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

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

[1]{School of Nature Conservation, Beijing Forestry University, Beijing, 100083, China}
[2]{Department of Environmental Sciences and Policy, Central European University, Budapest, Hungary}

[3] {International Institute for Sustainable Development, 161 Portage Avenue East, Winnipeg MB R3B 0Y7, Canada}

Correspondence to: Junguo Liu (junguo.liu@gmail.com; water21water@yahoo.com)

Abstract

China has dramatically increased its virtual water import over 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. In order to mitigate water scarcity and secure the food supply, virtual water should actively be incorporated into national water management strategies. And 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 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 virtual water 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 virtual water can be considered as an anthropogenically-driven hydrological process closely linked to the socioeconomic sphere. To mitigate water scarcity, it's 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 virtual water 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, virtual water trade 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 virtual water trade have been carried out at different scales. At a global level, Hoekstra and Hung (2005) calculated the volume of crop-related international virtual water flows from 1995 to 1999 and found that conservatively 13% of the water used in crop production is for export in virtual water form. Chapagain et al. (2005, 2006) estimated that virtual water trade has saved 6% of global agricultural water use, which equals 28% of the total amount of virtual water 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 virtual water trade. Dalin et al. (2012a) used a network approach to analyze the evolution of the global virtual water flows from 1986 to 2007. Their findings support the argument that global virtual water trade associated with international food trade has increased global water use efficiency and thus contributing to global water resource saving, although both regional and national virtual water trade 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 affluence (Ozkaynak et al. 2012). 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 virtual water from their abundant water resources. Allan (1998b) pointed out that it is virtual water import that 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 virtual water 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 virtual water import of Egypt has amounted to 24% of its water resources. Other study on Mediterranean countries such as Spain showed its virtual water 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 virtual water trade (Novo et al., 2009). A study on the inter-state virtual water flows in India showed similar results (Verma et al., 2009). They found that the existing virtual water trade 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 virtual water trade of China, which is influenced by both micro- and macro-economic conditions and weather fluctuations, has developed unconsciously and suggested that active virtual water 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 virtual water 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.

Literature is available on the amount of virtual water traded between China and other countries, but there is a lack of research on the geographic distribution of China’s virtual water trade network, 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 virtual water trade network have never been analysed. This study is aimed at reconstructing the evolution, geographic distribution and patterns of China’s crop-related virtual water trade network 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 virtual water trade network 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, climate fluctuations, 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

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

[Insert Table 1]

2.4 Virtual Water Trade

Virtual water trade is associated with the international food trade of corresponding agricultural commodities, and consists of virtual water import and virtual water export. Trade data were adopted from FAOSTAT's (2012) detailed trade matrix. Each traded crop has its own country-specific and crop-specific virtual water content. Virtual water trade between two countries is calculated by multiplying the virtual water content by the traded amounts and adding the values obtained for all the traded crops. Virtual water balance is defined by substracting Virtual water export from Virtual water import. If the value of Virtual water balance is positive then there is a net virtual water import; and if the value of virtual water balance is negative then there is a net virtual water export. Virtual water flow is also referred to virtual water trade in some literature. It better illustrates virtual water trade as an important anthropogenic way of hydrological process in socioeconomic sphere. For convenience, the countries which import / export virtual water from / to China are denominated as 'virtual water import partners' (*VWIPs*) and 'virtual water export partners' (*VWEPs*). Since some countries can be importers and exporters simultaneously, 'net *VWIPs*' and 'net *VWEPs*' are also introduced in this study.

2.5 Virtual Water Trade Network

The virtual water trade relationships between China and 'virtual water trade partners' (*VWTPs*) can be viewed collectively as a directed and weighted virtual water trade network (Dalin et al., 2012a). Each trade partner forms a node in the trade network in a given year, and virtual water flows associated with corresponding agricultural commodities form the links between nodes with the direction pointing to China as net virtual water import and the direction pointing from China as net virtual water export, respectively. The volume of traded virtual water 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 virtual water trade network 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 partners as the impact of such data divergence is assumed negligible if any. 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 virtual water trade 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 and there are 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 virtual water 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. Fig. 1 shows the evolution of crop-related *VWTPs* of China over the period 1986 – 2009. Although there are more countries in Asia, Europe and Africa in total, there is no evidence showing that a simple relationship exists between the number of countries in one certain continent and the growth rate of the number of trade partners in that same continent. The building of trade partnership is driven by multiple factors including geographic distance, economic comparative advantage, international relationship etc. The correlation between the geographic location of the trade partners by continent and water endowment of the corresponding continent implies water endowment might be an important factor driving to form such a pattern.

