**A thesis submitted to the Department of Environmental Sciences and Policy of Central European University in part fulfilment of the Degree of Master of Science**

# Recent Evolution of Crop-related Virtual Water Trade Network of China and Policy Implications



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No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

(signed)

SHI Jin

**CENTRAL EUROPEAN UNIVERSITY**

**ABSTRACT OF THESIS**

submitted by:
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In this paper, the virtual water trade associated with 27 major primary crops of China over the period of time 1986 – 2009 has been calculated and the virtual water trade network been analyzed. The results show that the crop-related virtual water import of China has increased dramatically during the studied period of time; there is a net virtual water import from water resource relatively abundant areas of North and South Americas, and a net virtual water export towards water resource relatively stressful areas of Asia, Africa, and Europe. Virtual water import is far larger than virtual water export and in both import and export a rather small number of trade partners control the whole trade. Grain crops are the major contributors of the total virtual water trade and among grain crops, soybeans (mostly imported from USA, Brazil and Argentina) take the most prominent role. As crop water use efficiencies in North and South Americas are generally higher than those in Asia and Africa, the effect of China's crop-related virtual water trade positively contributes to optimizing world crop water use efficiency.

In order to mitigate water scarcity and secure food supply, virtual water strategy should be actively incorporated into national integrated water management. China should reduce export of water-intensive crops and increase import of them. But the source of virtual water import need to be further diversified to strengthen market power and crop structure especially in water stressed North China Plain also need to be adjusted.



**Keywords:** virtual water, crop-related virtual water trade, China, network theory

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*At last, I would like to dedicate this thesis to my dearest Mom and Dad. Without your long-standing love and understanding and support, it’s impossible for me to keep my courage to map out my road.*

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| | |
|---|---|
| CWR | Crop Water Requirement |
| ET | Evapotranspiration |
| FAO | Food and Agriculture Organization |
| NVWE | Net Virtual Water Export |
| NVWEPs | Net Virtual Water Export Partners |
| NVWI | Net Virtual Water Import |
| NVWIPs | Net Virtual Water Import Partners |
| SNWTP | South-North Water Transfer Project |
| TVWB | Total Virtual Water Balance |
| TVWE | Total Virtual Water Export |
| TVWI | Total Virtual Water Import |
| VWB | Virtual Water Balance |
| VWC | Virtual Water Content |
| VWE | Virtual Water Export |
| VWEPs | Virtual Water Export Partners |
| VWF | Virtual Water Flow |
| VWI | Virtual Water Import |

| | |
|---|---|
| VWIPs | Virtual Water Import Partners |
| VWT | Virtual Water Trade |
| VWTPs | Virtual Water Trade Partners |

# 1. INTRODUCTION

## 1. 1 Background

Virtual water is referred to the volume of water used in the production process of a crop commodity. It was first termed by Allan (1998) to provide a new perspective as well as policy tool for food safety and water management strategy. As agriculture is the most fresh-water consuming sector with a share of 80% in total human consumptive water use (Rost et al 2008) and most of that is in crop production (Morison et al 2008), therefore water is closely linked with food security (Falkenmark et al 1998, Merrett et al 2003) and it is crucial to investigate the crop-related virtual water. Transfer of virtual water between economies in different regions take place when crop commodities are traded in the global market. Economies which are trading commodities are essentially exchanging water resources with each other. The flow of virtual water can be considered as an anthropogenic-driven water cycle within socioeconomic sphere other than hydrological process. It's the redistribution of water resource with flow direction influenced by various factors including food shortage, trade policy, and free market power, etc. 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 huge costs, but trade of virtual water is realistic (Hoekstra and Hung 2002) and has been carried on unconsciously for thousands of years. At national level, water-poor economies can mitigate their water-scarcities by actively importing water-intensive commodities instead of producing all of them domestically, while water-rich countries can also benefit economically by exporting virtual water from their abundant water resources. Although some studies (Fraiture et al 2004) suggested that virtual water strategy seems not likely to fully solve global water scarcity due to non-water constraints and there could be some downsides of virtual water trade for both importers and exporters, it's been showed (Chapagain et al 2005, Hoekstra and Hung 2005, Yang and Zehnder 2007) to have already and will continue to help alleviate water-scarcity in some worst water-stressed regions. Furthermore, the flow of virtual water from economies with higher water productivity to those with lower productivity has been raising the average water use efficiency globally by 5% (Hoeskstra 2010).

China is a water-poor country in terms of water resource per capita and there exists a trend of exacerbating water inequality between water-abundant South and water-stressed North in general. What's more, the demand for water resource has kept growing due to the continuing growth of the world-largest population and the very rapid expansion of resource-intensive but low efficient economy, while weak regulation and poor management on protection of water has seen the widely spread of water pollution, which further reduces the water resource available (Jiang 2009). To secure water supply, the Chinese government has been taking a series of measures, including strengthening legislative regulation, limiting the total water consumption, reforming water pricing system, developing water conservation technologies, and constructing new water projects etc. (Jiang 2009). On the other side, during the last two decades, China has significantly increased virtual water import unconsciously associated with international food trade, while intra-regional virtual water flow from water-stressed North to water-abundant South within China has been taking place as well; so it's necessary to further study the virtual water trade of China and enhance its policy relevance to actively incorporate it into national integrated water management strategy.

### 1.2 Aim and objectives

This paper is aimed to analyze the recent two-decade evolution of crop-related virtual water trade network of China and interpret corresponding policy implications. There are following objectives:

- to calculate the virtual water trade associated with 27 crops in China over the period 1986 -2009;
- to illustrate contributions of crops under 4 categories to the total virtual water traded;
- to map the evolution of geographic distribution of virtual water trade network of China;
- to identify the properties and patterns of virtual water trade network of China
- to present policy implications based on findings from the calculations



### 1.3 Outline of the thesis structure

The important literature on the concept, methodology, potential application, and policy implication of virtual water trade will be first reviewed, followed by the elaboration of methods applied in this paper. Then the results will be presented as well as discussions.

The next will be the policy implications based on the obtained results and the general conclusion will be drawn at last.

# 2. LITERATURE REVIEW

## 2.1 Virtual water and virtual water trade

The concept of virtual water was originally defined by Allan (1998) as “the water embodied in food crops that are traded internationally” and it’s within the context of food security and water strategy. It was then expanded to cover many other commodities such as live stocks and industrial products and services. Virtual water trade is believed by some to be a cost-effective market-approach to reduce water inequality and raise global water productivity (Chapagain et al 2005, Hoekstra and Hung 2005, Yang and Zehnder 2007).

Studies on virtual water have been done at different scales. Chapagain et al (2005) estimated that the saving of water resource in agricultural production is 6% of the global water use in agriculture and 28% of the total amount of virtual water flows associated with international agricultural trade. Hoekstra and Hung (2005) calculated the global volume of crop-related international virtual water flows from 1995 to 1999 and found out that conservatively 13% of the water used in crop production is for export in virtual water form. Further research of Hoeskstra (2010) estimated current water use in agriculture is reduced by international trade by 5%. Dalin et al (2012) first used a network approach to analyze the evolution of the global virtual water trade from 1986 to 2007 and found out that both of trade connections and traded virtual water doubled in studied period of time; and also both regional and national virtual water patterns have changed a lot. Their research showed that virtual water imports of Asia grew by 170%

with main partner switched from North America to South America; more intra-regional virtual water trade emerged within North America; the sharp increase in virtual water import of China, mainly associated with soybeans imports has resulted in a global water saving but also contributed to deforestation in Amazon. 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. However, this is still disputable. Fraiture et al (2004) estimated that the crop water use (effective rainfall or rainfall plus irrigation) would be higher by 6% and irrigation depletion by 11% without global virtual water trade in 1995 and argued that although the potential of virtual water trade in water resource saving may seem large theoretically, the actual role would be modest. They pointed out that four factors limit or will continue to limit virtual water trade as a policy tool in water strategy: a. trade between water-rich countries takes the majority; b. "water savings" cannot be fully reallocated; c. "water saving" happens due to the productivity differences not water scarcity; d. political and economic concerns constraint the free trade of virtual water. Despite the disputes, virtual water trade has been recognized by more and more countries as an effective option to mitigate water scarcity and will remain a valid concern especially for water-scarcity countries (Qadir et al 2003).

At national level and river-basin level, 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 the progressive liberation of food market in China. Yang and Zehnder (2001) analyzed the water scarcity in the North China Plain and pointed out that virtual water import should be taken as additional measure in spite of the conventional wisdom of "opening up new sources and economizing on the use of resources" to meet the growing water demand.

Assessment of the crop-related virtual water has been carried out mostly on the total amount of water (Chapagain and Hoekstra 2004). The contribution of different water resource as "green water" (defined as soil water originating from rainfall) and "blue water" (defined as irrigation with water abstracted from ground or surface water systems) have been taken into consideration recently as there are much higher opportunity costs and more negative environmental externalities in the use of "blue water" (Chapagain et al 2006, Aldaya 2010) and therefore it plays a more important role in the relevant policy-making. Aldaya (2010) further showed that the share of green water in exported virtual water associated with maize, soybeans, and wheat from main exporting countries (USA, Canada, Australia and Argentina) is by far the largest over the studied period of time 2000 – 2004. And the role of green virtual water trade appears more important in water, water-dependent food security, and avoiding further potential damage to the water environment as the importing countries usually heavily depends on their blue water resources. Liu et al (2009) showed the low-opportunity cost "green water" accounts for the origin of around 94% of the global crop-related virtual water trade over the period 1998 – 2002. They pointed out that countries with low per capital consumptive water use usually import more virtual water, however, in which income is a constraint, therefore, to enhance the economic capacity of low-income countries could enable them to apply the virtual water strategy to fight against malnutrition of their people. Other study (Hoff et al 2010) reconfirmed the predominant role of “green water” in consumptive water use, which is 4 - 5 times greater than “blue water” and suggested that “green water”-based virtual water trade can help mitigate water scarcity in some countries especially as the water inequalities keeps enlarging in the future due to population growth, climate change, etc. In efforts to incorporate water quality into assessment of virtual water, Guan and Hubacek (2007) calculated the intra-regional virtual water trade within China and found out that the water-scarce North China are importing virtual wastewater, while water-abundant South China is exporting virtual waste water, based on the assumption that crop production impacts on water quality and that such impacts can contribute significantly to water scarcity within a country.

Some studies (Ma et al 2004, Ma et al 2006, Chen 2011, Sun et al 2011) have revealed a very peculiar fact that while the ongoing South-North Water Transfer Project (SNWTP) is carrying real water (40 - 50 $km^3$/yr when fully developed) from water-abundant South China to water-stressed North China (particularly North China Plain), a comparable amount of virtual water (52 $km^3$/yr) associated with agricultural products is flowing reversely. This is mainly because of more arable areas in the North and more developed economies in the South. It indicates that despite water resource endowments, other factors contribute significantly to the mechanism forming and maintaining the pattern of virtual water flows as well. Study on the inter-state virtual water flows in India (Verma et al 2009) showed similar results. They found out 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. Wichelns (2004) pointed out that the metaphor of virtual water only addresses resource endowment and does not consist in production technologies or opportunity costs. In order to enhance the policy-relevance of virtual water metaphor, the theory of comparative advantages could be applied to determine optimal production and trading strategies. His research found that optimal strategies cannot always be fulfilled if only considering resource endowment. In a working paper for WTO, Hoeskstra (2010) warned the serious risk of lack of international trade agreements including provisions on sustainable water use or sustainable products and called for joining the liberation of agricultural products trade and promotion of sustainable agricultural water use through mechanisms such as water label, International Water Pricing Protocol and International Water-Footprint System. These findings can also shed lights on the further understanding of global virtual water trade pattern and give hints to better global water governance to optimize the reallocation of global water resource through international fair trade treaties.



## 2.2 Quantification of virtual water

The calculation of virtual water depends largely on the type of products. For example, it is often quite clear to assess virtual water content of crops through evapotranspiration but can be very difficult for other products as many more different processes are involved in the production. Zimmer and Renault (2003) categorized products into six different groups:

- Primary Products (e.g. cereals, vegetables, fruits, etc.)

  The relationship between virtual water content and production is simple and clear. Virtual water content can be directly calculated from dividing crop water requirement ($m^3$/ha) by yield (ton/ha):

- Processed Products (e.g. sugar, seed oil, alcoholic beverages, etc.)

- Transformed Products (e.g. live stocks)

  Transformed products consume primary products (cereals, grass, other by-products). Efficiency of processes should be taken into consideration when dealing with processed products.

- By-Products (e.g. cotton seed is used to produce oil, while cotton is grown mainly for fiber production)

  By-products are produced by crops primarily for other purposes than their nutritional values. There are three methods to estimate the virtual water content of crops in this category. The first is to allocate the virtual water content proportionally to the quantities of all sub-products; the second is to allocate the virtual water content according to the economic value; while the third is based on the nutritional equivalence principle (Renault 2003).

- Multiple-Products

  Multiple-products are grown not for single purpose. It is also proposed to apply the nutritional equivalence principle (Renault 2003) to estimate the virtual water content.

- Low or Non-Water Consumption Products (e.g. sea food and sea fish)

  These products do not consume any water through evapotranspiration during production, and the nutritional equivalence principle (Renault 2003) also applies.

