Water Research 94 (2016) 73–85

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

The effect of inter-annual variability of consumption, production, trade and climate on crop-related green and blue water footprints and inter-regional virtual water trade: A study for China (1978–2008)

La Zhuo, Mesfin M. Mekonnen, Arjen Y. Hoekstra*

Twente Water Centre, University of Twente, 7500AE, Enschede, Netherlands

ARTICLE INFO

Article history:
Received 12 September 2015
Received in revised form
10 February 2016
Accepted 14 February 2016
Available online 16 February 2016

Keywords:
Water footprint accounting
Inter-regional virtual water trade
Inter-annual variation
Crop trade
Water import dependence

ABSTRACT

Previous studies into the relation between human consumption and indirect water resources use have unveiled the remote connections in virtual water (VW) trade networks, which show how communities externalize their water footprint (WF) to places far beyond their own region, but little has been done to understand variability in time. This study quantifies the effect of inter-annual variability of consumption, production, trade and climate on WF and VW trade, using China over the period 1978–2008 as a case study. Evapotranspiration, crop yields and green and blue WFs of crops are estimated at a 5 × 5 arc-minute resolution for 22 crops, for each year in the study period, thus accounting for climate variability. The results show that crop yield improvements during the study period helped to reduce the national average WF of crop consumption per capita by 23%, with a decreasing contribution to the total from cereals and increasing contribution from oil crops. The total consumptive WFs of national crop consumption and crop production, however, grew by 6% and 7%, respectively. By 2008, 28% of total water consumption in crop fields in China served the production of crops for export to other regions and, on average, 35% of the crop-related WF of a Chinese consumer was outside its own province. Historically, the net VW within China was from the water-rich South to the water-scarce North, but intensifying North-to-South crop trade reversed the net VW flow since 2000, which amounted 6% of North's WF of crop production in 2008. South China thus gradually became dependent on food supply from the water-scarce North. Besides, during the whole study period, China's domestic inter-regional VW flows went dominantly from areas with a relatively large to areas with a relatively small blue WF per unit of crop, which in 2008 resulted in a trade-related blue water loss of 7% of the national total blue WF of crop production. The case of China shows that domestic trade, as governed by economics and governmental policies rather than by regional differences in water endowments, determines inter-regional water dependencies and may worsen rather than relieve the water scarcity in a country.

1. Introduction

Since the beginning of this millennium the body of scientific literature on water footprint and virtual water trade assessment is expanding exponentially, as witnessed by the number of papers published on the topic in Web of Science. The water footprint (WF), as a multi-dimensional measure of freshwater used both directly and indirectly by a producer or a consumer, enables to analyse the link between human consumption and the appropriation of water to produce the products consumed (Hoekstra, 2013). The consumptive WF of producing a crop includes a green and blue component, referring to consumption of rainfall and irrigation water respectively, thus enabling the broadening of perspective on water resources as proposed by Falkenmark and Rockström (2004). The consumptive WF is distinguished from the degradative WF, the so-called grey WF, which represents the volume of water required to assimilate pollutants entering freshwater bodies. The WF of human consumption within a certain geographic area consists of an internal WF, referring to the WF within the area itself for making products that are consumed within the area, and an external WF, referring to the WF in other areas for making products imported by and consumed within the geographic area considered (Hoekstra

* Corresponding author. Twente Water Centre, University of Twente, P. O. Box 217, 7500AE, Enschede, Netherlands.
E-mail address: a.y.hoekstra@utwente.nl (A.Y. Hoekstra).

http://dx.doi.org/10.1016/j.watres.2016.02.037

et al., 2011). Thus, trade in water-intensive commodities like crops results into so-called virtual water (VW) flows between exporting and importing regions (Hoekstra, 2003). Crop trade saves water resources for an administrative region if it imports water-intensive crops instead of producing them domestically (Chapagain et al., 2006).

WF and VW trade studies have been carried out for geographies at different scales, from the city (Zhang et al., 2011) to the globe (Hoekstra and Mekonnen, 2012). Despite the vast body of literature, little attention has been paid to the annual variability and long-term changes of WFs and VW flows as a result of climate variability and structural changes in the economy. Most work thus far focussed on employing different models and techniques to assess WFs and VW flows, considering a specific year or short period of years. The effects of long-term changes in spatial patterns of production, consumption, trade and climate on WFs and VW flows have hardly been studied. This is paramount, though, for understanding how human pressure on water resources develops over time and how changing trade patterns influence inter-regional water dependencies.

The objective of the current study is to quantify the effect of inter-annual variability of consumption, production, trade and climate on crop-related green and blue WFs and inter-regional VW trade, using China over the period 1978–2008 as a case study. First, we assess the historical development of the green and blue WFs related to crop *consumption* in China, per province. Second, we estimate, accounting for the climate variability within the period considered, the green and blue WFs related to crop *production*, at a 5×5 arc-minute resolution, year by year, crop by crop. Third, we quantify the annual inter-regional VW flows based on provincial crop trade balances for each crop. Finally, we estimate national water savings as a result of international and inter-regional crop trade. We consider twenty-two primary crops (Table 3), which covered 83% of national crop harvested area in 2009 (NBSC, 2013) and 97% and 78% of the total blue and green WF of Chinese crop production in the period 1996–2005, respectively (Mekonnen and Hoekstra, 2011). In this study we exclude the grey WF of crops because of our focus on inter-annual variability and the fact that variability in climate plays a role particularly in estimating green and blue WFs, not in estimating grey WFs. We focus on the direct green and blue WF of crop growing in the field, thus excluding the indirect WF of other inputs into crop production, like the WF of machineries and energy used. The study area is Mainland China, which consists of 31 provinces and can be grouped into eight regions (Fig. 1).