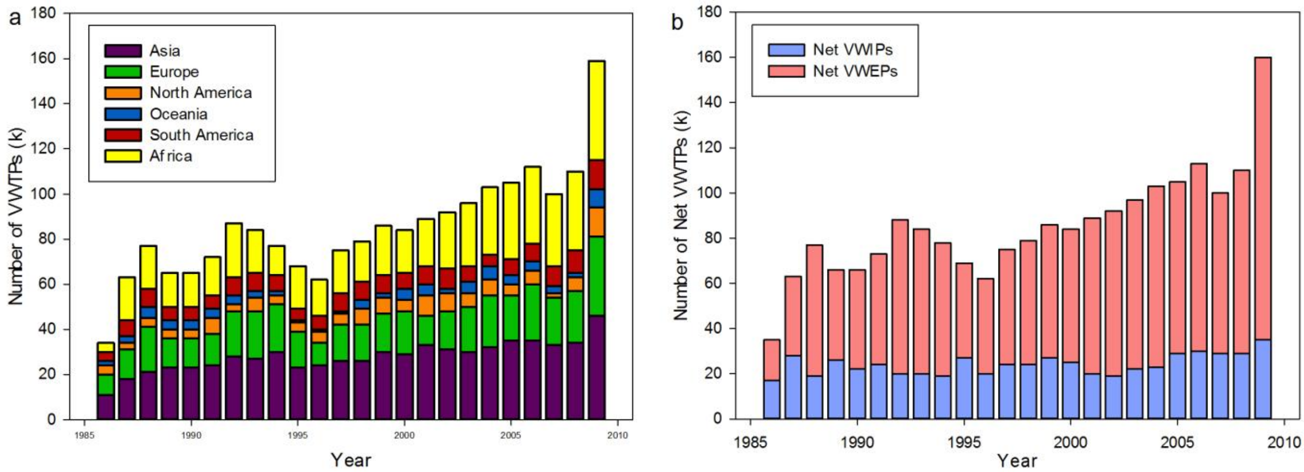

Fig. 1. (a) The evolution of geographic distribution in number of China's *VWTPs* by continent over the period of 1986 – 2009; (b) The evolution of import-export relationship in number of China's *VWTPs* over the period of 1986 – 2009.

China has a positive crop-related total virtual water balance with the total net virtual water import of 934 km^3 and yearly average of 39 km^3 over the period 1986 - 2009. Grain crops account for 97% of all virtual water imports and 53% for all virtual water exports. Despite the overwhelmingly dominant role of grain crops, cash crops also play an important role as they contribute to 46% for all virtual water exports. Furthermore, according to most recent trends, cash crops may replace grain crops as the largest contributor in total virtual water exports. As shown in 2008 and 2009, they accounted for 80% and 84%, respectively, a double jump from 48% in 2007. Fig. 2 shows the crop-related virtual water trade of China.

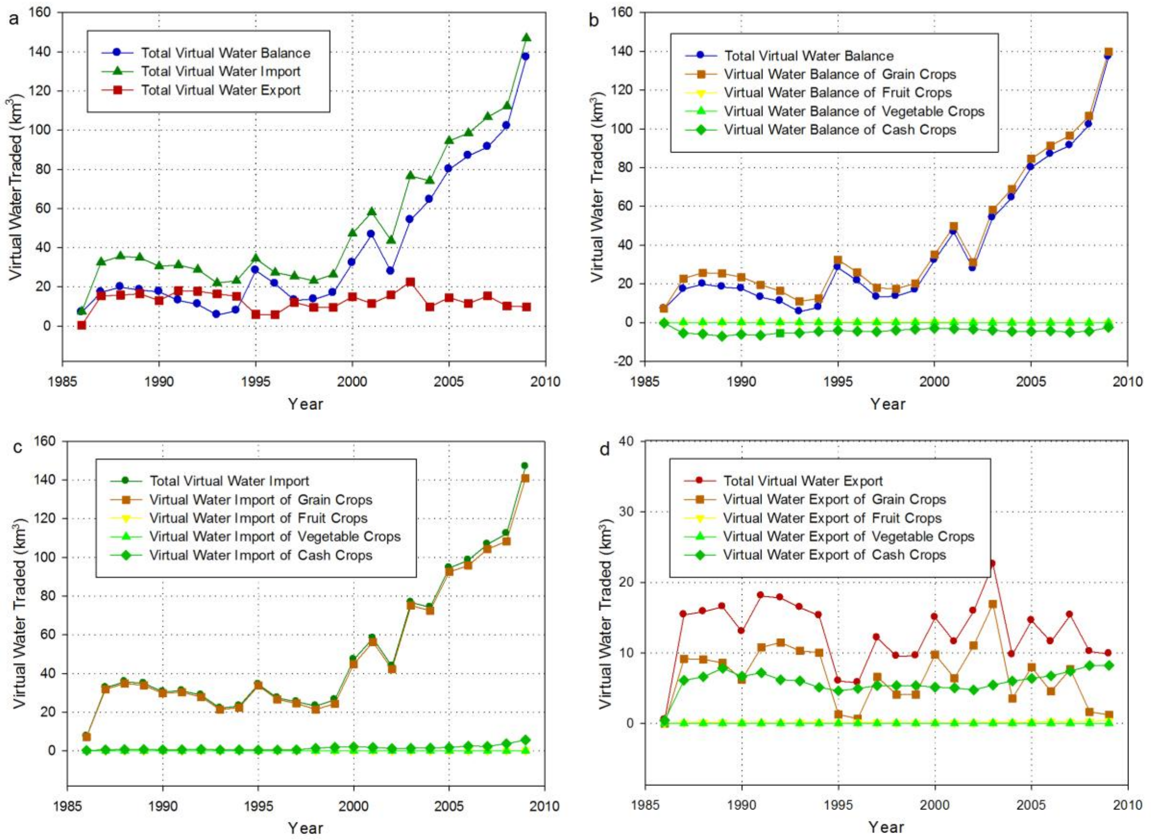

Fig. 2. Crop-related virtual water trade of China over the period of 1986 – 2009: (a) Total virtual water trade of China; (b) Contributions of different crops to total virtual water balance; (c) Contributions of different crops to total virtual water import; (d) Contributions of different crops to total virtual water export.

3.2 Geographic distribution of virtual water trade network of China

China mainly imported virtual water from North America before 2000 but added South America as another major trade partner of virtual water import afterwards. In 1986, China imported 6.70 km^3 virtual water 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 virtual water import from South America has been catching up with that of North America. The geographic distribution of virtual water export is more balanced and smaller in volume. Asia has generally been the major destination of virtual water export over the study period of time, but Europe and Africa have also been important trade partners for China's exports. The distribution of virtual water export among these three continents has become more even since 2008 (See Fig. 3).