Renault (2003) suggested five major steps needed to be considered in calculating virtual water, namely: characterize food products with regard to processes, mapping the flux of products, specify the production process for each type of food product, specify the scope of the study, and calculate virtual water content and flows.

# 3. METHODOLOGY

## 3.1 Selection of studied crops

Twenty-seven primary crops in four groups (see Table 1) including 8 grain crops, 6 fruit crops, 6 vegetable crops and 7 cash crops were selected to carry out the calculations and portrait the profile of crop-related virtual water trade of China over the period 1986 -2009.

Table 1: Selected crops.

| | |
|---|---|
| **Grain** | Rice (paddy), Wheat, Maize, Soybeans, Millet, Sorghum, Potatoes, Barley |
| **Fruit** | Apples, Citrus, Pears, Watermelons, Bananas, Grapes |
| **Vegetable** | Tomatoes, Cabbages, Carrots, Cucumbers, Lettuce, Spinach |
| **Cash** | Rapeseed, Sunflower, Sesame, Sugar Beet, Sugar Cane, Tobacco, Tea |

These crops constitute around 80% of the total harvested area of the primary crops in China from 1986 to 2009 by average (FAOSTAT 2012). In order to compare the results, the grouping of selected crops followed Liu et al (2007), which included soybeans into grain crops as the usual categorization in China's statistics and separated fruits and vegetables from cash crops.

## 3.2 Crop water requirement (CWR)

The crop water requirement (CWR) is defined as the accumulated crop evapotranspiration (ET) over the complete growing period under suitable growing conditions (Chen et al 1995). This definition applies for most crops, however, Chen et al (1995) pointed out that for rice, percolation within certain range could actually benefit the rice yield based on many experiments in China, so it's reasonable to use the total water requirement to calculate the CWR for rice. The CWR depends on various factors, including type of crops, weather conditions, soil moisture content, irrigation, agricultural technologies, etc. (Chen et al 1995). So different crops have different CWRs and for a certain crop, CWR can also vary in different places and different years, due to fluctuations of all affecting factors. The CWR can be measured directly by experiments on the field level or be calculated using theoretical and empirical equations or a combination of both (Chen et al 1995). In this paper, the CWR data (see Table 2) of selected crops were adopted from the national average CWR data used in Liu et al (2007), which mainly based on the authoritative experimental data in Chen et al (1995) and were calculated with weighted average method as in Eq. (1). The CWRs were assumed to remain constant despite of the variation in affecting factors between different years as the yearly data in China are not readily available.

$$\overline{CWR_{c,j}} = \frac{\sum_i CWR_{c,i,j} \times A_{c,i,j}}{TA_{c,j}} \qquad \text{Eq. (1)}$$

$\overline{CWR_{c,j}}$ (m$^3$/ha) is the weighted average of the CWR by producing regions for crop $c$ in year $j$ in China, and $\overline{CWR_{c,i,j}}$ (m$^3$/ha) the CWR for crop $c$ in year $j$ in main producing province. $A_{c,j}$ (ha) is the cultivated area of crop $c$ in year $j$, and $TA_{c,j}$

(ha) the total area for crop $c$ in year $j$ in the selected main producing provinces.

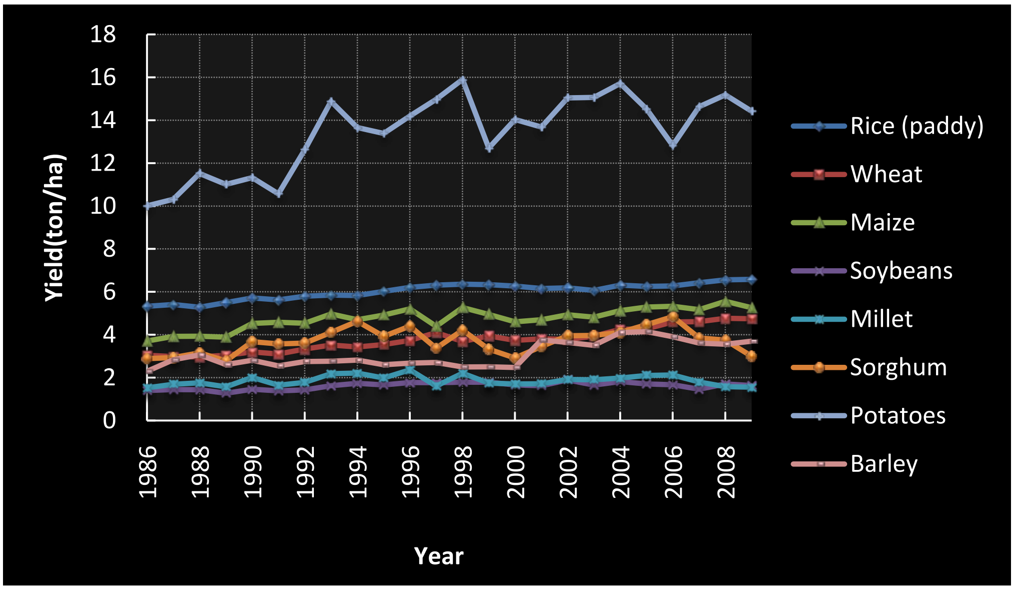
Table 2: CWRs of selected crops in China. Modified from Liu et al (2007). Data source: barley and grapes from Zhang (2003); others from Chen et al (1995).

| Crop | Experimental Locations | Rang of CWR ($m^3$/ha) | National Average CWR ($m^3$/ha) |
|---|---|---|---|
| **Rice (paddy)** | Hunan, Jiangsu, Jiangxi, Sichuan, Hubei and Anhui Provinces | 2500-6670 | 4550 |
| **Wheat** | Henan, Shandong, Hebei, Anhui and Jiangsu Provinces | 3250-5500 | 4300 |
| **Maize** | Shandong, Jilin, Henan, Hebei and Liaoning Provinces | 3000-6000 | 4000 |
| **Soybeans** | Heilongjiang, Jilin, Henan, Neimenggu and Anhui Provinces | 3500-5500 | 4900 |
| **Millet** | Shanxi Provinces | 4230-4650 | 4440 |
| **Sorghum** | Shanxi, Shaanxi and Henan Provinces | 3000-5000 | 4000 |
| **Potatoes** | Shanxi Province | 3036 | 3040 |
| **Barley** | Beijing City | 4100 | 4100 |
| **Apples** | Liaoning Province | 3700-5300 | 4500 |

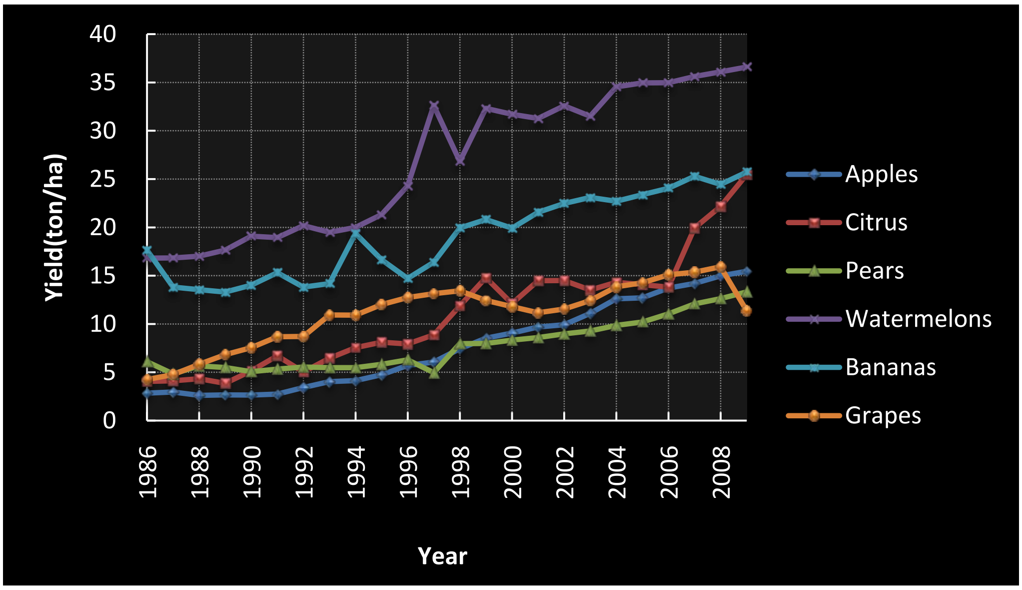
| | | | |
|---|---|---|---|
| **Citrus** | Sichuan, Hunan and Guangdong Provinces | 7500-10000 | 8850 |
| **Pears** | - | 3700-6000 | 4850 |
| **Watermelons** | Qingdao City | 3400 | 3400 |
| **Bananas** | Guangzhou City | 11000-14800 | 12900 |
| **Grapes** | Zhangye City | 5940 | 5940 |
| **Tomatoes** | Shanxi Province | 3996-5502 | 4750 |
| **Cabbages** | Shanxi Province | 3618-4400 | 4010 |
| **Carrots** | Beijing City | 5601 | 5600 |
| **Cucumbers** | Shanxi Province | 4061-5747 | 4900 |
| **Lettuce** | Beijing City | 3216 | 3220 |
| **Spinach** | Shanxi Province | 1599-3294 | 2450 |
| **Rapeseed** | Sichuan, Shaanxi and Liaoning Provinces | 1370-4800 | 3090 |
| **Sunflower** | Liaoning Provinces | 3850-4330 | 4090 |
| **Sesame** | - | 2800-4000 | 3400 |
| **Sugar Beet** | - | 4600-5700 | 5150 |
| **Sugar Cane** | - | 7500-10950 | 9230 |
| **Tobacco** | - | 4500-5500 | 5000 |
| **Tea** | South-west China | 6000-13000 | 9500 |

### 3.3 Crop yields

The data of crop yields were extracted from FAOSTAT (2012). Yields of all the selected crops showed a general increasing trend over the studied period 1986 - 2009 with complicated oscillating patterns (see Figure 1) due to the mutual impacts from improvement of technologies, fluctuation of weather conditions, warming trend of climate change (also growing concentrating of $CO_2$), and adjustment of social and economic policies.




(a)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Yield(ton/ha)
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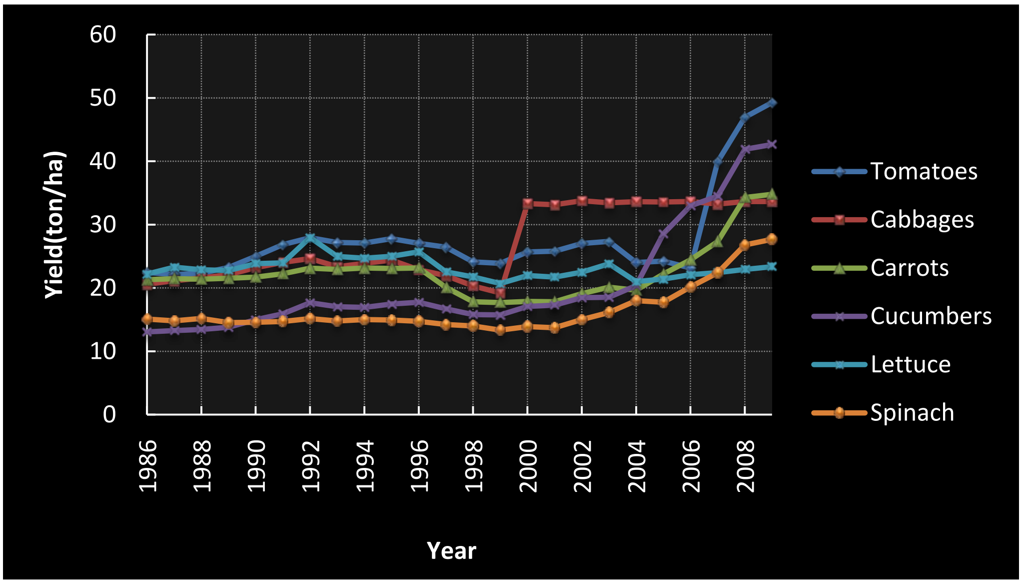
Bananas
Grapes

(b)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Yield(ton/ha)
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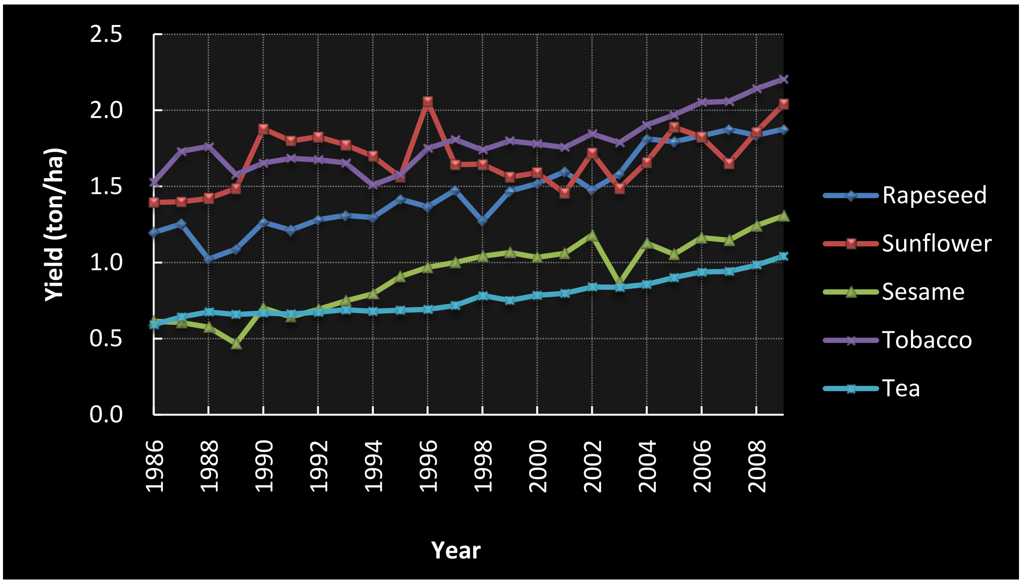
Lettuce
Spinach