China is facing severe water scarcity (Jiang, 2009). Since the economic reforms in 1978, the Chinese people consume increasing levels of oil crops, sugar crops, vegetables and fruits (Liu and Savenije, 2008). Chinese crop consumption per capita rose by a factor 2.1 over the period 1978–2008 (FAO, 2014), while China's population grew from 0.96 to 1.31 billion (NBSC, 2013). In order to meet the increasing food demand, China's crop production grew by a factor 2.8 from 1978 to 2008 (FAO, 2014), with an increase of only 4% in total harvested area, but a 31% growth in irrigated area. The expansion of the irrigated area occurred mainly (77%) in the water-scarce North, which now has 51% of the national arable land, but only 19% of the national blue water resources (Wu et al., 2010; Zhang et al., 2009). Agriculture is the biggest water user in China, responsible for 63% of national total blue water withdrawals (MWR, 2014) and 88% of the total WF within China (Hoekstra and Mekonnen, 2012). Currently, the Yellow River basin in the North suffers moderate to severe blue water scarcity during seven months of the year, mostly driven by agricultural water use (Zhuo et al., 2016). The Yongding He Basin in northern China, a densely populated basin serving water to Beijing, faces severe water scarcity all year long (Hoekstra et al., 2012). It is estimated that about 64% of China's total population, mainly from the North, regularly faces severe blue water scarcity (Mekonnen and Hoekstra, 2016). The competition between different sectors over water resources has become severe (Zhu et al., 2013), which has led to the adoption of the No. 1 Document by the State Council of China (SCPRC, 2010), announcing a four trillion CNY (~US$600 billion) investment over ten years to guarantee water supplies through the improvement of water supply infrastructure. This includes the construction of new reservoirs, drilling of wells, and implementation of inter-basin water transfer projects (Gong et al., 2011; Yu, 2011), as well as targets to increase water productivity.

Today, China is the country with the largest WF related to crop consumption and the second largest WF related to crop production (Hoekstra and Mekonnen, 2012). Furthermore, China has substantive VW import through crop imports (Dalin et al., 2014). At present, net VW trade through crop trade is from the drier North to the wetter South (Ma et al., 2006; Cao et al., 2011). In 2005, China's domestic food trade resulted in national net water saving overall, but a net loss of blue water (Dalin et al., 2014), as a result of differences in WF of crops ($m^3\ t^{-1}$) among trading provinces (Mekonnen and Hoekstra, 2011).

There have been quite a number of previous studies on the WF of Chinese crop consumption (Hoekstra and Chapagain, 2007, 2008; Liu and Savenije, 2008; Mekonnen and Hoekstra, 2011; Ge et al., 2011; Hoekstra and Mekonnen, 2012; Cao et al., 2015), the WF of Chinese crop production (Hoekstra and Chapagain, 2007, 2008; Siebert and Döll, 2010; Liu and Yang, 2010; Fader et al., 2010; Mekonnen and Hoekstra, 2011; Ge et al., 2011; Cao et al., 2014a,b), on China's international VW imports and exports associated with crop trade (Hoekstra and Hung, 2005; Hoekstra and Chapagain, 2007, 2008; Liu et al., 2007; Fader et al., 2011; Hoekstra and Mekonnen, 2012; Dalin et al., 2012; Chen and Chen, 2013; Shi et al., 2014) and on VW trade flows within China (Ma et al., 2006; Guan and Hubacek, 2007; Wu et al., 2010; Cao et al.,

Table 1
Crop source regions per region for Mainland China.

	Region[a]	Provinces	Crop source regions per allocation round						
			1	2	3	4	5	6	7
R1	Northeast (N)	Heilongjiang, Jilin, Liaoning	R3	R7	R6	R8	R5	R4	R2
R2	Jing-Jin (N)	Beijing, Tianjin	R3	R7	R1	R6	R8	R5	R4
R3	North Coast (N)	Hebei, Shandong	R7	R1	R6	R8	R2	R5	R4
R4	East Coast (S)	Jiangsu, Shanghai, Zhejiang	R6	R7	R3	R1	R8	R5	R2
R5	South Coast (S)	Fujian, Guangdong, Hainan	R6	R8	R7	R3	R1	R4	R2
R6	Central	Shanxi (N), Henan (N), Anhui (N), Hubei (S), Hunan (S), Jiangxi (S)	R3	R7	R1	R8	R5	R4	R2
R7	Northwest (N)	Inner Mongolia, Shaanxi, Ningxia, Gansu, Qinghai, Xinjiang	R6	R3	R8	R1	R5	R4	R2
R8	Southwest (S)	Sichuan, Chongqing, Guangxi, Yunnan, Guizhou, Tibet	R7	R1	R6	R3	R5	R4	R2

[a] N = North China; S = South China.

