table 1. National average crop water requirements, crop yields (average between 1986 and 2009) and VWCs (average between 1986 and 2009) for selected crops. Data source for national average crop water requirements: Liu et al. (2007), data source for crop yields: FAOSTAT (2012).

Crop Category	Crop Type	CWR (m^3 Ha^{-1})	Yield (t ha^{-1})	VWC (m^3 t^{-1})
Grain	Rice (paddy)	8000	6.03	1333
	Wheat	4300	3.75	1171
	Maize	4000	4.76	850
	Soybeans	4900	1.61	3069
	Millet	4440	1.86	2428
	Sorghum	4000	3.70	1107
	Potatoes	3040	13.42	231
	Barley	4100	3.08	1377
Fruit	Apples	4500	7.67	864
	Citrus	8850	10.97	1093
	Pears	4850	7.76	692
	Watermelons	3400	26.80	138
	Bananas	12900	19.01	714
	Grapes	5940	11.04	610
Vegetable	Tomatoes	4750	27.78	179
	Cabbages	4010	27.01	155
	Carrots	5600	22.43	257
	Cucumbers	4900	20.49	269
	Lettuce	3220	23.14	140
	Spinach	2450	16.53	154
Cash	Rapeseed	3090	1.46	2177
	Sunflower	4090	1.68	2465
	Sesame	3400	0.92	4007
	Sugar Beet	5150	26.29	214
	Sugar Cane	9230	63.16	148
	Tobacco	5000	1.79	2823
	Tea	9500	0.77	12623

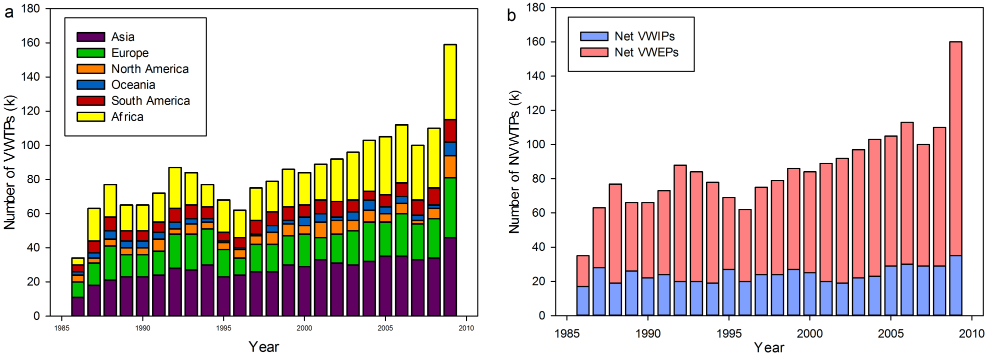

Fig. 1. (a) The evolution of geographic distribution in number of China's VWTPs by continent over the period of 1986–2009; **(b)** The evolution of import-export relationship in number of China's VWTPs over the period of 1986–2009.