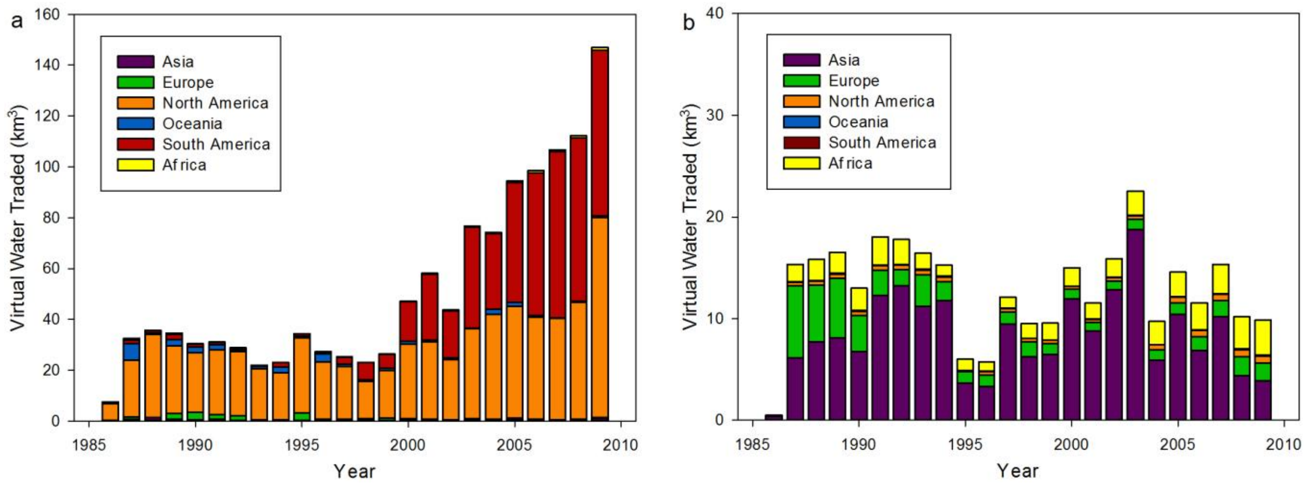

Fig. 3. The evolution of geographic distribution of China's virtual water trade over the period of 1986 – 2009: (a) Geographic distribution of virtual water import; (b) Geographic distribution of virtual water export.

Fig. 4 combines the numbers of *VWTPs* and geographic distribution of virtual water trade to give a holistic view of the evolution of China's virtual water trade network over 1986 – 2009.

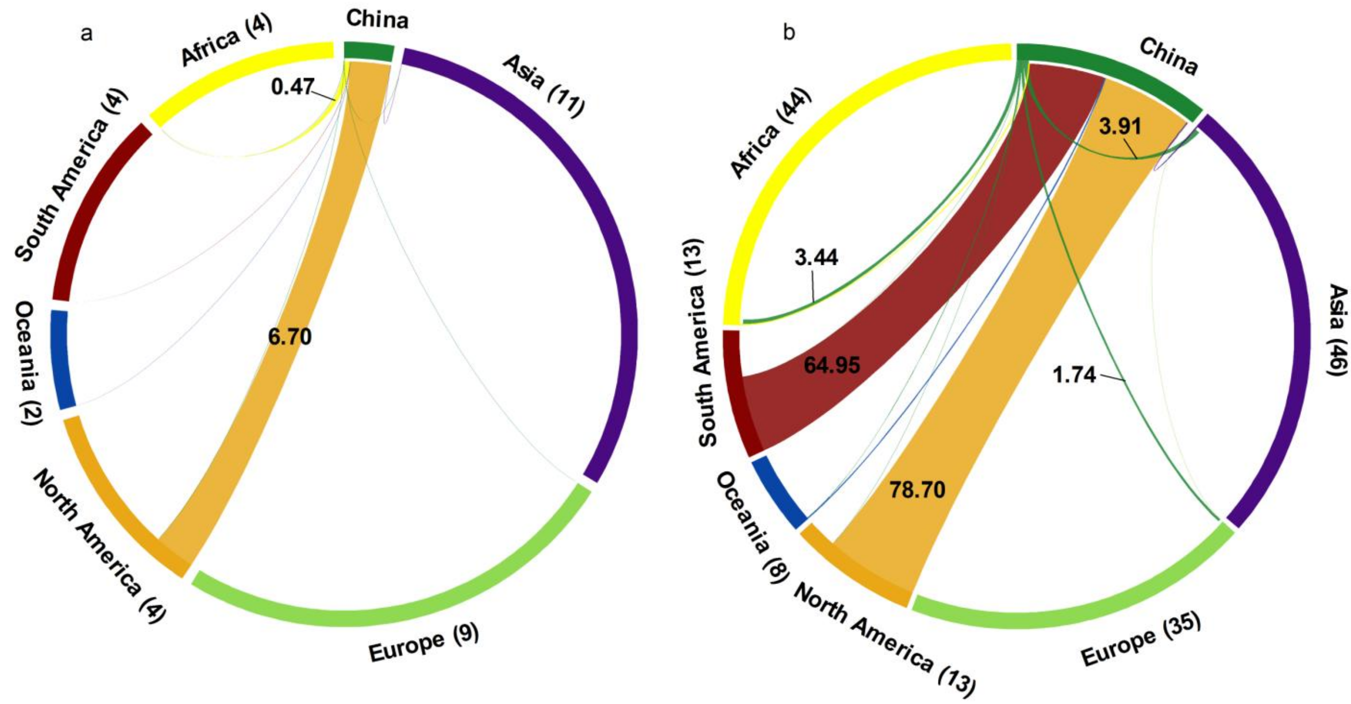

Fig. 4. Geographic distribution of China's virtual water trade in 1986 and 2009. The size of the segment represents the number of *VWTPs* in corresponding continent with labels in the brackets (the size of China is not in proportion); the size of the contribution track represents the volumes of virtual water traded with label unit of km^3. (a) 1986; (b) 2009. Figures produced with Circos (Krzywinski et al., 2009)