Table 2
Overview of data sources.

Data type	Spatial resolution	Product and sources
GIS database of administrations	provincial	NASMG (2010)
Annual population statistics	provincial	NBSC (2013)
Statistics on annual total production and total harvested area of each crop	provincial/national	NBSC (2013)/FAOSTAT (FAO, 2014)
Statistics on crop trade	international	FAOSTAT (FAO, 2014)
Monthly climate data on precipitation and ET_0	30 × 30 arc minute	CRU-TS v3.10 (Harris et al., 2014)
Irrigated and rainfed area of each crop	5 × 5 arc minute	MIRCA2000 (Portmann et al., 2010)/Monfreda et al. (2008)
Soil texture	1:1 million	SOTER_China (Dijkshoorn et al., 2008)
Total soil water capacity	5 × 5 arc minute	ISRIC-WISE (Batjes, 2012)

Table 3
National average WF of crops consumed in China for the years 1978 and 2008.

	1978			2008		
	Green WF	Blue WF	Total WF	Green WF	Blue WF	Total WF
	$m^3\ t^{-1}$	$m^3\ t^{-1}$	$m^3\ t^{-1}$	$m^3\ t^{-1}$	$m^3\ t^{-1}$	$m^3\ t^{-1}$
Wheat	2080	817	2897	839	312	1151
Maize	1412	121	1534	754	66	819
Rice	1486	615	2101	961	384	1345
Sorghum	1080	88	1168	714	45	759
Barley	839	558	1397	832	198	1030
Millet	2042	184	2225	1811	133	1945
Potatoes	264	7	271	189	7	196
Sweet potatoes	74	40	114	67	21	88
Soybean	3718	677	4395	2024	110	2134
Groundnuts	3165	395	3560	1345	191	1536
Sunflower seed	2177	289	2466	1087	184	1270
Rapeseed	4292	0	4292	1736	0	1736
Seed cotton	5093	539	5632	1278	503	1781
Sugar cane	208	3	211	120	1	121
Sugar beet	372	0	372	66	0	66
Spinach	100	8	107	79	4	83
Tomatoes	126	3	129	68	2	70
Cabbages	181	15	196	130	7	137
Apples	1367	157	1524	314	39	353
Grapes	1011	304	1314	316	104	421
Tea	33,518	226	33,744	8517	144	8662
Tobacco	2381	84	2465	1633	13	1646

National averages are calculated weighing the WFs of domestically produced and imported crops.

2011; Han and Sun, 2013; Sun et al., 2013; Dalin et al., 2014; Feng et al., 2014; Wang et al., 2014; Zhang and Anadon, 2014; Zhao and Chen, 2014; Fang and Chen, 2015; Jiang et al., 2015; Zhao et al., 2015). Despite all those studies, analyses of *inter-annual variability* and *long-term changes* in spatial WF and VW trade patterns are rare, not only in studies for China but in general. While in another paper (Zhuo et al., 2016) we show the inter-annual variations in WFs of *crop production* as well as inter-annual variation of blue water scarcity (with a focus on the Yellow River basin), in the current study we also consider inter-annual variability in WFs of *crop consumption* and in inter-regional and international VW trade (for China as a whole).

2. Method and data

The annual green and blue WFs of crop *consumption* (in $m^3\ y^{-1}$) were estimated per crop per year at provincial level based on the bottom-up approach (Hoekstra et al., 2011). The WF related to consumption of a crop ($m^3\ y^{-1}$) was calculated per year by multiplying the provincial crop consumption volume ($t\ y^{-1}$) with the WF of the crop for the province ($m^3\ t^{-1}$). Crop consumption volumes per capita were obtained from the Supply and Utilization Accounts expressed in crops primary equivalent of FAO (2014). We assumed consumption per capita data the same for all provinces. For edible crops, we took the sum of the "food" and "food manufactured" columns and added an amount representing seed and waste. Regarding the latter amount, we took a part of the utilization for seed and waste based on the utilization of crops for food and food manufactured relative to the utilization of crops for feed. For cotton and tobacco, we took the "other use" column as consumed quantities. The WFs of crops per province were calculated as:

$$WF_{prov}[p] = \frac{P_{prov}[p] \times WF_{prod,prov}[p] + \sum_e \left(I_e[p] \times WF_{prod,e}[p] \right)}{P_{prov}[p] + \sum_e I_e[p]} \quad (1)$$

in which $P_{prov}[p]$ ($t\ y^{-1}$) represents the production quantity of crop p, $I_e[p]$ ($t\ y^{-1}$) the imported quantity of crop p from exporting place e (other regions in China or other countries), $WF_{prod,\ prov}[p]$ ($m^3\ t^{-1}$) the specific WF of crop production in the province, and $WF_{prod,\ e}[p]$ ($m^3\ t^{-1}$) the WF of the crop as produced in exporting place e.