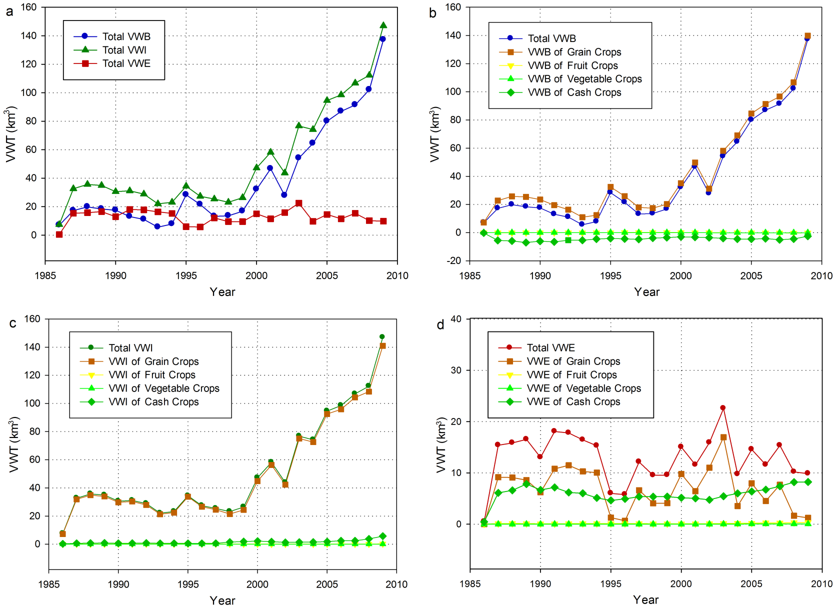

Fig. 2. Crop-related VWT of China over the period of 1986 – 2009: **(a)** total VWT of China; **(b)** contributions of different crops to total VWB; **(c)** contributions of different crops to total VWI; **(d)** contributions of different crops to total VWE.

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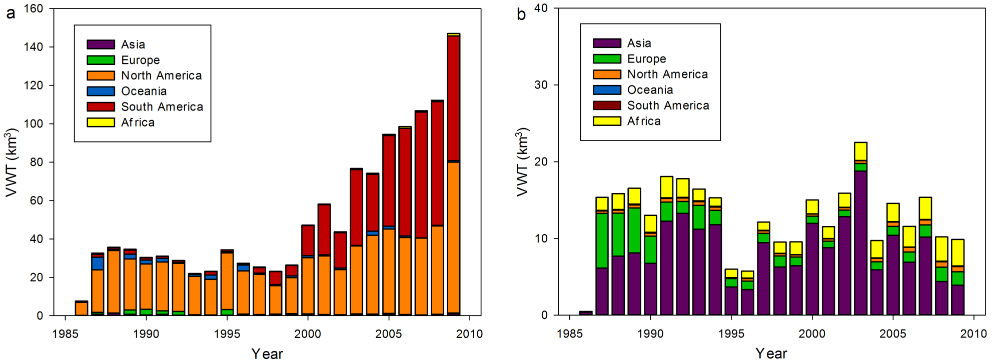

Fig. 3. The evolution of geographic distribution of China's VWT over the period of 1986–2009: **(a)** Geographic distribution of VWI; **(b)** Geographic distribution of VWE.

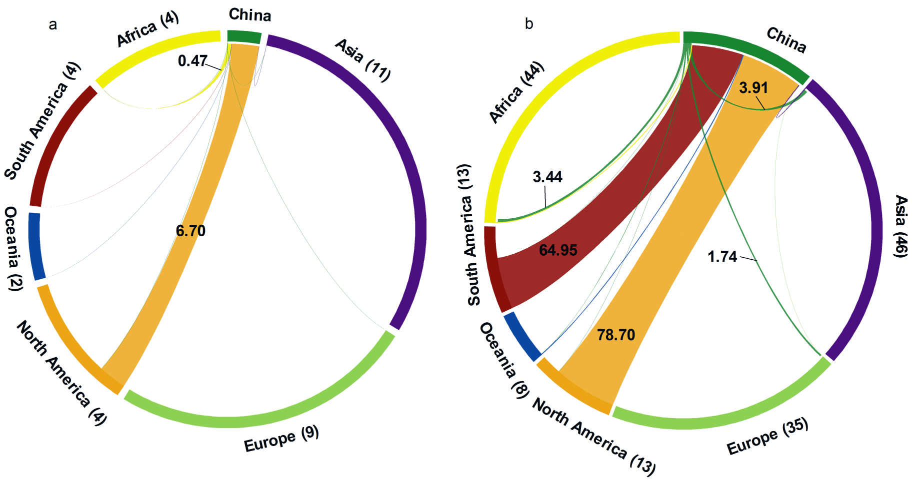

Fig. 4. Geographic distribution of China's VWT in 1986 and 2009. The size of the segment represents the number of VWTPs in corresponding continent with labels in the brackets (the size of China is not in proportion); the size of the contribution track represents the volumes of VW traded with label unit of km^3. **(a)** 1986; **(b)** 2009.