3.3 Properties of virtual water trade network of China

Considering trade links and the total amount of virtual water 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. 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 virtual water 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 virtual water traded has been unchanged over the study period.

If we take the number of China's *VWTPs* (trade links k) and the corresponding virtual water 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 virtual water trade network 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 characteristic which had remained unchanged during the study period of time. Scale-free property shows the existence of trade partners with node strength that greatly exceeds the average ('hubs'). This implies both the robustness and weakness of the network. If failures occur at random and the vast majority of nodes are those with small strength, the likelihood that a 'hub' would be affected is almost negligible; even if a hub-failure occurs, the network will generally not lose its connectedness. However, on the other hand, if any of the very few major trade partners are removed, then the pattern of the network would be entirely changed, which is not at the favor of a steady food supply chain.

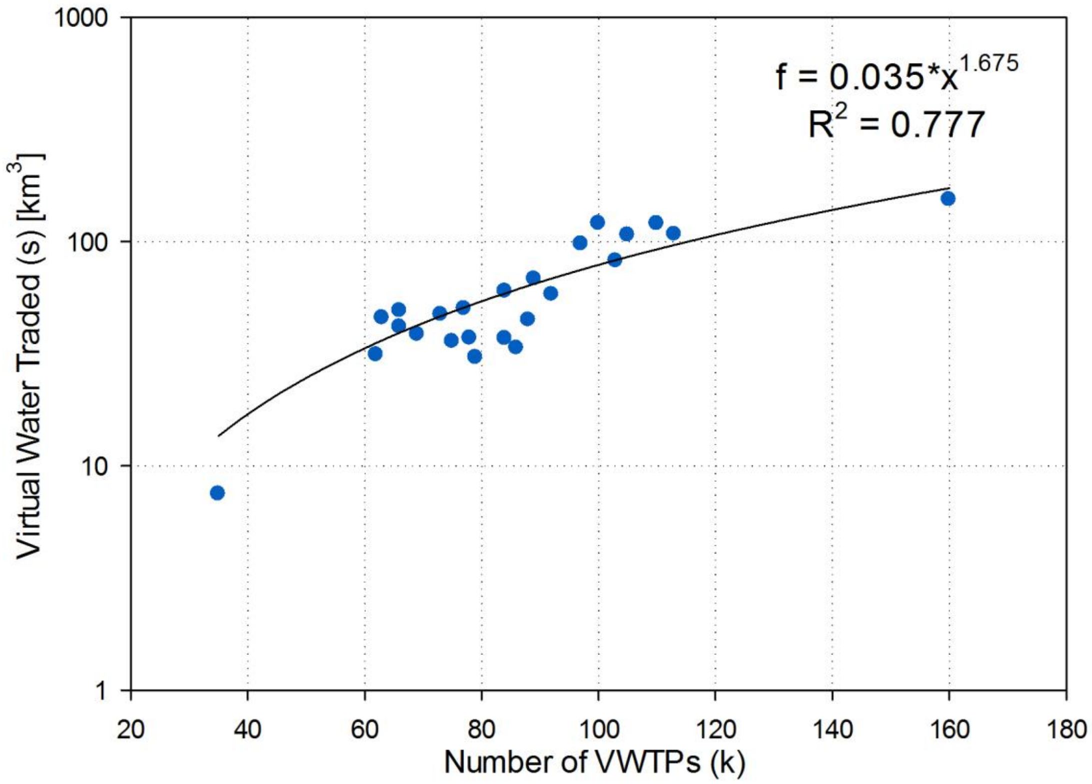

Fig. 5. Power law shows the 'scale-free' degree distribution of virtual water trade network of China as power-laws have the property of having the same functional form at all scales.

Further network analysis confirms that the virtual water trade network of China is heterogeneous and highly polarized. A few 'big partners' (defined as trade partners who traded larger than average volumes of virtual water) dominated China's virtual water trade (see Fig. 6a and 6b). In terms of net virtual water import, the number of 'big partners' was relatively small and rather steady. The yearly average number of 'big partners' is 3.1, with an absolute deviation (referring to the absolute difference between an element in a data set and the mean value of that data set) of 0.45, constituting 12.98% of the total number of net *VWIPs*. But they accounted for 95.97% of total net virtual water import. 'Other partners' contributed mostly to the increase of the number of trade partners. The polarity is also prominent within net virtual water export. In net virtual water export, 'big partners' has a yearly average number of 11.7, with an absolute deviation of 3.6, constituting 18.97% of the total number of

VWEPs. They took up 83.55% of the total net virtual water export.