The green and blue WFs of crop *production* were estimated year by year at 5 × 5 arc minute resolution. The green and blue WF (in $m^3\ t^{-1}$) of a crop within a grid cell is calculated as the actual green and blue evapotranspiration (ET, $m^3\ ha^{-1}$) over the growing period divided by the crop yield (Y, $t\ ha^{-1}$). ET and Y were simulated per crop per grid per year at daily basis using the plug-in version of FAO's crop water productivity model AquaCrop version 4.0 (Steduto et al., 2009; Reas et al., 2009; Hsiao et al., 2009). The separation of

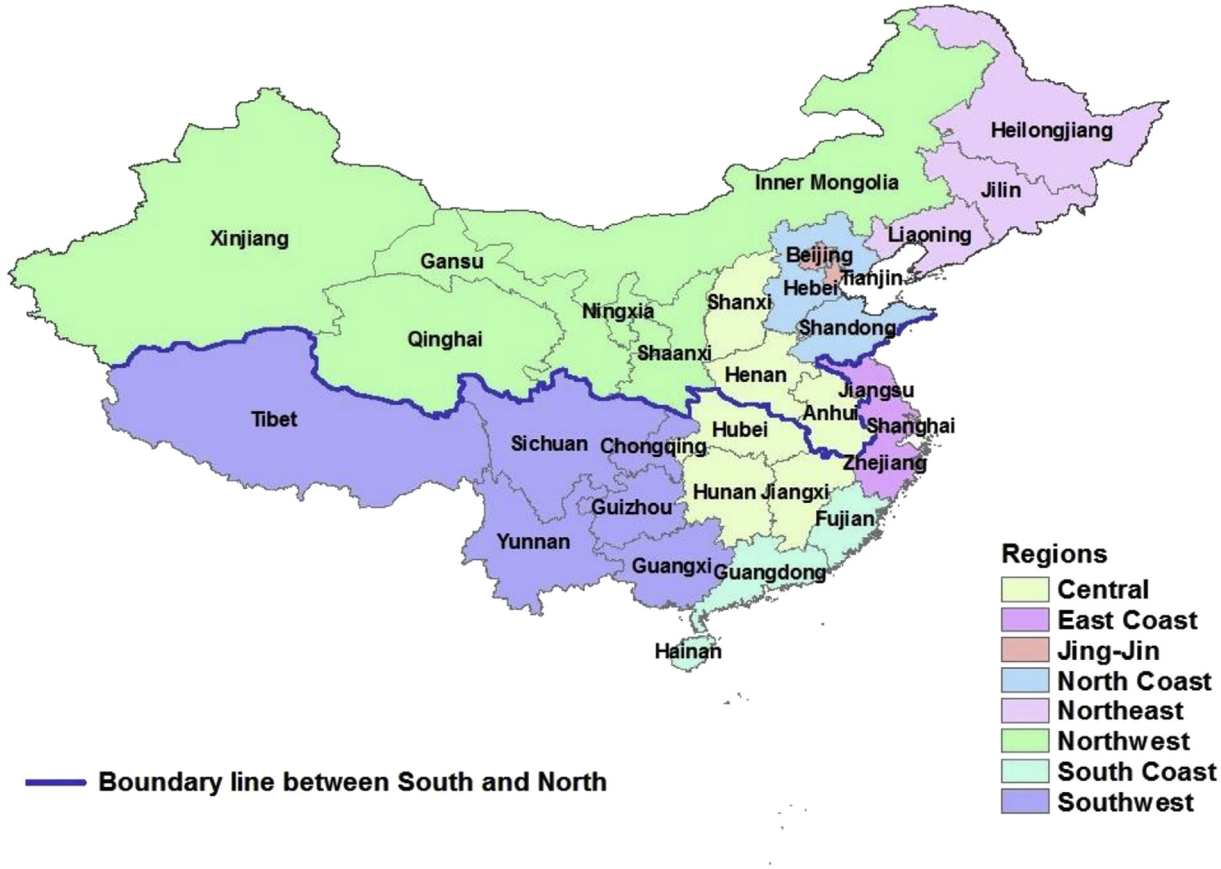

Fig. 1. Provinces and regions of Mainland China.

green and blue ET was carried out by tracking the daily green and blue soil water balances based on the contribution of rainfall and irrigation, respectively, following Chukalla et al. (2015) and Zhuo et al. (2016).

Inter-regional VW flows ($m^3\ y^{-1}$) related to crop trade were calculated per year by multiplying the inter-regional crop trade flows ($t\ y^{-1}$) with the WF of the crop ($m^3\ t^{-1}$) in the exporting region. Since inter-regional crop trade statistics are not available, we took the following steps:

1) The provincial crop trade balance or net import of a crop ($t\ y^{-1}$) was estimated as the total provincial crop utilization minus the provincial crop production. The national use of a crop for direct and manufactured food as given by FAO (2014) was distributed over the provinces based on provincial populations. The national use of a crop for feed was distributed over provinces proportional to the national livestock units (LU) per province. LU is a reference unit which facilitates the aggregation of different livestock types to a common unit, via the use of a 'livestock unit coefficient' obtained by converting the livestock body weight into the metabolic weight by an exchange ratio (FAO, 2005). We used the livestock unit coefficients for East Asia from Chilonda and Otte (2006): 0.65 for cattle, 0.1 for sheep and goats, 0.25 for pigs, 0.5 for asses, 0.65 for horses, 0.6 for mules, 0.8 for camels, and 0.01 for chickens. Finally, we downscale national variations in crop stock to provincial level by assuming provincial stock variations proportional to the provincial share in national production.
2) We assume that international crop imports and exports relate to the provinces with deficit and surplus of the crop, respectively (following Ma et al., 2006). Further we assume that crop-deficit provinces primarily receive from crop-surplus provinces within the same region and subsequently – if insufficient surplus within the region itself – from other crop-surplus regions.
3) A crop-deficit region is assumed to import the crop preferentially from the crop-surplus region which has the highest agricultural export values to the crop-deficit region, according to the multi-regional input–output tables of the agricultural sector for the years 1997 (SIC, 2005), 2002 and 2007 (Zhang and Qi, 2011). How source regions supply deficit regions is determined in a few subsequent rounds. The source regions per region per allocation round are listed in Table 1. We assume that in each round the crop source regions supply crops to the deficit regions proportionally to their deficit.