(c)

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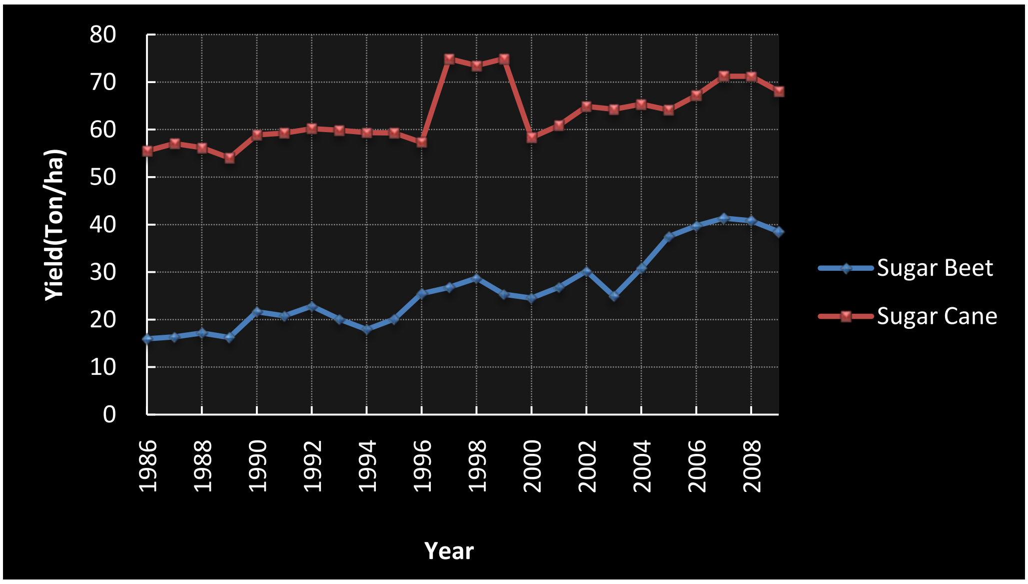



(e)

Figure 1: Yields of selected crops in China over the period 1986 – 2009: (a) grain crops; (b) fruit crops; (c) vegetable crops (d) cash crops excluding sugar beet and sugar cane; (e) sugar beet and sugar cane. Data source: FAOSTAT (2012).



### 3.4 Virtual water content (VWC)

Virtual water content (VWC) here is defined as the volume of water used in order to produce one unit of a crop. For primary crops, it can be calculated by directly dividing the national average CWR by corresponding crop yield in each year as in Eq. (2). Table 3 shows the CWRs, crop yields and VWCs of selected crops from1986 to 2009.

$$VWC_{c,j} = \frac{\overline{CWR}_{c,j}}{Y_{c,j}} \qquad \text{Eq.(2)}$$

$VWC_{c,j}$ (m$^3$/ton) is the virtual water content for crops $c$ in year $j$, and $Y_{c,j}$ (ton/ha) is the crop yield for crop $c$ in year $j$. All other symbols have been defined earlier.

Table 3: National average CWRs, yields and VWCs for selected crops. Data source for national average CWRs: Liu et al (2007), data source for yields: FAOSTAT (2012).

| Crop | CWR (m$^3$/Ha) | Yield (ton/ha) | VWC (m$^3$/ton) |
|---|---|---|---|
| **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 |
| **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 |
| **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 |
| **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 |



### 3.5 Virtual water trade (VWT)

Virtual water trade (VWT) is associated with the international food trade of corresponding agricultural commodities, and it consists in virtual water import (VWI) and virtual water export (VWE). The trade data were adopted from FAOSTAT (2012) detailed trade matrix. VWI and VWE were given by Eq. (3) and Eq. (4) and virtual water balance (VWB) was calculated by subtracting VWE from VWI as in Eq. (5). If the volume of VWI is larger than that of VWE, the sign of VWB will be positive and the value is net virtual water import (NVWI); if the volume of VWI is less than that of VWE, the sign of VWB will be negative and the value is net virtual water export (NVWE). Virtual water flow (VWF) is also referred to VWT in some literature. It better illustrates the fluid nature of water no matter “real” or “virtual” and emphasizes the virtual water trade as a crucial anthropogenic way of water cycle in socioeconomic sphere. Total virtual water import (TVWI), exports (TVWE) and balances (TVWB) of all the selected crops are the sum of VWI, VWE and VWB in each year as in Eq. (6) – Eq. (8). 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 virtual water import partners (NVWIPs)” and “net virtual water export partners (NVWEPs)” are also introduced in this paper. The whole calculation procedure is illustrated by Figure 2.



$$VWI_{c,n,j} = VWC_{c,n,j} \times I_{c,n,j} \qquad \text{Eq. (3)}$$

$$VWE_{c,n,j} = VWC_{c,n,j} \times E_{c,n,j} \qquad \text{Eq. (4)}$$

$$VWB_{c,n,j} = VWI_{c,n,j} - VWE_{c,n,j} \qquad \text{Eq. (5)}$$

$VWI_{c,n,j}$ is the virtual water import of crop $c$ from country $n$ in year $j$, $VWE_{c,j}$ the virtual water export of crop $c$ to country $n$ in year $j$, and $VWB_{c,j}$ the virtual water balance of crop $c$ with country $n$ in year $j$.

$$TVWI_j = \sum_c \sum_n VWI_{c,n,j} \quad \text{Eq. (6)}$$

$$TVWE_j = \sum_c \sum_n VWE_{c,n,j} \quad \text{Eq. (7)}$$

$$TVWB_j = \sum_c \sum_n VWB_{c,n,j} \quad \text{Eq. (8)}$$

$TVWI_j$ is the total virtual water import in year $j$, $TVWE_j$ the total virtual water export in year $j$, and $TVWB_j$ the total virtual water balance in year $j$.

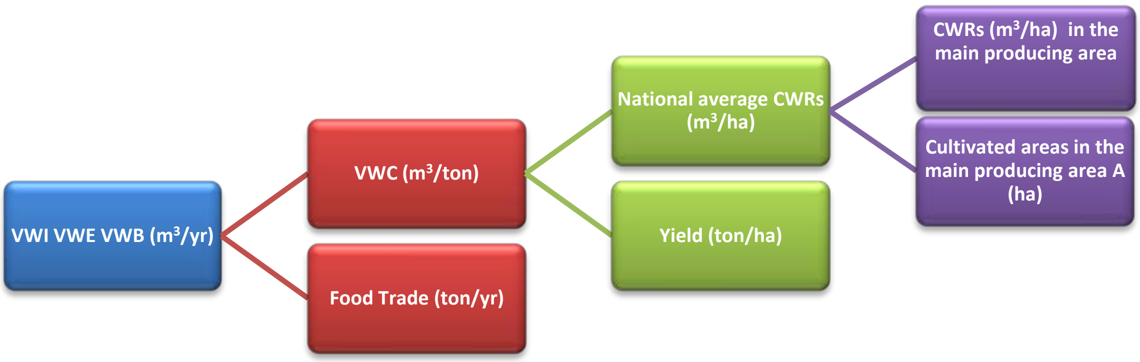



Figure 2: Calculation procedure of VWT. Modified from Liu et al (2007).

### 3.6 Virtual water trade network

The VWT relationships between China and trade partners can be viewed collectively as a directed and weighted VWT network (Dalin et al 2012). 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 NVWI and the direction pointing from China as NVWE, 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 paper constructed the VWT network centred at China for the period 1986 – 2009. The data reported by China were solely used despite of any divergence from the data reported by the other trade partner. It is also assumed that no trade was taking place if no data were reported between China and a certain country in a given year. Figure 3 shows the numbers of VWT partners with China over the period 1986 – 2009.

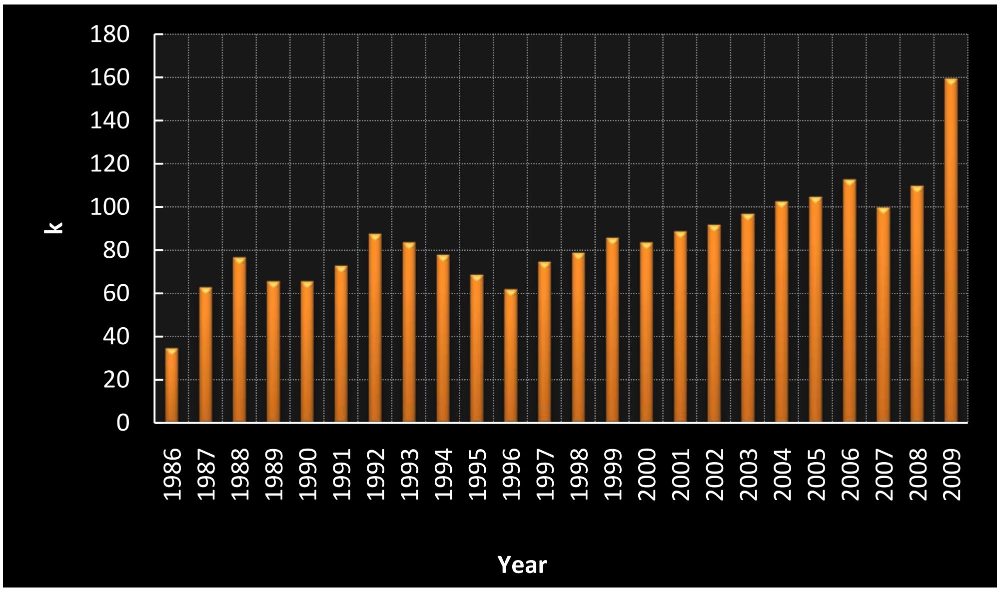



Figure 3: Number of VWT partners with China over the period 1986 – 2009. Data source: FAOSTAT (2012).

# 4. RESULTS AND DISCUSSIONS

## 4.1 Overview

China has a positive crop-related TVWB with the TNVWI of 934 km$^3$ and yearly average of 39 km$^3$ over the time period 1986 - 2009. The volume of the TVWI is about 1242 km3 which is 3 times greater than that of the TVWE (308 km$^3$). Figure 4 shows the crop-related VWT of China. From 1986 to 2000, the TVWB fluctuated below or around 20 km$^3$/year 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 6 times higher. Note that the curves of the TVWB and the TVWI are very close to each other, which reflects that virtual water import dominated the overall virtual water flow of China during the studied period of time, while the TVWE is generally below 20 km$^3$/yr.