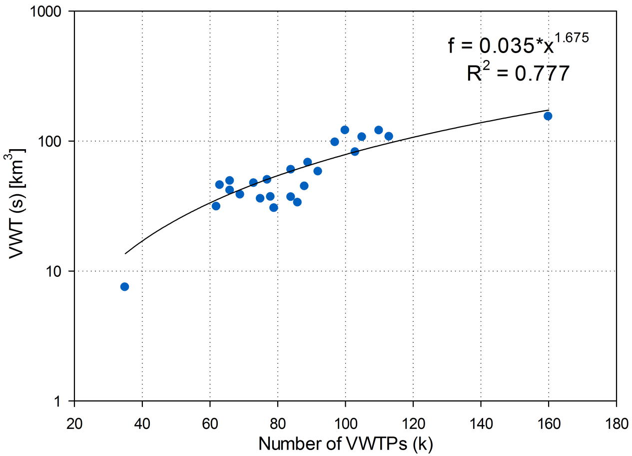

Fig. 5. Power law shows the “scale-free” degree distribution of VWTN of China as power-laws have the property of having the same functional form at all scales.

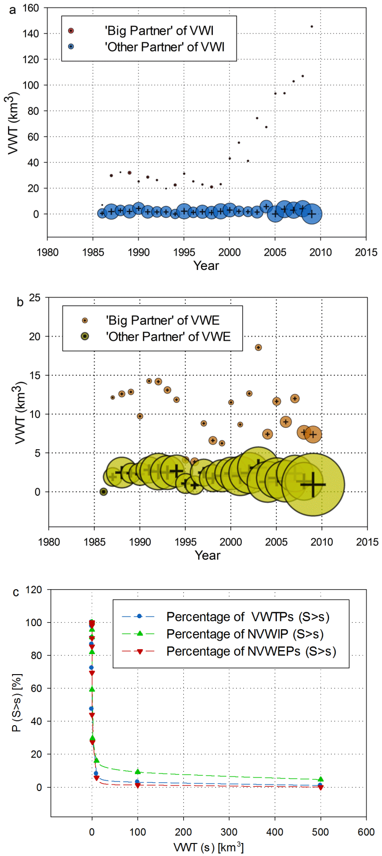

Fig. 6. (a) Polarization of China's net VWI network. The size of bubbles corresponds to the numbers of "big partners" and "other partners" in net VWI respectively; **(b)** Polarization of China's net VWE network. The size of bubbles corresponds to the numbers of "big partners" and "other partners" in net VWE respectively; **(c)** Node strength exceedance probability distribution of VWTN of China.

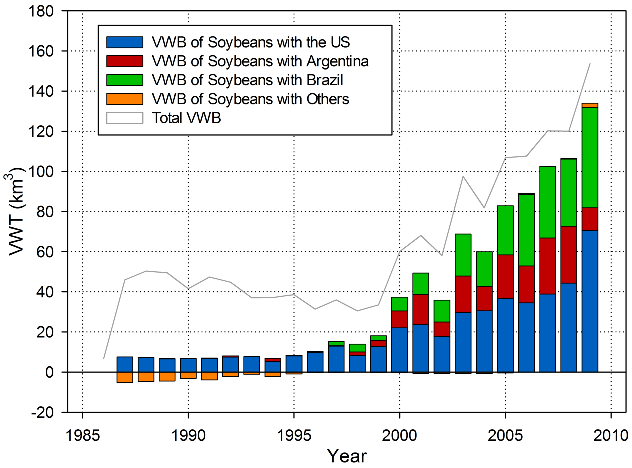

Fig. 7. VWTN associated with soybeans of China over the period of 1986–2009.