The total crop-related net VW import ($m^3\ y^{-1}$) of a province is equal to the international net VW import plus the inter-regional net VW import of the province. The WFs ($m^3\ t^{-1}$) of crops imported from abroad were obtained from Mekonnen and Hoekstra (2011), assuming constant green and blue WFs of imported crops per source country. The provincial net VW export related to a certain crop export is calculated by multiplying the net crop export volume ($t\ y^{-1}$) with the WF ($m^3\ t^{-1}$) of the crop in the province.

Water savings through crop trade were estimated using the method of Chapagain et al. (2006). The international crop trade-related water saving of a province ($m^3\ y^{-1}$) was calculated by multiplying the net international import volume of the province ($t\ y^{-1}$) by the WF per tonne of the crop in the province ($m^3\ t^{-1}$). The inter-regional crop trade-related water saving was estimated similarly, by multiplying the net inter-regional import volume of

the province (t y^{-1}) with the WF per tonne of the crop in the province (m^3 t^{-1}). If a specific crop is imported and not grown in the province itself at all, the national average WF per tonne of the crop was used. Overall trade-related water savings follow from the difference in the WF of a crop in the importing and exporting province (Hoekstra et al., 2011). When calculated trade-related water savings are negative, we talk about trade-related 'water losses', which refer to cases whereby crops are traded from a region with relatively low water productivity to a region with relatively high water productivity.

The GIS polygon for Chinese provinces was obtained from NASMG (2010). Provincial population statistics over the study period and numbers of the different livestock types were obtained from NBSC (2013), and data on China's international trade per crop (in t y^{-1}) from FAO (2014), and Data on monthly precipitation, reference evapotranspiration and temperature at 30 × 30 arc minute resolution were take from Harris et al. (2014). Fig. 2 shows the inter-annual variation of national average precipitation and reference evapotranspiration (ET_0) across China over the period 1978–2008. Data on irrigated and rain-fed areas for each crop at 5 × 5 arc-minute resolution were taken from Portmann et al. (2010). For crops not available in this source, we used Monfreda et al. (2008). Harvested areas and yields for each crop were scaled per year to fit the annual agriculture statistics at province level obtained from NBSC (2013). For crops not reported in NBSC (2013), we used FAO (2014). Soil texture data were obtained from Dijkshoorn et al. (2008). For hydraulic characteristics for each type of soil, the indicative values provided by AquaCrop were used. Data on total soil water capacity were obtained from Batjes (2012). Details on datasets used can be found in Table 2.

3. Results

3.1. Water footprint of crop consumption

Over the study period 1978–2008, Chinese annual per capita consumption of the 22 considered crops has grown by a factor 1.4, from 391 to 559 kg cap^{-1}. The national average WF per capita related to crop consumption reduced by 23%, from 625 m^3 cap^{-1} (149 m^3 cap^{-1} blue WF) in 1978 to 481 m^3 cap^{-1} (94 m^3 cap^{-1} blue WF) in 2008 (Fig. 3), which was mainly due to the decline in the WF per tonne of crops (Table 3). The decline in the WF per tonne of crop resulted from improved crop yields within China as well as the expanded international import of crops from other countries with relatively small WF. The share of the WF related to the consumption of oil crops (soybean, groundnuts, sunflower and rapeseed) in the total consumptive WF per capita grew from 8% in 1978 to 21% in 2008 (Fig. 3), as a result of the increased proportion of oil crops in Chinese consumption.

Due to differences in the WF (in m^3 t^{-1}) of the consumed crops in the different provinces, there were differences among provinces in terms of WFs per capita, ranging from 367 to 604 m^3 cap^{-1} y^{-1} for the total consumptive WF and from 29 to 228 m^3 cap^{-1} y^{-1} for the blue WF in the year 2008. Fourteen provinces, mostly located in Southwest, Northeast, North Coast and East Coast, have a WF per capita below the national average (Fig. 4). The three provinces with the largest WF per capita related to crop consumption in 2008 were Ningxia (604 m^3 cap^{-1} y^{-1}), Guangxi (587 m^3 cap^{-1} y^{-1}) and Guangdong (586 m^3 cap^{-1} y^{-1}). Chongqing had the smallest WF per capita (367 m^3 cap^{-1} y^{-1}). Provinces with a blue WF per capita smaller than the national average are mostly located in Southwest, Northeast and East Coast. The three provinces with the largest blue WF per capita in 2008 are all located in the semi-arid Northwest: Inner Mongolia (228 m^3 cap^{-1} y^{-1}), Xinjiang (214 m^3 cap^{-1} y^{-1}) and Ningxia (213 m^3 cap^{-1} y^{-1}). Anhui had the smallest blue WF per capita (29 m^3 cap^{-1} y^{-1}).