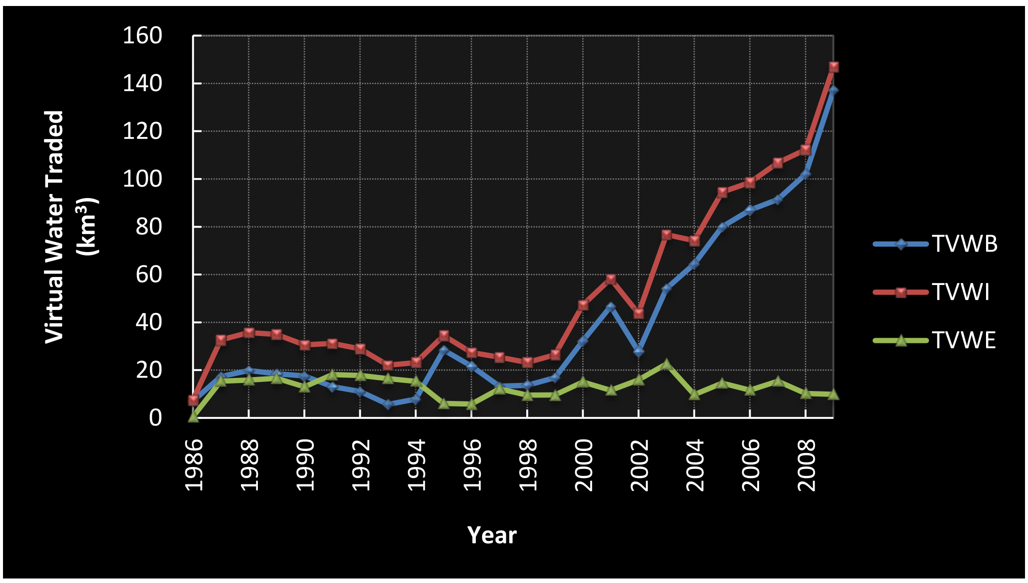
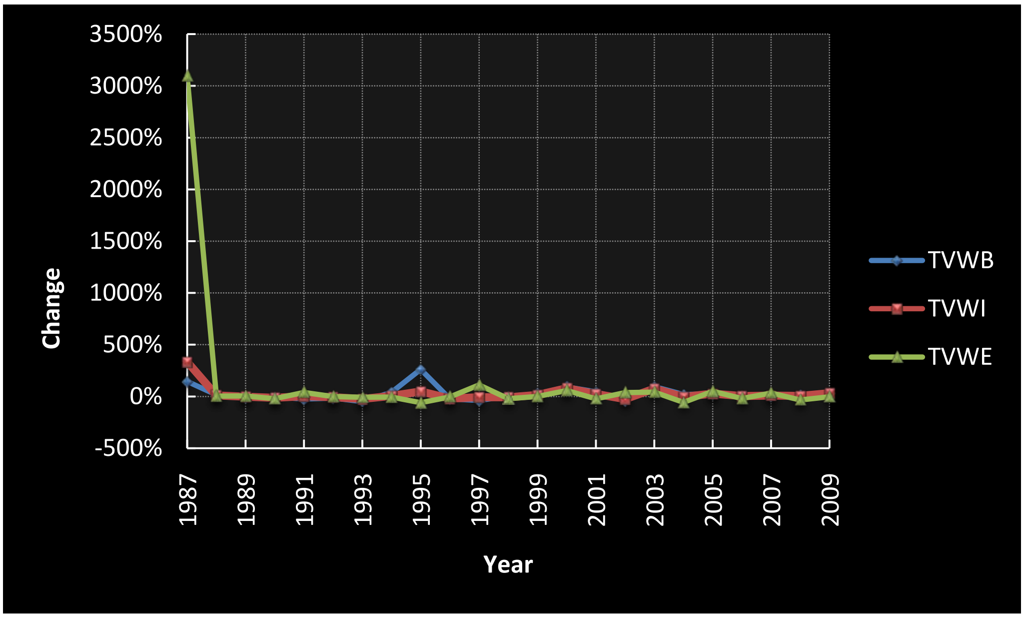
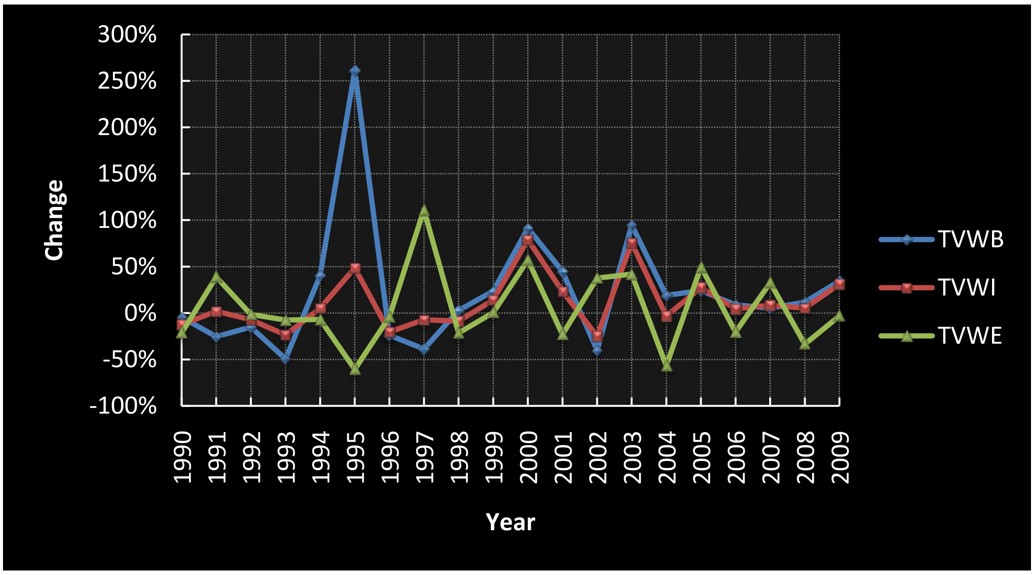


Figure 4: Crop-related VWT of China over the period 1986 – 2009.

Figure 5 and Table 4 shows the yearly change in percentage of the VWT. The TVWB decreased from 1989 to 1993 and kept growing since 1998 with the only exception in 2002, and the change in TVWI showed a very similar pattern. But the change in TVWE is much more complicated. During 1992 to 1996 it kept decreasing but displayed a rather oscillating pattern for the remaining years. As the volume of the TVWE is much smaller than the TVWI, there is little impact on the TVWB from the TVWE.




(a)




(b)

Figure 5: Yearly change in percentage of the VWT of China over the period 1986 – 2009: (a) yearly change of the VWT over the period 1986 – 2009; (b) yearly change of the VWT over the period since 1990 as to show the details.

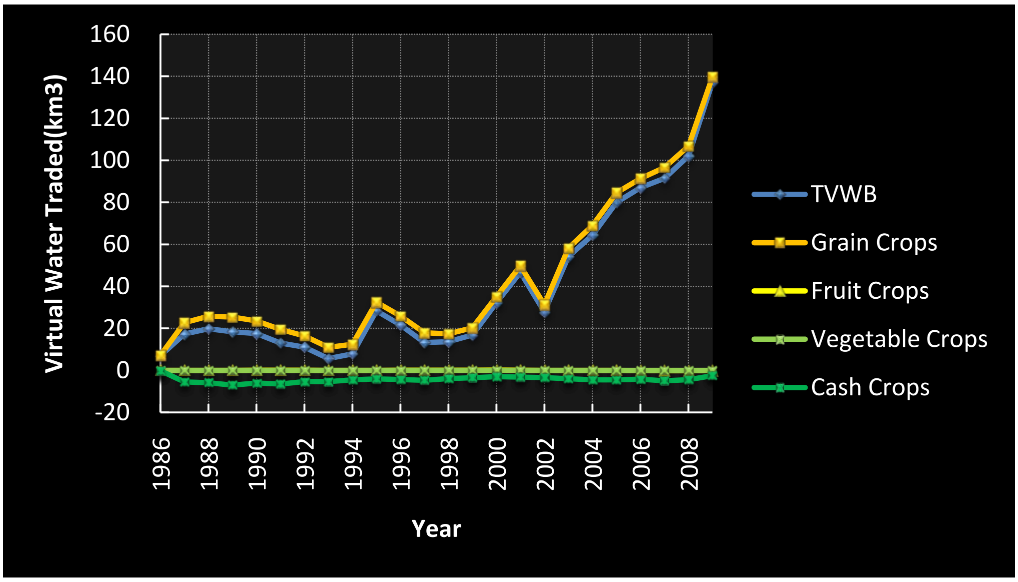
Table 4: Yearly change in percentage of the VWT of China 1986 – 2009.

| Year | Change in TVWB (%) | Change in TVWI (%) | Change in TVWE (%) |
|---|---|---|---|
| **1987** | 146% | 335% | 3097% |
| **1988** | 15% | 9% | 3% |
| **1989** | -7% | -2% | 4% |
| **1990** | -5% | -13% | -21% |
| **1991** | -26% | 2% | 39% |
| **1992** | -15% | -7% | -2% |
| **1993** | -49% | -24% | -8% |
| **1994** | 40% | 5% | -7% |
| **1995** | 261% | 49% | -61% |
| **1996** | -24% | -20% | -4% |
| **1997** | -39% | -7% | 111% |
| **1998** | 3% | -9% | -21% |
| **1999** | 24% | 14% | 0% |
| **2000** | 91% | 79% | 57% |
| **2001** | 45% | 23% | -23% |
| **2002** | -40% | -25% | 38% |
| **2003** | 95% | 76% | 42% |
| **2004** | 19% | -3% | -57% |
| **2005** | 24% | 27% | 50% |
| **2006** | 9% | 4% | -21% |

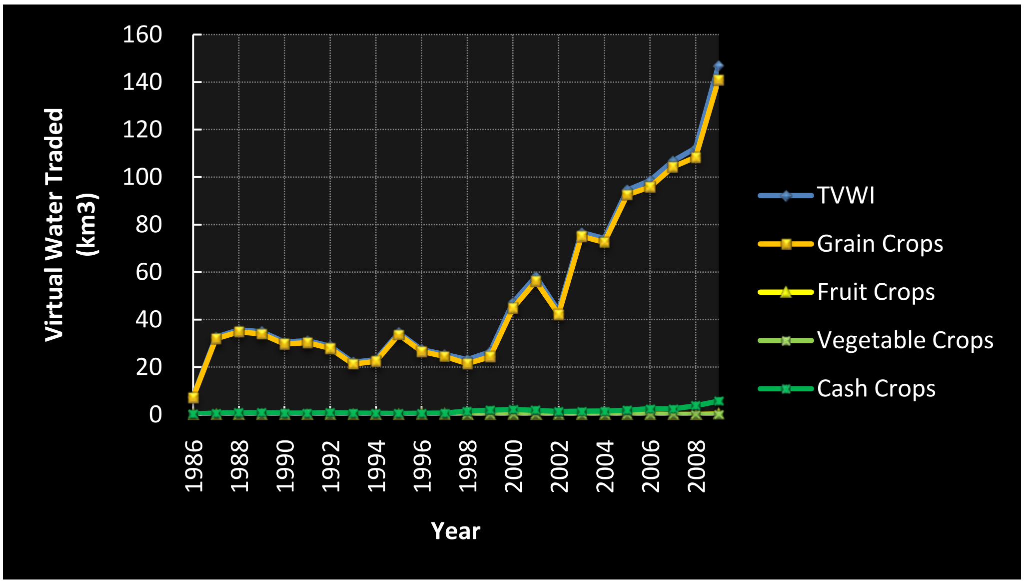
| | | | |
|---|---|---|---|
| **2007** | 5% | 8% | 33% |
| **2008** | 12% | 5% | -34% |
| **2009** | 34% | 31% | -3% |

### 4.2 Contribution of different crops to VWT

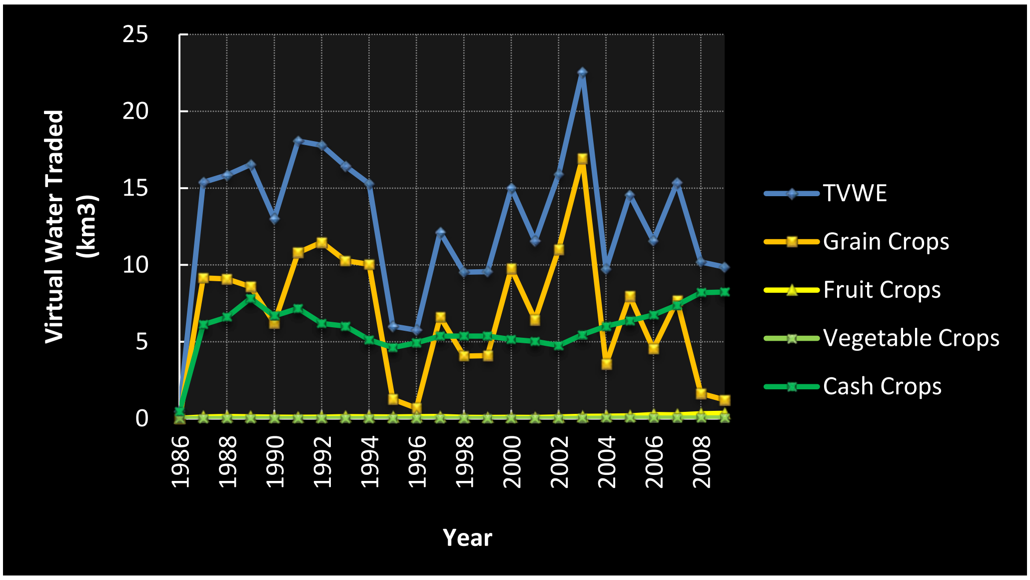
Grain crops contribute the most in all TVWB, TVWI and TVWE (see Figure 6). In TVWI, the VWI associated with grain crops is 1203 $km^3$ in total and 50 $km^3$/yr by average, both of which take up to 97% of all. In TVWE, VWE associated with grain crops is 163 $km^3$ in total and 7 $km^3$/yr by average, accounting for 53% of all. Despite the overwhelmingly dominated role of grain crops, cash crops play a, if not less, equally important role in TVWE as they contribute 141 $km^3$ virtual water of all and 6 $km^3$/yr by average, which have a share of 46%, comparing to that of grain crops. Furthermore, there is a most recent trend that cash crops may replace grain crops as the biggest contributor in TVWE. As showed in 2008 and 2009, they accounted for 80% and 84%, respectively, a double jump from 48% in 2007. However, as the volume of TVWI is much greater than that of TVWE, it can still be stated that VWI associated with grain crops dominated VWT of China.