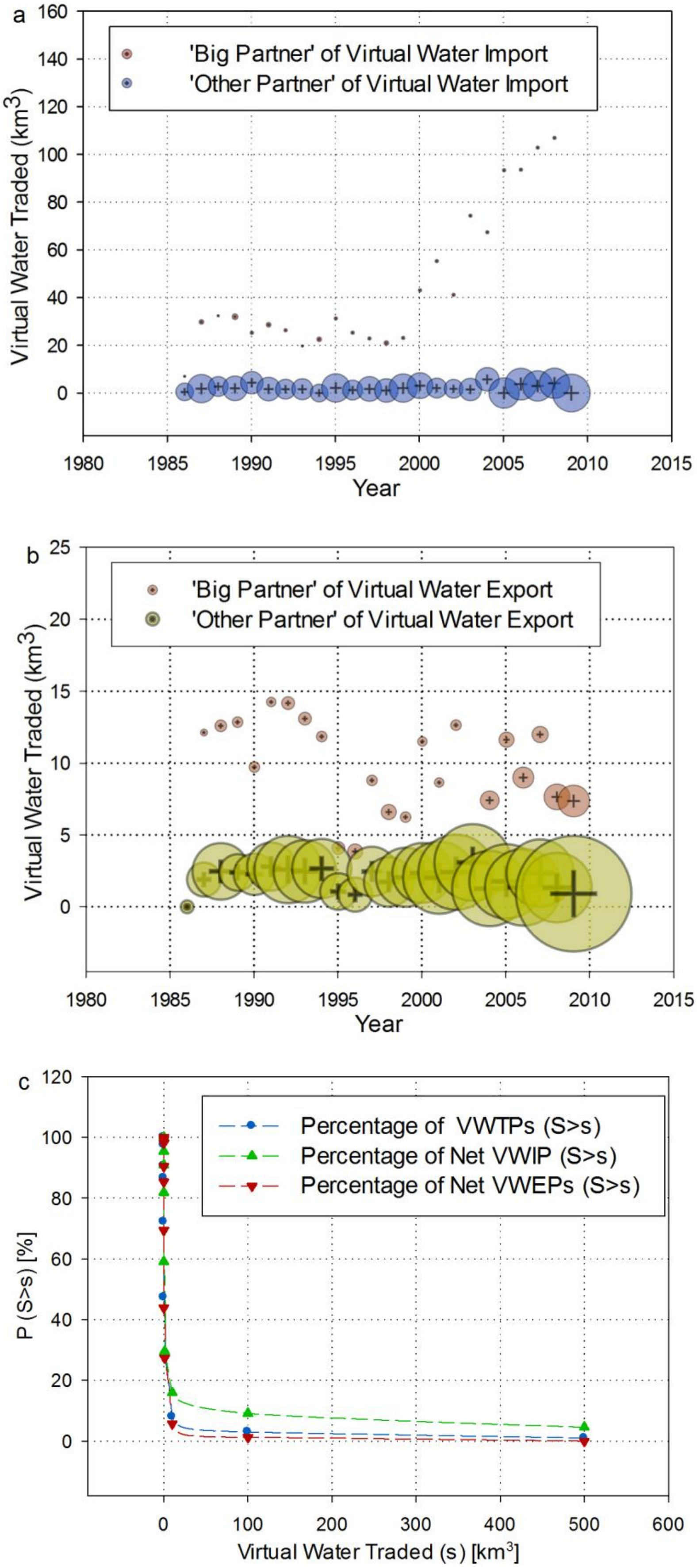
a
'Big Partner' of Virtual Water Import
'Other Partner' of Virtual Water Import
Virtual Water Traded (km3)
Year
b
'Big Partner' of Virtual Water Export
'Other Partner' of Virtual Water Export
Virtual Water Traded (km3)
Year
c
Percentage of VWTPs (S>s)
Percentage of Net VWIP (S>s)
Percentage of Net VWEPs (S>s)
P (S>s) [%]
Virtual Water Traded (s) [km3]

Fig. 6. (a) Polarization of China's net virtual water import network. The size of bubbles corresponds to the numbers of 'big partners' and 'other partners' in net virtual water import respectively; (b) Polarization of China's net virtual water export network. The size of bubbles corresponds to the numbers of 'big partners' and 'other partners' in net virtual water export respectively; (c) Node strength exceedance probability distribution of virtual water trade network of China.

Node strength exceedance probability distribution of virtual water trade reconfirmed the highly-polarized characteristics of China's virtual water network. The probability distribution shows the feature of a 'fat tail' in each net virtual water trade network, net virtual water import network, and net virtual water export 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 virtual water trade 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 virtual water trade 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 virtual water to China over the period of 1986 - 2009 while all the other countries imported 29 km^3 from China. The accumulated virtual water balance associated with soybeans accounted for 56.97% in the total virtual water balance of China between 1986 and 2009, and 78.26% between 2000 and 2009.