Although the total consumption of the 22 considered crops doubled between 1978 and 2008, with 37% of population growth in China, the national WF related to crop consumption increased only by 6%, from 599 to 632 billion m^3 y^{-1} (Fig. 5), thanks to the decline in the WF of crops (m^3 t^{-1}). The share of North China in the total national consumptive WF of crop consumption decreased from 48 to 44% over the study period, amongst other driven by the slightly faster population growth in the South. At provincial level, Shanghai had the largest increase in the WF of crop consumption, a 2.3 times increase over the study period (from 4.6 to 10.5 billion m^3 y^{-1}), followed by Beijing with a 2.0 times increase (from 4.4 to 8.6 billion m^3 y^{-1}). This was mainly driven by the doubling of the population in these two megacities (from 11.0 to 21.4 million in Shanghai and from 8.7 to 17.7 million in Beijing).

3.2. Water footprint of crop production

The total green plus blue WF in China of producing the 22 crops considered increased over the period 1978–2008 by 7%, from 682 billion m^3 y^{-1} (23% of blue) to 730 billion m^3 y^{-1} (19% of blue) (Fig. 6), while total production of those crops grew by a factor 2.2. The relatively modest growth of the WF can be attributed to a significant decrease in the WFs per tonne of crop, which in turn result from an increase in crops yield. The national average WF of

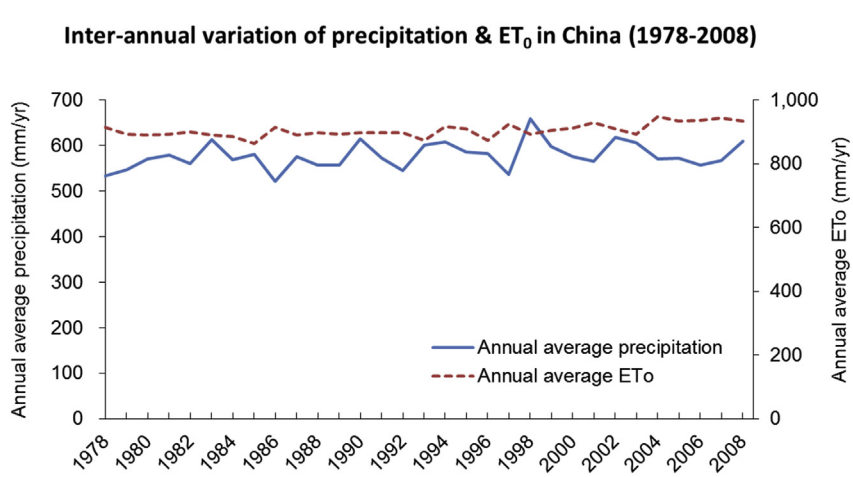

Fig. 2. Inter-annual variation of national average precipitation and reference evapotranspiration (ET_0) across China over the period 1978–2008. Data source: Harris et al. (2014).

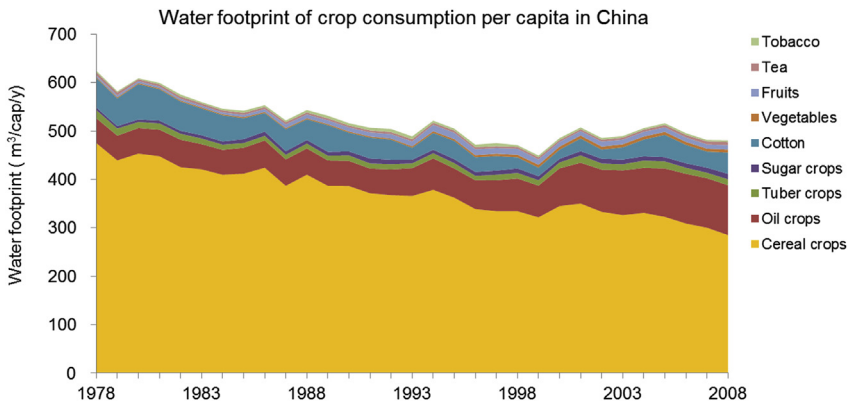

Fig. 3. National average WF per capita (m^3 cap^{-1} y^{-1}) of crop consumption in China, per crop group. The figures represent crop consumption for food, thus excluding crop consumption for feed.