Virtual Water Traded(km3)
160
140
120
100
80
60
40
20
0
-20
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Year
TVWB
Grain Crops
Fruit Crops
Vegetable Crops
Cash Crops

(a)


Virtual Water Traded (km3)
160
140
120
100
80
60
40
20
0
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Year
TVWI
Grain Crops
Fruit Crops
Vegetable Crops
Cash Crops

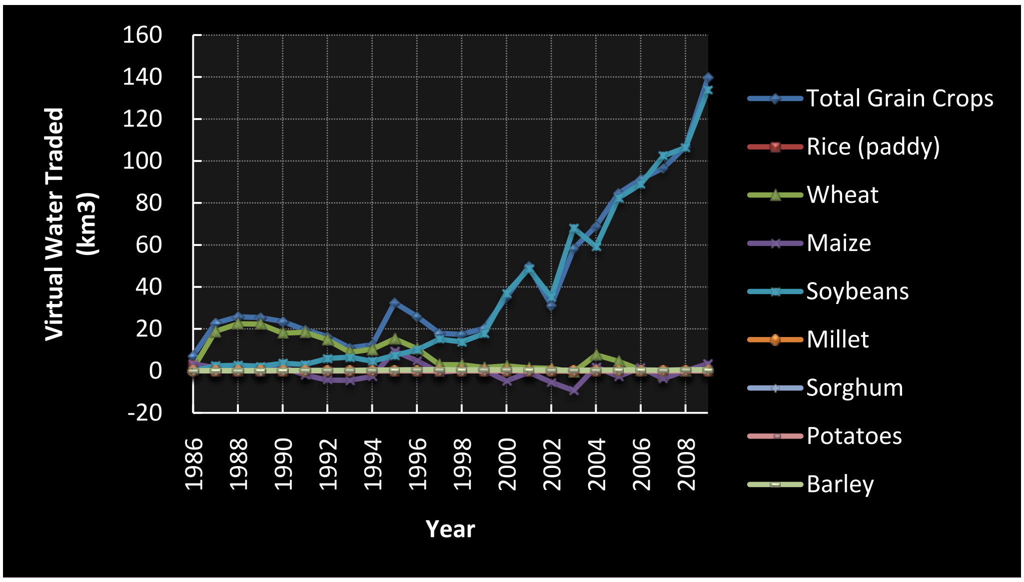
(b)



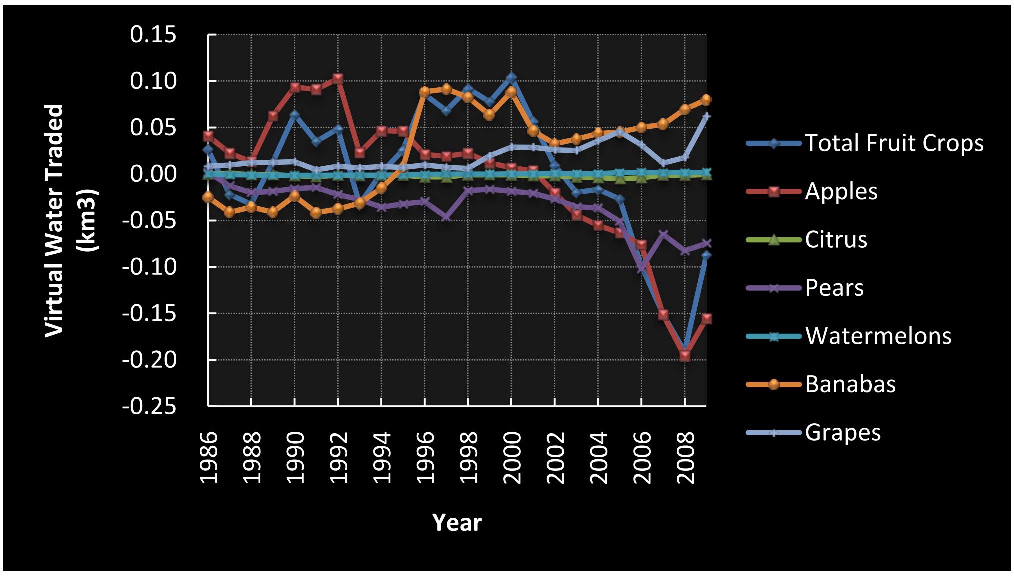

(c)

Figure 6: Contribution of different crops to VWT of China over the period 1986 – 2009: (a) contribution of different crops to TVWB of China over the period 1986 – 2009; (b) contribution of different crops to TVWI of China over the period 1986 – 2009; (c) contribution of different crops to TVWE of China over the period 1986 – 2009.

If we take a closer look into the share of contributions to VWT of various specific crops under each crop category, again, a few critical crops display dominance in the crop-related VWT of China (see Figure 7). Grain crops are the greatest source of VWI of China, in which wheat was the biggest contributor before 1997 and afterwards soybean began to take the lead, especially doubling the volume of VWI associated with it in 2000 and completely dominated the VWT since then. This is because of a major policy change, which allowed China to dramatically increase import of soybeans from North and South Americas. As mentioned before, the scales of virtual water traded by the other three categories are much smaller than that of grain crops. The range of traded virtual water associated with fruit crops is between -0.20 (negative indicates export) to 0.10 (positive indicates import) km$^3$/yr, and the range of traded virtual water associated with vegetable crops between -0.05 to 0.00 km$^3$/yr. The range of traded virtual water associated with cash crops is a bit broader from 0.17 to 7.00 km$^3$/yr. Within selected fruit crops, apples, bananas, pears and grapes are the main contributors. During 1986 -2002, China imported net virtual water associated with fruit crops as the VWB was mostly positive with only three exceptions in 1987, 1988 and 1993, and exported net virtual water afterwards. In terms of the VWT associated with vegetable crops, China kept increasing export of virtual water during the studied period of time and carrots and cabbages are the major contributors. As for the VWT associated with cash crops, China also kept exporting virtual water overall which were influenced mostly by tea (export) and rapeseed (import).

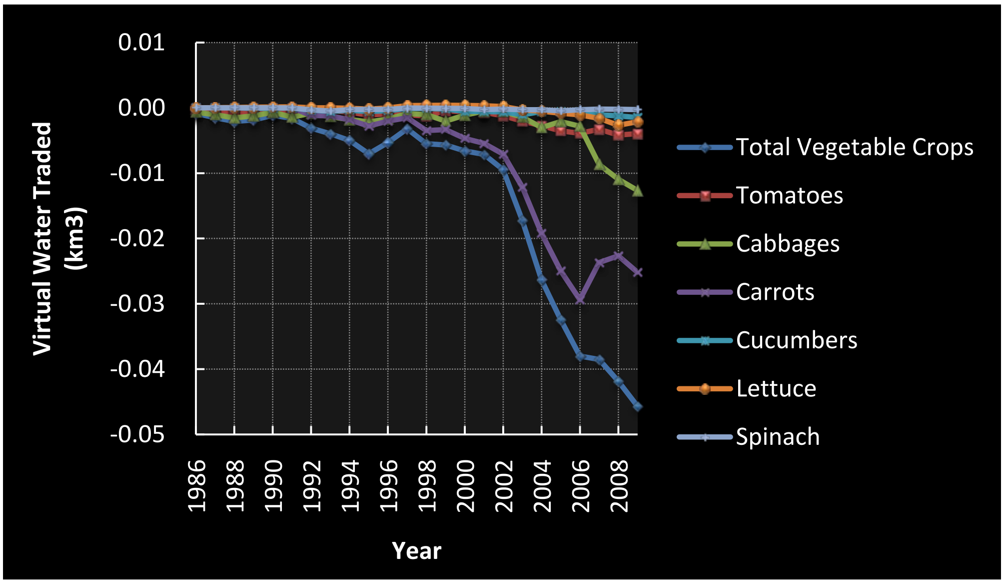



(a)



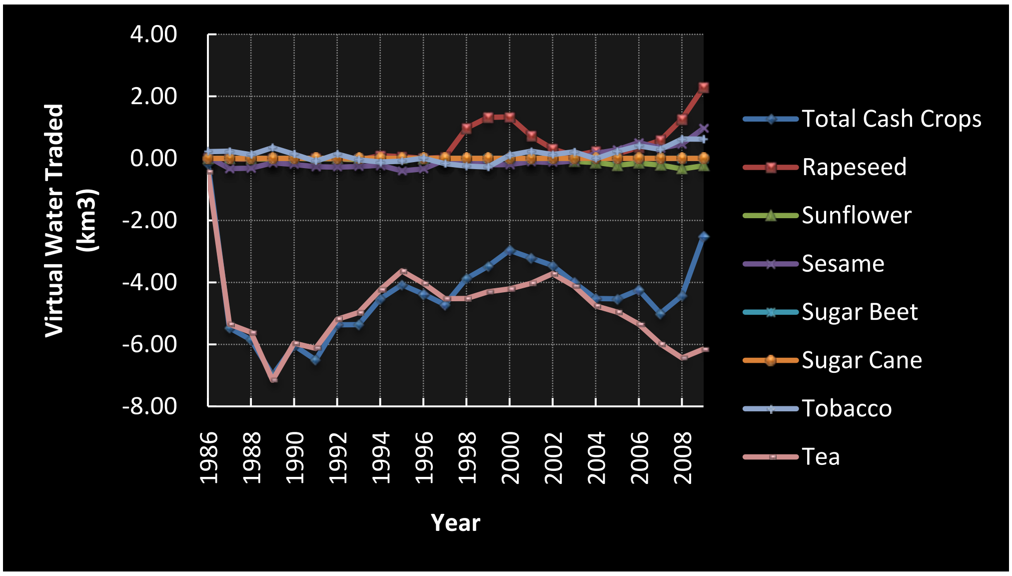
Virtual Water Traded (km3)
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Year
Total Fruit Crops
Apples
Citrus
Pears
Watermelons
Banabas
Grapes


(b)



Virtual Water Traded (km3)
0.01
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Year
Total Vegetable Crops
Tomatoes
Cabbages
Carrots
Cucumbers
Lettuce
Spinach


(c)

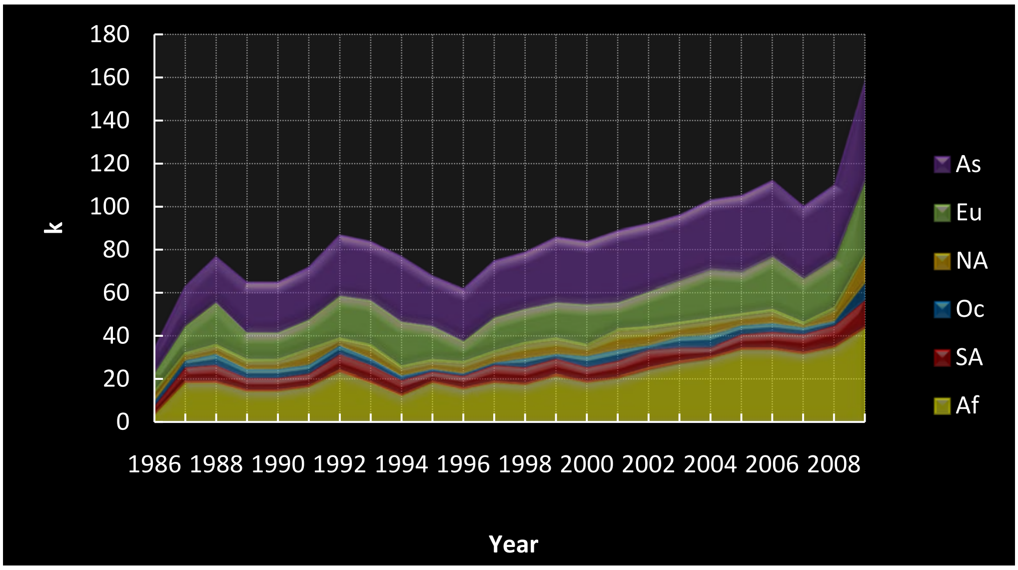



(d)

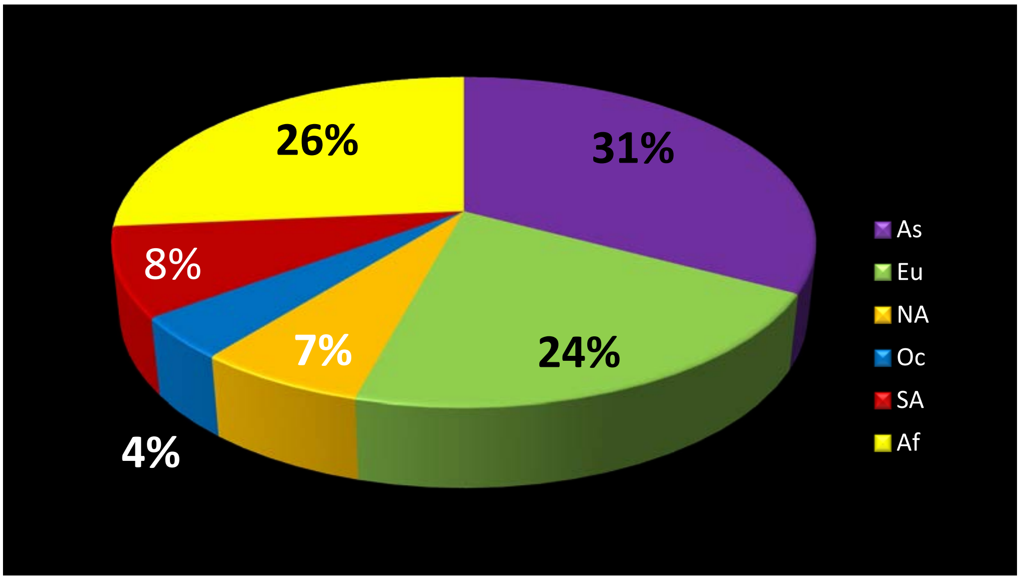
Figure 7: Share of contributions to VWT of specific crops under different categories: (a) grain crops; (b) fruit crops; (c) vegetable crops; (d) cash crops.