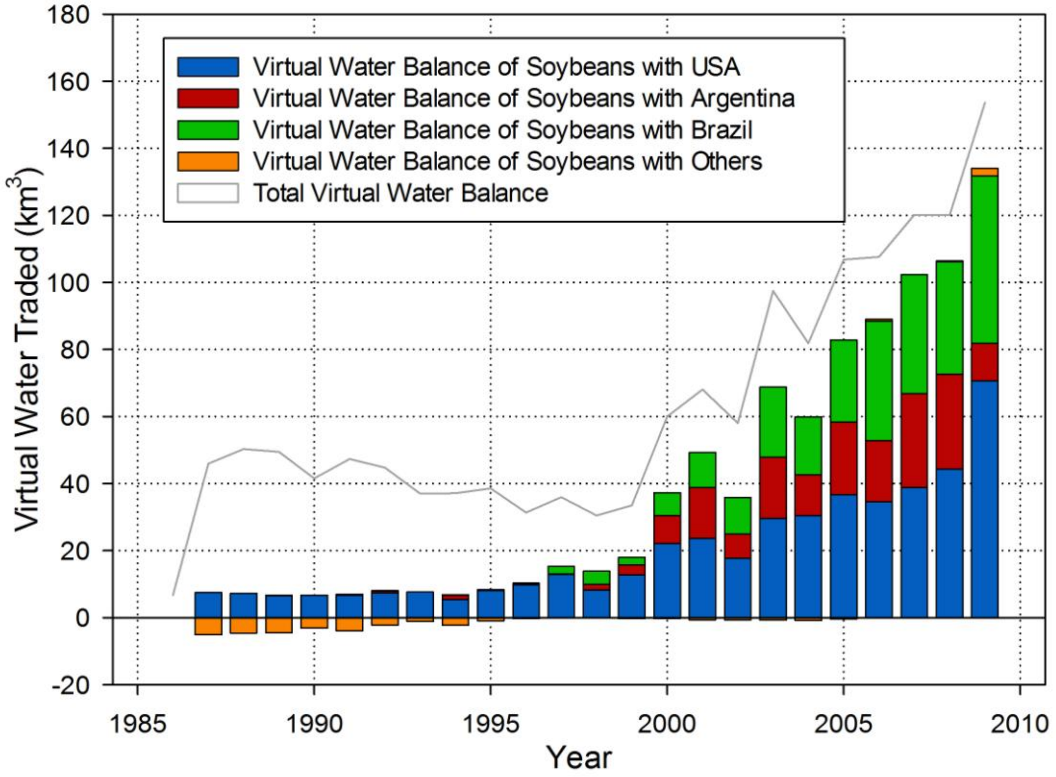

Fig. 7. Virtual water trade network associated with soybeans of China over the period of 1986 – 2009.

4. Discussion

4.1 Comparison and Analysis

China has significantly raised its net virtual water import from 7.02 km^3 in 1986 to 137.14 km^3 in 2009. The pattern of historic trend of virtual water trade are essentially the same and values of traded virtual water 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 virtual water trade in their study. This dramatic rise in China's net virtual water import is mostly due to a major food trade policy shift in 2001 (Carter and Rozelle, 2001). China's virtual water import is far larger than virtual water export, and grain crops overwhelmingly dominate virtual water import, 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 virtual water export with a share of 53%, although not as dominant as in virtual water import. virtual water export of fruits and vegetables are minor but cash crops are significant, with a share of 46%, among which, virtual water export of tea is the most important source. This finding, again, goes along with the study of Liu et al. (2007) on China's virtual water trade between 1961 and 2004. The comparison suggests that the recent trend of China's virtual water trade 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 virtual water satisfies the power law and reflects the 'scale-free' feature of China's virtual water trade network, which is also observed in the global virtual water trade network (Dalin et al., 2012a). This network property implies the existence of trade partners with traded virtual water greatly exceeds the average. It is also important for the projection of the way China's virtual water trade may continue to evolve with modelling methods. Despite of the increase in both *VWTPs* and traded virtual water, which is coherent with the general behaviour of the global virtual water trade network (Dalin et al., 2012a), there is a consistency of the geographic distribution in import-export relationship of virtual water trade: a net virtual water import from water-abundant areas of North and South America, and a net virtual water export 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 virtual water trade (Dalin et al., 2012a), China's crop-related virtual water trade 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, virtual water trade helps save the world water resources. But water endowment might not be the only factor affecting virtual water 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 virtual water trade network is the high heterogeneity i.e., within both import and export a small group of *VWTPs* control the entire trade. This is also coherent with the global virtual water trade network characteristics that a small number of global actors control a significant portion of virtual water export, which reflects Pareto Principle in the context of virtual water trade network (Carr et al., 2012a; Carr et al., 2012b; Carr et al., 2013).

Notably, soybeans, nearly all imported from the US, Brazil and Argentina (in fact, the soybean-associated virtual water balance of other countries is minor and negative), account for 91.7% of China's virtual water trade 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 virtual water import. The large demand for soybeans in China has not only changed China's virtual water trade network 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. 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* at it would consume more water if China produced those soybeans domestically. 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

The results show that grain crops have been the major source of imported virtual water of China, which is significantly contributed by the dramatic increase of soybeans import. And this recent trend has been kept since the policy turning point in 2001. China is facing increasingly severe water scarcity (Jiang, 2009; Liu et al., 2013). 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 available water resources will be further reduced by expanding water pollution (Piao et al., 2010; Mountford, 2011; Wang and Zhang, 2011). Therefore, China needs a more integrated water management strategy, including an active virtual water policy.

An active virtual water trade 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 virtual water trade 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). Whether China will take virtual water strategy as an active water policy, it can be expected that China will continue to increase import of grain crops and their associated virtual water. This may further impose pressure on the supply chain of international staple crop market and continue to drive up the food price, as being seen in the case of soybeans. In turn, this would recall the a long-standing concern about the food sovereignty and security of China. There is 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.

Taking the high heterogeneity of virtual water import in China via the tight coupling of the supply chain with a small group of countries into account, in order to reduce the risk of volatile international food market and increase resilience, the sources of virtual water import should be further diversified. In this study, we found China has already increased major *VWTPs*, i.e. shifting from North America alone to both North and South Americas. This helps control the supply chain risk and China should continue to seek for diversifying major trade partners. Furthermore, considering the fact that most of the virtual water resources available for export tend to remain concentrated in a small set of countries (Carr et al., 2013), which can be also seen from our results that most of *VWIPs* are located in Americas with a limited number, and the projection that the future structure of global virtual water trade network will become increasingly heterogeneous (Dalin et al, 2012b), it is not sufficient to diversify *VWIPs* as an element of an improved virtual water trade strategy. The structure of agriculture also needs to 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.