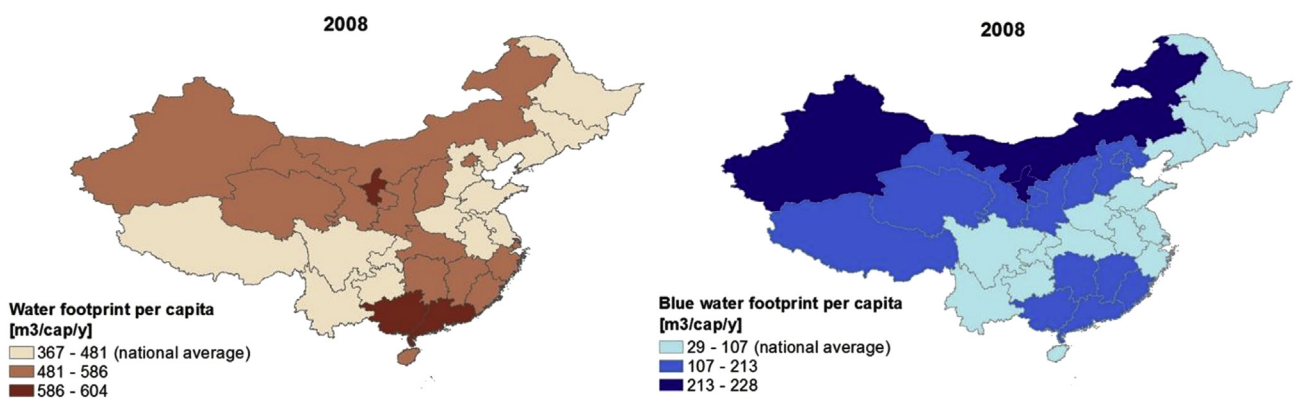

Fig. 4. China's provincial average total and blue WFs per capita (m^3 cap^{-1} y^{-1}) related to crop consumption in 2008. The figures refer to crop consumption for food, thus excluding crop consumption for feed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

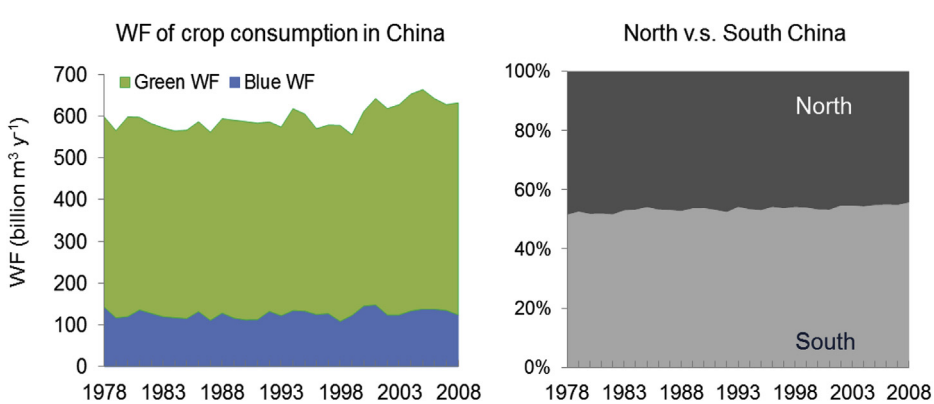

Fig. 5. WF of crop consumption in China (left), and the relative contributions of North and South China to the total (right). The figures refer to crop consumption for food, thus excluding crop consumption for feed.

cereals (wheat, rice, maize, sorghum, millet, and barley), for example, decreased by 46%, from 2136 m^3 t^{-1} (540 m^3 t^{-1} blue WF) to 1146 m^3 t^{-1} (249 m^3 t^{-1} blue WF), due to an almost two-fold increase in cereal yield (from 2.9 to 5.6 t ha^{-1}) (Fig. 7). These findings correspond to long-term decreases in WFs per tonne found in a case study for the Yellow River basin by Zhuo et al. (2016). Inter-annual climatic variability contributed to the fluctuations in consumptive WFs (m^3 t^{-1}) over the years. When comparing the fluctuations in the average green and blue WFs of a cereal crop in China over the period 1978–2008 (as shown in Fig. 7) to the variations in annual precipitation and ET_0 over the same period (Fig. 2), we find that the blue WF inversely relates to precipitation, and that the green and total consumptive WFs show a weak positive relation to ET_0. In years with relatively large precipitation, the ratio of blue to total consumptive WF is generally smaller, a finding that could be expected because irrigation requirements will generally be less.

The total harvested area of the considered crops increased by 16% in the North and decreased by 13% in the South. The harvested

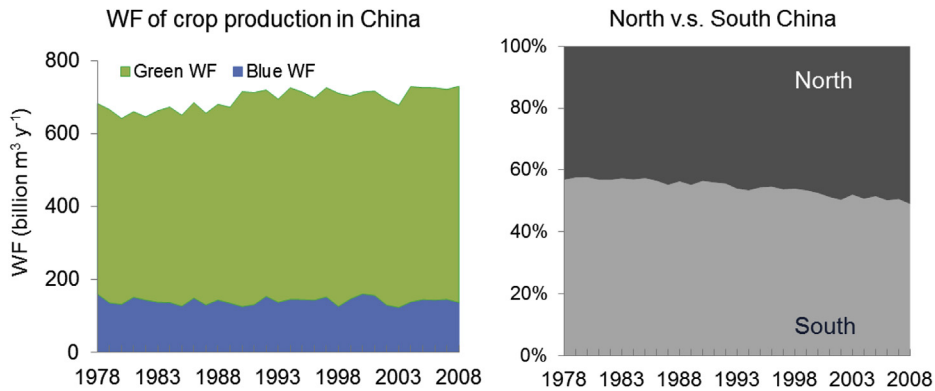

Fig. 6. Consumptive WF of crop production in China, and the relative contributions of North and South China.