### 4.3 Geographic distribution

Figure 8 shows the evolution in terms of the number of VWT partners between continents with China. Although the total number of trade partners has increased significantly, most of the trade partners are located in Asia, Europe and Africa. This geographic distribution in terms of the number of VWT partners has remained unchanged over the studied period of time.



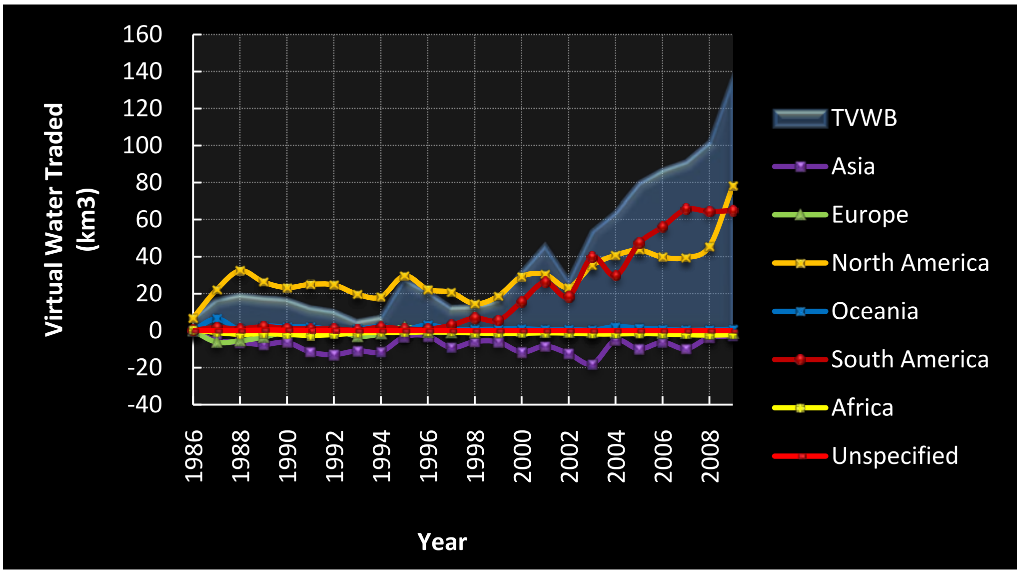

(a)



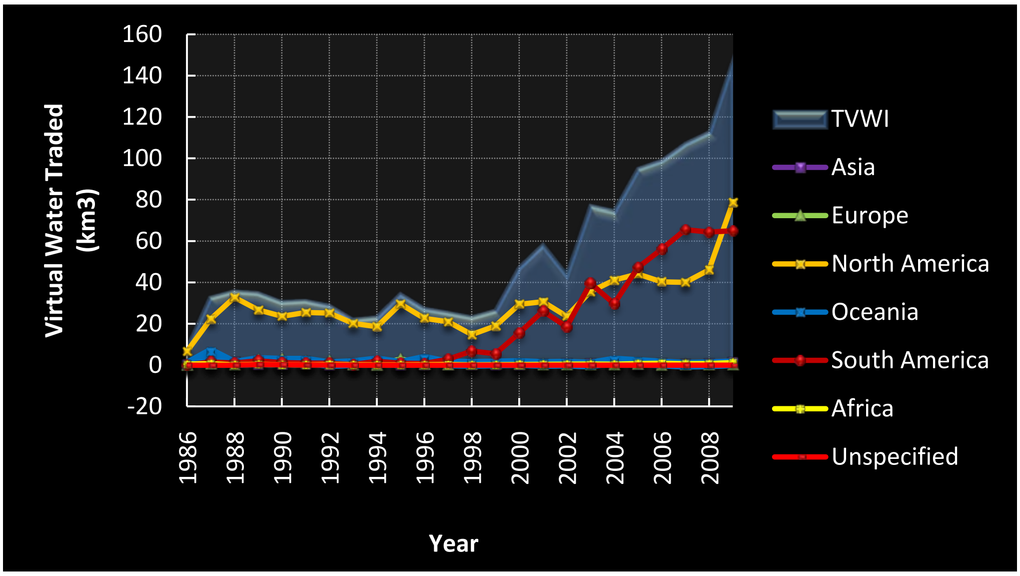

(b)

Figure 8: The Evolution in terms of the number of VWT partners between continents with China over the period 1986 - 2009: (a) the evolution of the number of VWT partners; (b) the share of average number of VWT partners.

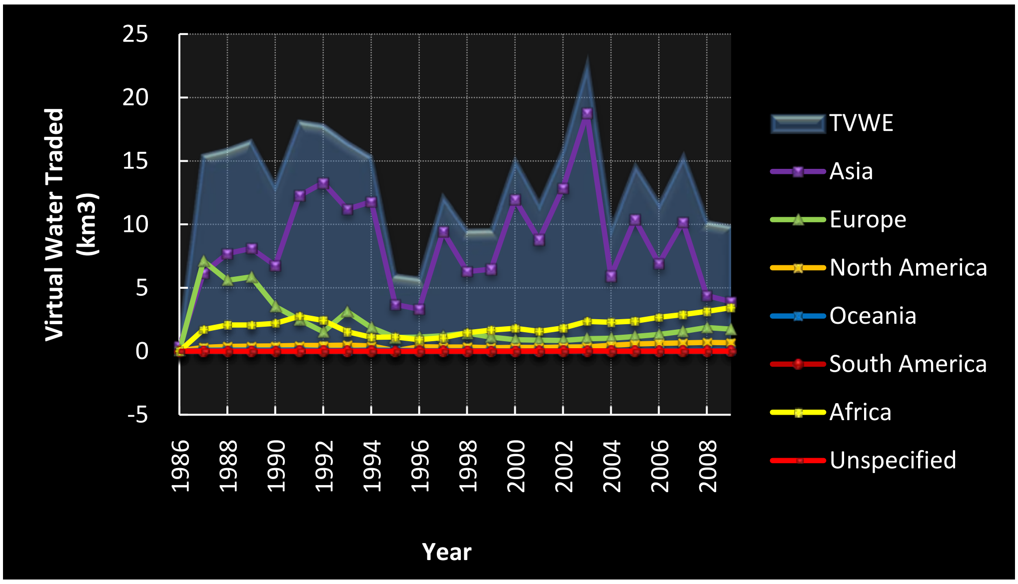
Figure 9, 10 and Table 5 show the geographic distribution of VWT of China. The patterns have changed a lot over the time period of 1986 -2009. In terms of NVWIPs, China mainly imported virtual water from North America before 2000 but added South America as another major source of virtual water import afterwards. The accumulated amount of virtual water import from South America has been catching up with that of North America. The situation of NVWEPs is more balanced. Asia has generally been the major destination of virtual water export over the studied period of time but Europe and Africa also have important roles to play. The distribution of NVWE among these three continents became more evenly since 2008.




(a)

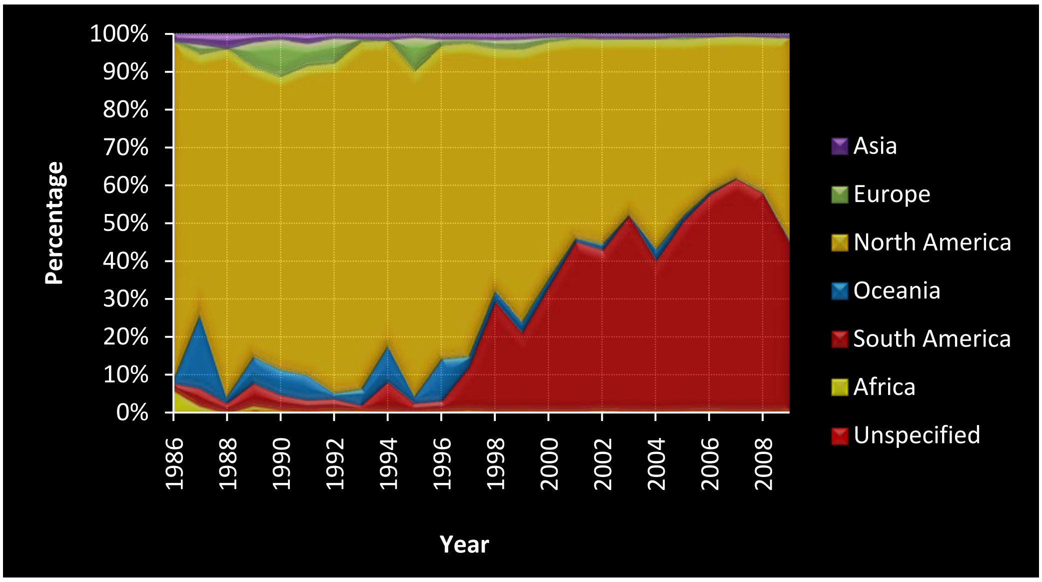



(b)

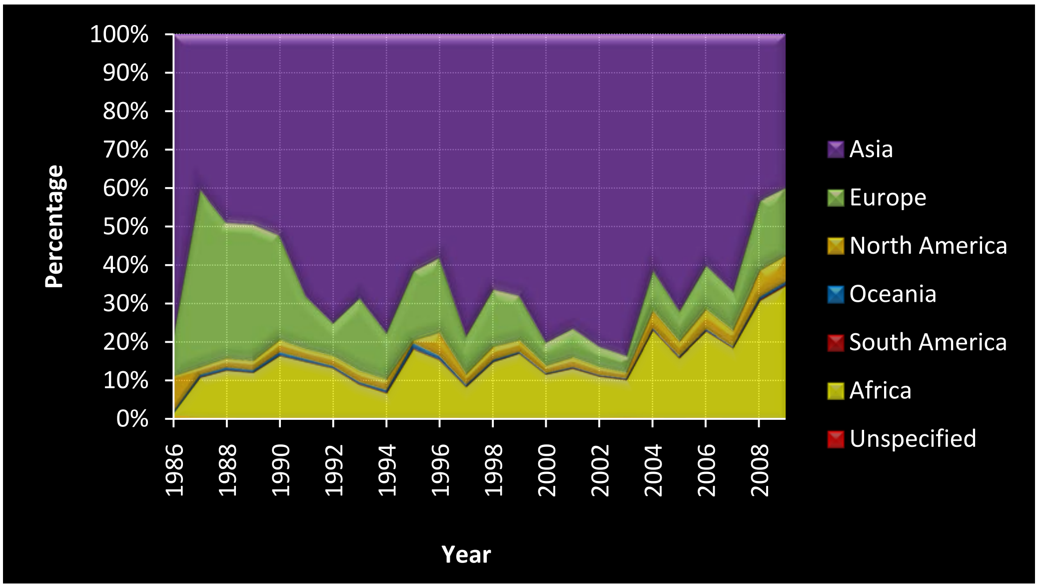



(c)

Figure 9: Evolution of geographic distribution of VWT of China over the period 1986 – 2009: (a) evolution of geographic distribution of VWB; (b) evolution of geographic distribution of VWI; (c) evolution of geographic distribution of VWE.




(a)




(b)

Figure 10: Share of geographic distribution of VWT of China over the period 1986 – 2009: (a) share of geographic distribution of VWI; (b) share of geographic distribution of VWE.

Table 5 Share of geographic distribution of VWT of China 1986 -2009: (a) share of geographic distribution of NVWI; (b) share of geographic distribution of NVWE.

(a)

| Region | Accumulated | Yearly Average | Percentage |
|---|---|---|---|
| **TNVWI** | 1191.86 | 49.66 | 100% |
| **NVWI from North America** | 707.87 | 29.49 | 59.39% |
| **NVWI from Oceania** | 30.38 | 1.27 | 2.55% |
| **NVWI from South America** | 453.61 | 18.90 | 38.06% |

(b)

| Region | Accumulated | Yearly Average | Percentage |
|---|---|---|---|
| **TNVWE** | 258.21 | 10.76 | 100% |
| **NVWE to Asia** | 189.14 | 7.88 | 73.25% |
| **NVWE to Europe** | 32.28 | 1.35 | 12.50% |
| **NVWE to Africa** | 36.79 | 1.53 | 14.25% |

### 4.4 VWT network properties

Considering trade links and the total amount of virtual water traded, the number of trade partners generally grew from 35 in 1986 to 160 in 2009, a four times increase, which mainly came from the increase of the NVWEPs from 18 in 1986 to 125 in 2009, with an average of 61.5 each year and an absolute deviation of 15.7. But the number of the NVWIPs remained rather steady from 17 in 1986 to 35 in 2009, with an average of 24.1 each year and an absolute deviation of 3.7. In contrast to the relatively small number, the NVWIPs contributed 81.15% of the total net virtual water traded with a percentage of 28.14% in number by yearly average. Also, the pattern of a small number (less than 30%) of NVWIPs contributing to a large percentage (greater than 70%) of total net virtual water traded has been kept over the studied period of time (see Figure 11).