Our results also indicate that cash crops may replace grain crops as the largest contributor in total virtual water export of China. Liu et al. (2007) pointed out that the goal of the structural adjustment of agriculture is to achieve so-called "three-high" agriculture: high output, high quality, and high efficiency. They showed that most crops that turn water into high economic value 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 crops characterized by low water intensity but high economic-value. It's crucial to strive for a more efficient agricultural use of water as an element of a virtual water trade strategy. Our results show that Asia, Africa, and Europe have been the main and fast growing destinations of China's exported virtual water. Those are also water-stressed regions in general, which implies greater potential markets for China's virtual water export.

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Reference

Allan, J. A.: Virtual water: A strategic resource: Global solution to regional deficits, Groundwater, 36 (4), 545-546, 1998a.

Allan, J. A.: Watersheds and problemshed: Explaining the absence of armed conflicts over water in the Middle East, Middle East Review of International Affairs, 2 (1), 49-51, 1998b.

Boccaletti, S., Latora, V., Moreno, Y., Chavez, M., and Hwang, D.: Complex network: structure and dynamics, Physics Reports, 424, 186-191, 2006.

Carr, J.A., D'Odorico, P., Laio, F., Ridolfi, L., and Seekell, D.: Inequalities in the networks of virtual water flow, Eos Transaction, AGU, 93 (32), 309, 2012a.
DOI: 10.1029/2012EO320001

Carr, J.A., D'Odorico, P., Laio, F., and Ridolfi, L.: On the temporal variability of the virtual water network, Geophysical Research Letters, 2012b. DOI:10.1029/2012GL051247

Carr, J. A., D'Odorico, P., Laio, F., and Ridolfi, L.: Recent history and geography of virtual water trade, PLoS ONE, 8 (2), e55825, 2013. DOI: 10.1371/journal.pone.0055825

Carter, C. A. and Rozelle, S.: Will China's agricultural trade reflect its comparative advantage? China's Food and Agriculture: Issues for the 21st Century, ed. F. Gale, ERS, USDA, AIB, 775, 27-30, 2001.

Chapagain, A. K., Hoekstra, A. Y. and Savenije, H. H. G.: Saving water through global trade, Value of Water Research Report Series No. 17, UNESCO-IHE, Delft, the Netherlands, 2005.

Chapagain, A. K., Hoekstra, A. Y. and Savenije, H. H. G.: Water saving through international trade of agricultural products, Hydrology and Earth System Sciences, 10 (3), 455-468, 2006.

Dalin, C., Konar, M., Hanasaki, N., Rinaldo, A., and Rodriguez-Iturbe, I.: Evolution of the global virtual water trade network, Proceedings of National Academy of Sciences, 109 (16), 5989-5994, 2012a.

Dalin, C., Suweis, S., Konar, M., Hanasaki, N., and Rodriguez-Iturbe , I.: Modeling past and future structure of the global virtual water trade network, Geographical Research Letters, 39, L24402, 2012b. DOI:10.1029/2012GL053871

D'Odorico, P., Carr, J.A., Laio, F., and Ridolfi, L.: Spatial organization and drivers of the virtual water trade: a community-structure analysis, Environmental Research Letters, 7, 034007, 2012. DOI: 10.1088/1748-9326/7/3/034007

El-Sadek, A.: Virtual water trade as a solution for water scarcity in Egypt, Water Resources Management, 24 (11), 2437-2448, 2010.

FAOSTAT: FAO Statistical Database, Food and Agricultural Organization of the United Nations, Rome, Italy, available at: http://faostat.fao.org/, 2012. last access date: 1/7/2012.

Hoekstra, A. Y. and Hung, P. Q.: Globalization of water resources: international virtual water flows in relation to crop trade, Global Environmental Changes, 15, 45-56, 2005.

Hoekstra A. Y.: The relation between international trade and freshwater scarcity, Working Paper presented in the WTO working paper series as commissioned background analysis for the World Trade Report 2010 on "Trade in Natural Resources: Challenges in Global Governance", available at: http://www.wto.org/english/res_e/reser_e/ersd201005_e.pdf, 2010. last access date: 7/7/2012.

Huang, J. and Rozelle, S.: China's accession to WTO and shifts in the agriculture policy, Working Paper 02-002, University of California, Davis, California, 2002.

Jiang, Y.: China's water scarcity, Journal of Environmental Management, 90, 3185-3196, 2009.

Krzywinski, M., Schein, J., Birol, İ., Connors, J., Gascoyne, R., Horsman, D., Jones, S., and Marra, M.: Circos: an information aesthetic for comparative genomics. Genome Res, 19, 1639-1645, 2009.

Liu, J. and Savenije, H.H.G.: Time to break the silence around virtual-water imports, Nature, 453, 587-587, 2008.

Liu, J., Yang, H. and Savenije, H.H.G.: China's move to higher-meat diet hits water security, Nature, 454, 397-397, 2008. DOI: 10.1038/454397a

Liu J., Zang, C., Tian, S., Liu J., Yang, H., Jia, S., You, L., Liu, B., Zhang, M.: Water conservancy projects in China: achievements, challenges and way forward, Global Environmental Change, 23 (3), 633—643, 2013. DOI: 10.1016/j.gloenvcha.2013.02.002

Liu, J., Zehnder, A. J. B. and Yang, H.: Historical trends in China's virtual water trade, Water International, 32 (1), 78-90, 2007.