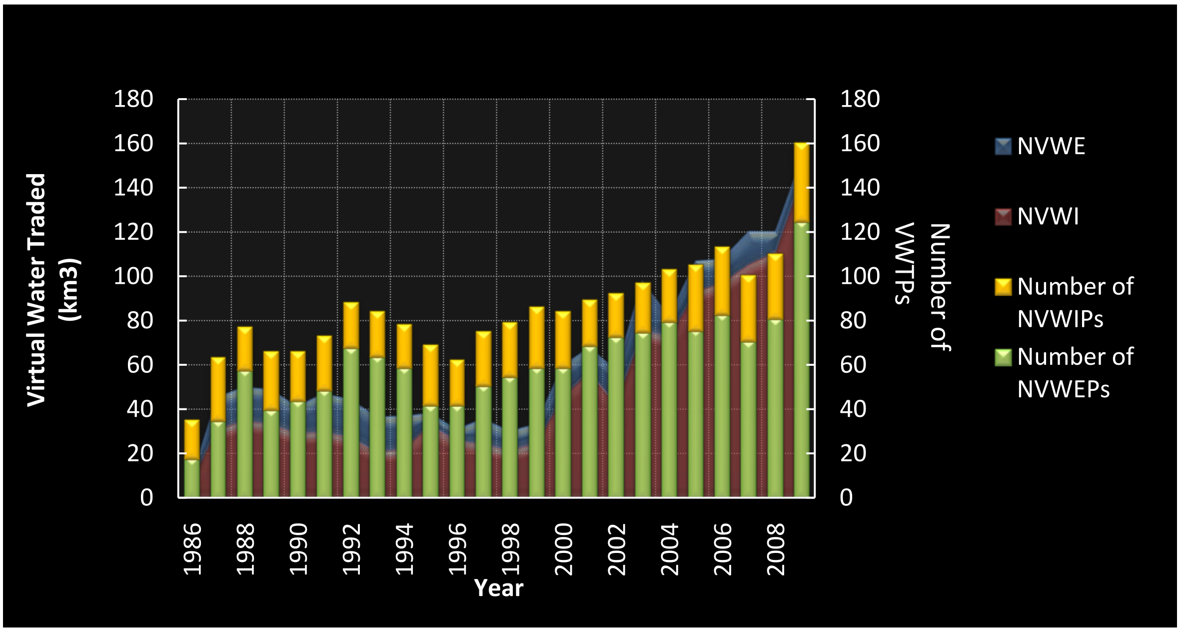



Figure 11: A small number of NVWIPs contributed a large percentage to the total net virtual water traded over the period 1986 – 2009.

The relationship between trade links $k$ and node strength $s$ satisfies the power law $s(k) \propto k^{\alpha}$ ($\alpha = 2.3$), which characterizes the feature of “scale-free” degree distribution in VWT network of China (see Figure 12). It’s an intrinsic characterization which had remained unchanged during the studied period of time.

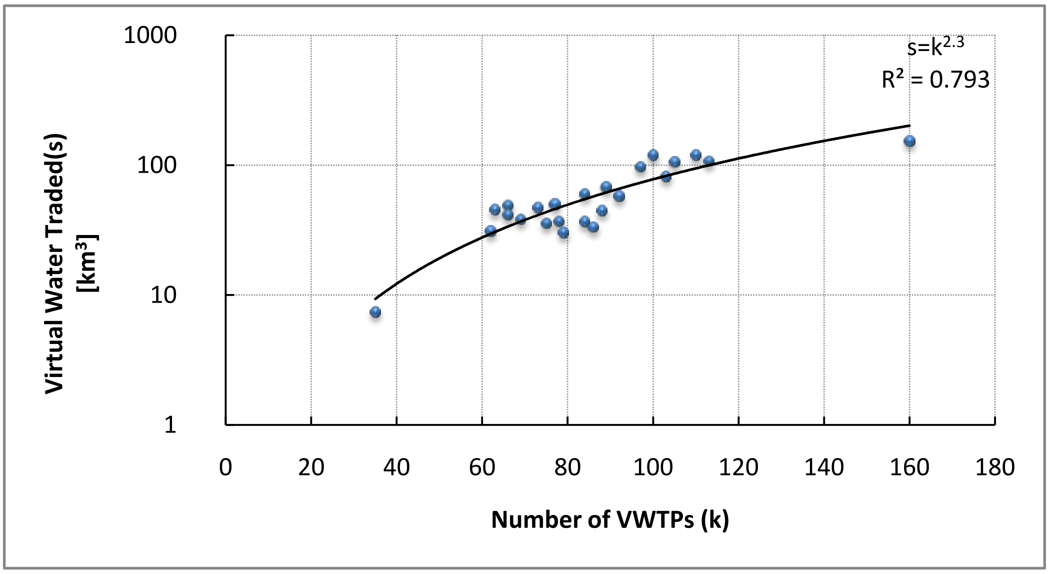
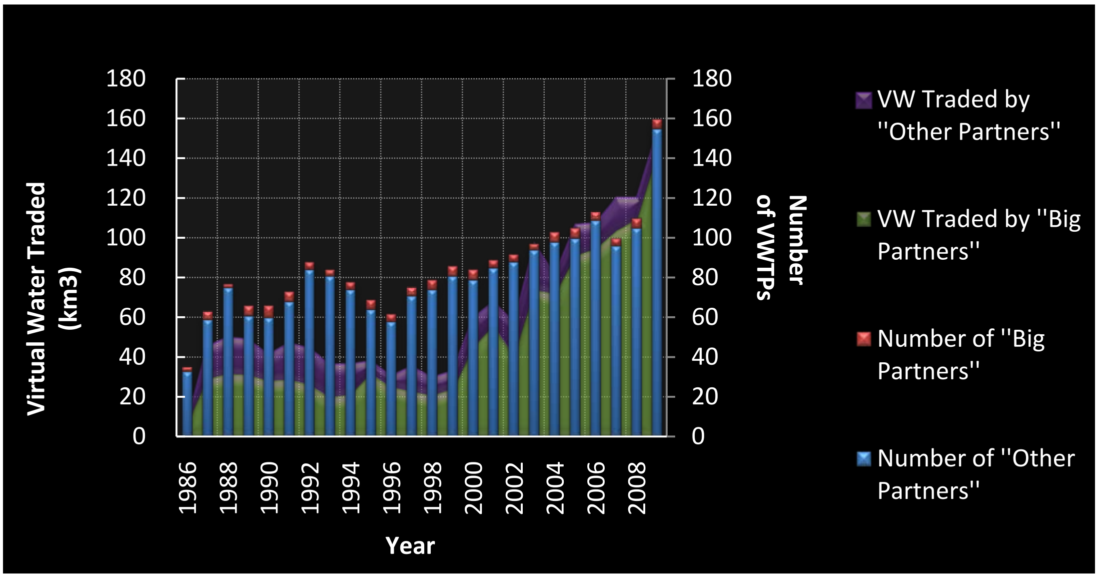
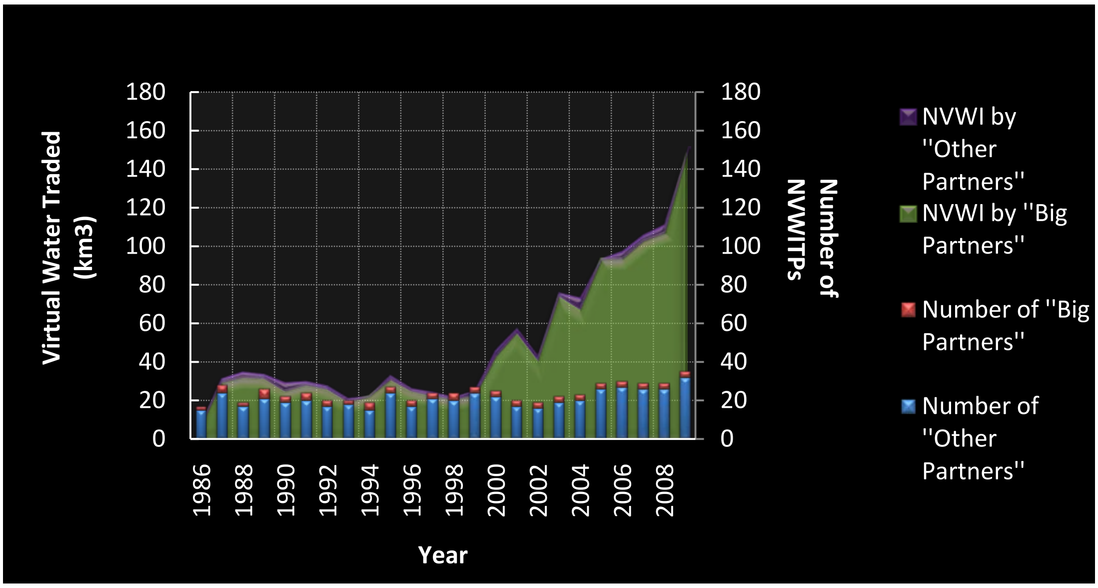



Figure 12: Power law shows the “scale-free” degree distribution of virtual water trade network of China.

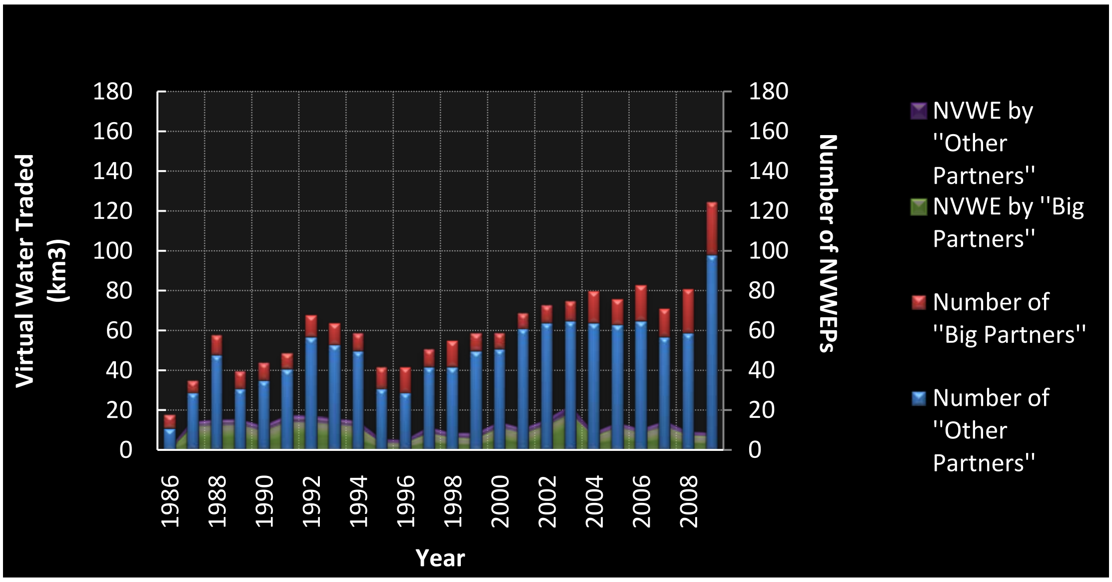
Further network analysis shows (see Figure 13) that the VWT network of China is inhomogeneous and highly polarized. A few “big partners” (defined as trade partners who traded volumes of virtual water larger than average) dominated China’s VWT. In terms of NVWB, the number of “big partners” was relatively small and rather steady, with an average of 4.3 each year, 4.97% of the total number of trade partners, and an absolute deviation of 0.8; but they traded 79.27% of the total net virtual water flow. “Other partner”’ contributed mostly to the increase in number of trade partners, with an average of 81.3 each year, 95.03% of the total number of trade partners, and an absolute deviation of 16.7; but they only took 20.73% of the total net virtual water flow. The polarity is also prominent within both NVWI and NVWE. In NVWI, “big partners”, with an average of 3.1 each year, 12.98% of the total number of NVWIPs, and an absolute deviation of 0.45, contributed 95.97% of the TNVWI. In NVWE, “big partners", with an average of 11.7 each year, 18.97% of the TVWEPs, and an absolute deviation of 3.6, took 83.55% of the TNVWE.