Liu, J., Zehnder, A. J. B. and Yang, H.: Global consumptive water use for crop production: the importance of green water and virtual water, Water Resource Research, 45 (5), W05428, 2009. DOI:10.1029/2007WR006051

Mountford, H.: Water: the environmental outlook to 2050, presented in the OCED Global Forum on Environment: Making Water Reform Happen, available at: https://community.oecd.org/servlet/JiveServlet/previewBody/40641-102-1-76036/OECD, 2011. last access date: 6/13/2013.

Novo, P., Garrido, A., Varela-Ortega, C.: Are virtual water “flows” in Spanish grain trade consistent with relative water scarcity, Ecological Economics, 68 (5), 1454-1464, 2009.

Ozkaynak, B., Pinter, L., and D. P. van Vuuren, D. P., Bizikova, L., Christensen, V., Floerke, M., Kok, M., Lucas, P., Mangalagiu, D., Alkemade, R., Patterson, T., Shilling, J., Swanson, D., Bassi, A., Feldmann, F., Jager, J., Ochola, Qu,W., Ramakrishna, K., Ringler, C., Ertor, P., and Pervushina, N.: Scenarios and sustainability transformation, in UNEP: Global Environment Outlook-5, Nairobi, Kenya, 419-456, 2012.

Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., Zhou, Li., Liu, H., Ma, Y., Ding, Y., Friedlingstein, P., Liu, C., Tan, K., Yu, Y., Zhang, T., and Fang, J.: The impacts of climate change on water resources and agriculture in China, Nature, 467, 43-51, 2010. DOI:10.1038/nature09364

Renault, D.: Value of virtual water for food: Principles and features, Value of Water Research Report Series No. 12, ed. A. Y. Hoekstra, UNESCO-IHE, Delft, the Netherlands, 2003.

Shuval, H.: ‘Virtual water’ in the water resource management of the arid Middle East, Water Resource in the Middle East, 2, 133-139, 2007.

Tamea, S., Allamano, P., Carr, J.A., Claps, P., Laio, F., and Ridolfi, L.: Local and global perspectives on the virtual water trade, Hydrology and Earth System Sciences, 17, 1205-1215, 2013. DOI: 10.5194/hess-17-1205-2013

Verma, S., Kampman, D. A., van der Zaag, P., and Hoekstra, A. Y.: Going against the flow: a critical analysis of inter-state virtual water trade in the context of India’s National River Linking Program, Physics and Chemistry of the Earth, 34, 261-269, 2009.

Wang, S. and Zhang, Z.: Effects of climate change on water resources in China, Climate Research, 47, 77-82, 2011. DOI: 10.3354/cr00965

Yang, H. and Zehnder, A.: China’s regional water scarcity and implications for grain supply and trade, Environment and Planning A, 33, 79-95, 2001.

Yang, H. and Zehnder, A.: ‘‘Virtual water’’: An unfolding concept in integrated water resources management, Water Resource Research, 43, W12301, doi:10.1029/2007WR006048, 2007.

Zimmer, D. and Renault, D.: Virtual water in food production and global trade: Review of methodological issues and preliminary results, Virtual Water Trade Proceedings of the International Expert Meeting on Virtual Water Trade, ed. A. Y. Hoekstra, UNESCO-IHE, Delft, the Netherlands, 93-107, 2003.

Table 1. National average crop water requirements, crop yields (average between 1986 and 2009) and virtual water contends (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).

Note: Liu et al. (2007) used NBSC data in the calculation of national average crop water requirements. The reasons are as follows. The national and provincial data are sufficient to analyze the virtual water trade patterns in China in this paper. Although more spatially explicit datasets are available, we do not need grid-based data for the virtual water trade analysis (and it is also difficult to do such analysis because trade data are not available at a grid cell level). For the national and provincial data, NBSC is the most commonly used data source.

Crop Category	Crop Type	National Average Crop Water Requirements (m^3/Ha)	Yield (ton/ha)	Virtual Water Contends (m^3/ton)
	Rice (paddy)	8000	6.03	1333
	Wheat	4300	3.75	1171
	Maize	4000	4.76	850
Grain	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
	Apples	4500	7.67	864
	Citrus	8850	10.97	1093
Fruit	Pears	4850	7.76	692
	Watermelons	3400	26.80	138
	Bananas	12900	19.01	714
	Grapes	5940	11.04	610
	Tomatoes	4750	27.78	179
	Cabbages	4010	27.01	155
Vegetable	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

Figure legends

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 virtual water trade of China over the period of 1986 – 2009: (a) Total virtual water trade of China; (b) Contributions of different crops to total virtual water balance; (c) Contributions of different crops to total virtual water import; (d) Contributions of different crops to total virtual water export.

Fig. 3. The evolution of geographic distribution of China's virtual water trade over the period of 1986 – 2009: (a) Geographic distribution of virtual water import; (b) Geographic distribution of virtual water export.

Fig. 4. Geographic distribution of China's virtual water trade 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 virtual water traded with label unit of km^3. (a) 1986; (b) 2009. Figures produced with Circos (Krzywinski et al., 2009)

Fig. 5. Power law shows the 'scale-free' degree distribution of virtual water trade network 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 virtual water import network. The size of bubbles corresponds to the numbers of 'big partners' and 'other partners' in net virtual water import respectively; (b) Polarization of China's net virtual water export network. The size of bubbles corresponds to the numbers of 'big partners' and 'other partners' in net virtual water export respectively; (c) Node strength exceedance probability distribution of virtual water trade network of China.

Fig. 7. Virtual water trade network associated with soybeans of China over the period of 1986 – 2009.