(a)



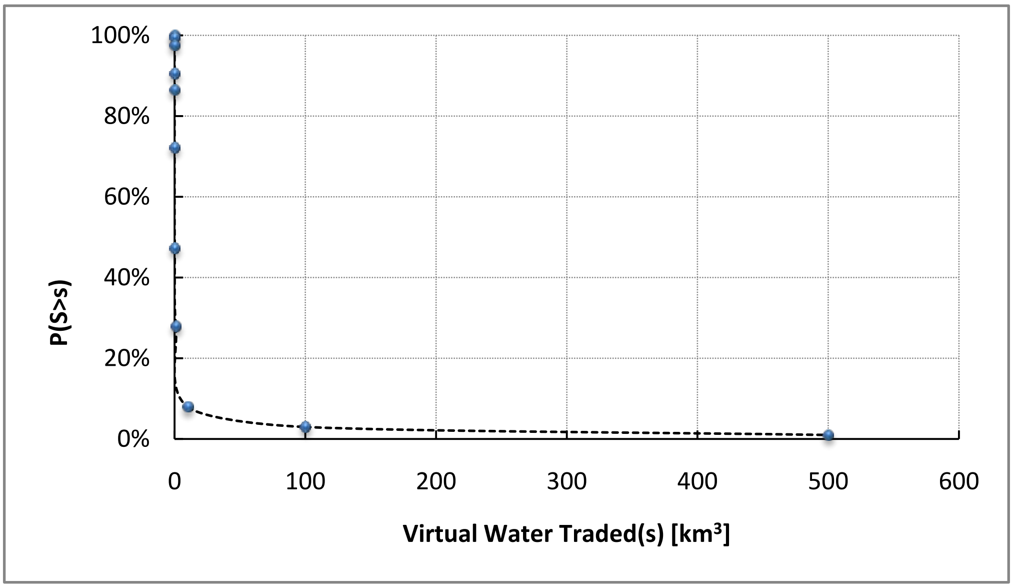

(b)




(c)

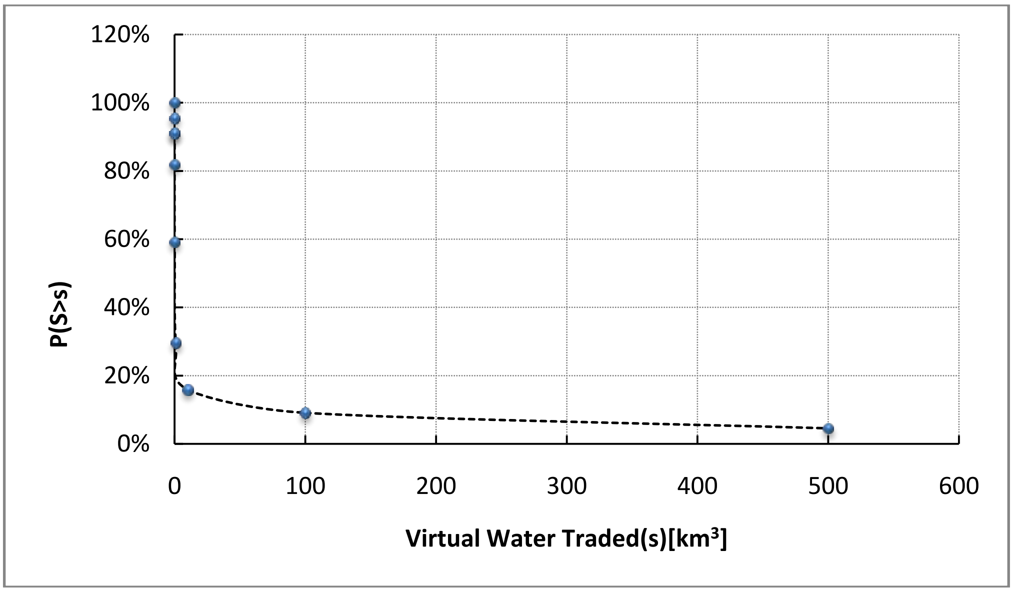
Figure 13: Polarization of VWT network of China: (a): NVWT; (b) NVWI; (c) NVWE.

Node strength exceedance probability distribution of VWT (see Figure 14) reconfirmed the highly-polarized characteristics of China's VWT network. The probability distribution show the feature of "super flat tail" in each of NVWT network, NVWI network and NVWE network, which highlight the fact that trades among a very small group of trade partners dominate the whole. Therefore any change in the trade with these "big partners" would result out fundamental influences in the whole trade pattern. This is a disadvantage in terms of food security.



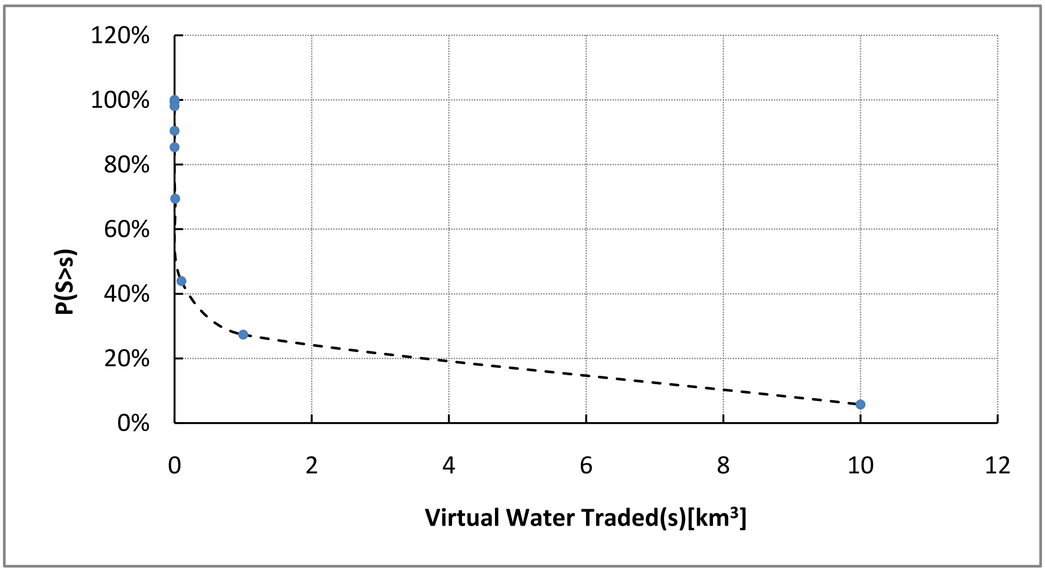
100%
80%
60%
40%
20%
0%
P(S>s)
0
100
200
300
400
500
600
Virtual Water Traded(s) [km³]


(a)



120%
100%
80%
60%
40%
20%
0%
P(S>s)
0
100
200
300
400
500
600
Virtual Water Traded(s)[km³]


(b)




(c)

Figure 14: Node strength exceedance probability distribution of VWT network of China: (a) NVWT network; (b) NVWI network; (c) NVWE network.

### 4.5 A typical case: Soybeans

China is the place of origin for soybeans and traditionally a major soybeans exporter. Before 1996, China was a net exporter of soybeans, however the situation changed and the import of soybeans has increased dramatically since then. Soybeans show a prominent role in China's VWT especially after 2000. The import of soybeans in 2003 exceeded the total domestic soybeans production in 2002. The increasing domestic demand and the shift of food trade policy since the entry to the World Trade Organization (WTO) both contributed to the jump of soybeans import of China. In the virtual water trade associated with import of soybeans, the highly-polarized pattern could also be identified (see Figure 15). A very small number of trade partners dominated the whole trade. Before 1996, USA was the only major trade partner but Brazil and Argentina gradually became another two major partners since 2000. These three countries accumulatedly exported 886 $km^3$ of soybeans-related virtual water to China over the period of time 1986 - 2009 while all the other countries imported 29 $km^3$ from China. And the accumulated NVWB water import associated with soybeans accounted for 56.97% in the TNVWB from 1986 to 2009, and 78.26% from 2000 to 2009.

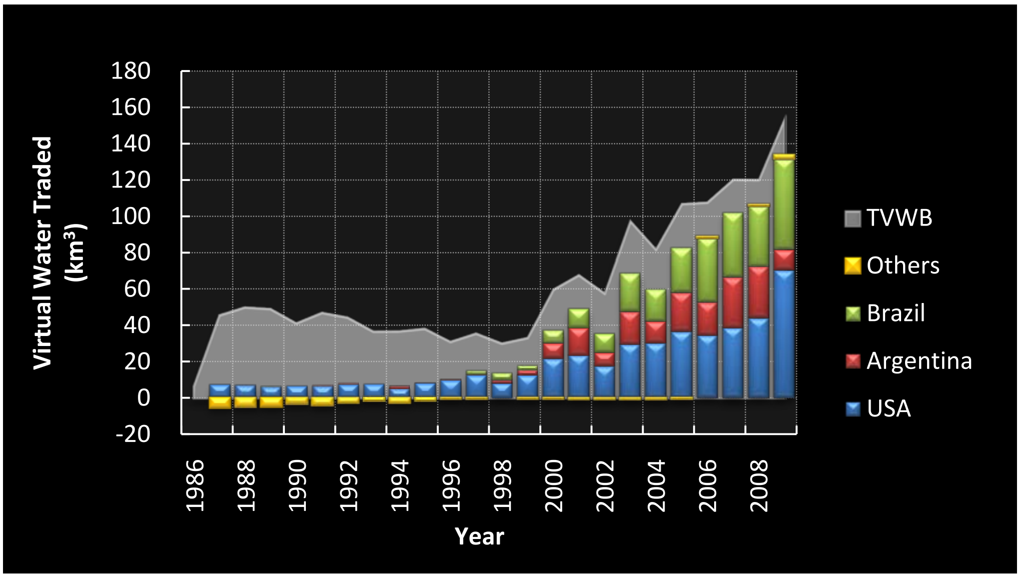



Figure 15: VWT associated with soybeans of China over the period 1986 – 2009.

## 4.6 The whole picture

The whole picture of China's virtual water trade of main crops over 1986 -2009 showed a net virtual water import from water resource relatively abundant areas of North and South Americas, and a net virtual water export towards water resource relatively stressful areas of Asia, Africa, and Europe. Net virtual water import is far larger than net virtual water export and in both import and export a rather small number of trade partners control the whole trade. Grain crops are the major contributors of the total virtual water trade and among grain crops, soybeans (mostly imported from USA, Brazil and Argentina) take the most prominent role. As crop water use efficiencies in North and South Americas are generally higher than those in Asia and Africa, the effect of China's crop-related virtual water trade positively contributes to optimizing world crop water use efficiency.

## 5. POLICY IMPLICATION

As China now is facing more and more severe water scarcity (Jiang 2009) which is intrinsically linked with food security, a more integrated water management strategy including active virtual water policy should be approached. As demand for water resource in China, which driven by the long-standing population pressure, rapid growth of resource-intensive economy and changing consumption behaviour (e.g. more meat than vegetables in diet structure), keeps growing, while at the other end, potential of sustainable supply is more and more stressed, as the unevenly-distributed water resource between North and South China, which is projected to be worsened by further climate change and the wide spreading water pollution. A series of measures are being taken by the Chinese government. More strict laws against water pollution have been passed, and proposals to adjust the water pricing system have been suggested, and moreover, enormous amount of investment is being put into water conservation technologies and water projects, including some “super-projects” like the South-North Water Transfer Project (Berkoff 2003), which is aimed to transfer real water from water-rich South to water-stressed North, particularly the drying North China Plain, which produce half of China’s wheat. However, the improvement of current situation of water pollution is costly and takes time. The average water use per capita of China is only one-fourth of the world average. There is some space in increasing the water productivity both in agriculture and industry. As for South-North Water Transfer Project, the quantity is limited comparing to the growing demand and agriculture is not likely to be compensated as the water value in industry is much higher and the costs could be too high for food production. There are also plenty of concerns on the water quality as well as the negative impacts on ecosystem as the western route of this project has been halted. Therefore, active virtual water trade could be a wise option to mitigate the water-scarcity as is successfully implemented in some water-stressed countries esp. in Mid-East and North Africa. Meanwhile, areas of irrigation in North China Plain should also be reduced and switch to some less water-intensive crops when increasing imports of grain crops. There has been a long-going major concern about the food sovereign security of China and consequently it is widely believed that China need remain a relatively high self-sufficiency (about 95%) of grain crops. However, as the increasing integration of Chinese economy into world's economy, especially entry to the World Trade Organization (WTO), which has resulted in a continuing loosening of used-to-be tightened policy on food trade, to maintain such a high rate of self-sufficiency of grains is becoming more and more unnecessary and unfeasible, both economically and environmentally. So it is reasonable to incorporate the virtual water trade as an active policy instrument into the integrated water management strategy, but with careful considerations. To reduce the risk of volatile international food market, the sources of virtual water import should be diversified. This paper showed the possible monopoly in virtual water import of China. Therefore, more efforts could be put to diversify the import partners in order to get stronger market power. At the other hand, adjust the crop structure as to grow more water-efficient crops in water-stressed region; reduce exporting high water-intensive but low economic-value products through financial incentives; and increasing exporting low water-intensive but high economic-value products.

## 6. FURTHER STUDY

As limitation to the available data and time of study, there remains much space for further study. Further attention should be paid to the reallocation of external virtual water import and the internal virtual water flow between provinces. The source (“blue” and “green” water) of virtual water and its effect on water quality should also be considered. There have been quite a few studies on the virtual water trade of China at the international level but studies at the intra-regional level remains scarce. There would be more policy relevance to scale down to regional or water-basin level in order to help specific policy-making. Also, apart from agriculture products, virtual water trade associated with industrial commodities of China is also crucial as the China is now as the world manufacturer. Some study has showed that China is net virtual water importer if only accounting for agriculture products but net virtual water exporter if combining industry. This would give a broader perspective into the virtual water trade of China. As mentioned before, it’s crucial to enhance the policy relevance of virtual water study. To combine with economic analysis like comparative advantage theory, which has actually been well applied since China’s economic reform and opening policy and to account for monetary value are more effective ways to promote virtual water trade as an option into the sphere of policy making.

## 7. CONCLUSION

China has significantly increased crop-related virtual water trade, especially virtual water import associated with soybeans unconsciously for the recent two decades, while the VWT network's property remains unchanged. This dramatic increase of VWI has to some extent contributed to mitigation of water scarcity of China and to optimizing the global water use efficiency. However, as water scarcity will continue to be a major concern in China, virtual water trade as a policy tool should be actively integrated into integrated water management strategy.

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