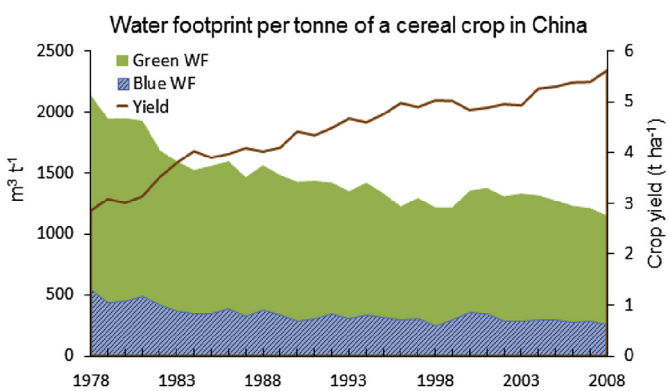

Fig. 7. Green and blue WF of cereals ($m^3\ t^{-1}$) and cereal yield ($t\ ha^{-1}$) in China. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

area and the total consumptive WF of crop production decreased in the provinces that have relatively high urbanization levels (Beijing, Tianjin, Shanghai, Chongqing, Zhejiang, Fujian, Hubei, and Guangdong) and are mostly located in the water-rich South. The most significant drop in the total consumptive WF of crop production (a 65% decrease) was in Shanghai and Zhejiang, with halved harvested areas. At the same time, the other provinces mostly located in the water-scarce North, experienced increases in the total consumptive WF of crop production. The most significant increase (fivefold) in the total consumptive WF was observed in Inner Mongolia, which is located in the semi-arid Northwest, where the harvested area expanded by a factor 3.5 and the irrigated area by a factor 2. The contribution of the water-scarce North to the WF of national crop production increased from 43% in 1978 to 51% in 2008 as a result of increasing cropping area in the North compared to the South and increased irrigation in the North (Fig. 6).

Fig. 8 shows the spatial distribution of the total consumptive WF (in mm y^{-1}) of crop production, as well as the share of blue in the total, averaged over the period 1999–2008. Large total consumptive WFs correlate with large overall harvested areas and/or the production of relatively water-intensive crops, while a large share of blue WF in the total reflects the presence of intensive irrigated agriculture. In the semi-arid Northwest and North Coast, blue WF shares exceed 40%, with Xinjiang having the highest share (54%), followed by Hebei (43%) and Ningxia (35%).

Cereals (wheat, maize, rice, sorghum, millet and barley) accounted for 74% of the overall consumptive WF of the 22 crops considered, 87% of the blue WF, and 71% of the green WF. More than half of the total blue WF within China was from rice fields (51%), followed by wheat (28%). Rice (32%) and wheat (20%) together also shared half of the total green WF.

3.3. Crop-related inter-regional virtual water flows in China

China's annual net VW import from abroad nearly tripled over the period 1978–2008 (from 34 to 95 billion $m^3\ y^{-1}$). The external WF related to crop consumption in China as a whole was 6% of the total in 1978 and 13% in 2008. The inter-regional VW flows within China were larger than the country's international VW flow. The sum of China's inter-regional VW flows was relatively constant over the period 1978–2000 (with an average of 187 billion $m^3\ y^{-1}$), and rose to a bit higher level during the period 2001–2008 (average 207 billion $m^3\ y^{-1}$) (Fig. 9). With a total consumptive WF of Chinese crop production in 2008 of 730 billion $m^3\ y^{-1}$ and a total gross inter-regional VW trade of 207 billion $m^3\ y^{-1}$, we find that 28% of total water consumption in crop fields in China serves the production of crops for export to other regions. When we consider blue water consumption specifically, we find the same value of 28%. Further we find that, on average, in 2008, 35% of the crop-related WF of a Chinese consumer is outside its own province. For some provinces we find much larger external WFs in 2008: 92% for Tibet (83% in other provinces, 10% abroad), 88% for Beijing (68% in other provinces, 20% abroad) and 86% for Shanghai (66% in other provinces, 20% abroad).

The estimated inter-regional trade of the crops considered increased by a factor 2.3 over the study period, but the sum of inter-regional VW trade flows increased only modestly due to the general decline in WFs per tonne of crops traded. Trade in rice is responsible for the largest component in the inter-regional VW trade flows, although its importance is declining: rice-trade related inter-regional VW flows contributed 48% to the total inter-regional VW flows in China in 1978, but 30% in 2008. More and more rice was transferred from the Central region, which has a relatively large WF per tonne of rice, to deficit regions. Rice production in Central accounted for 38% of total national rice production in 1978 and 44% in 2008. The South Coast became a net rice importer since 2005 due to its increased rice consumption (11% of national rice consumption in 2008) and reduced rice production (from 15% of national rice production in 1978 to 9% in 2008). Wheat- and maize-related inter-regional VW flows increased over the period 1978–2008 by 62% and 60%, respectively, due to the estimated increased inter-regional trade volumes of the two staple crops (from 9 to 36 million t y^{-1} for wheat, and from 17 to 51 million t y^{-1} for maize), driven by North China's increased share in national crop production but decreased share in national crop consumption.

Historically, VW flows within China went from South to North,

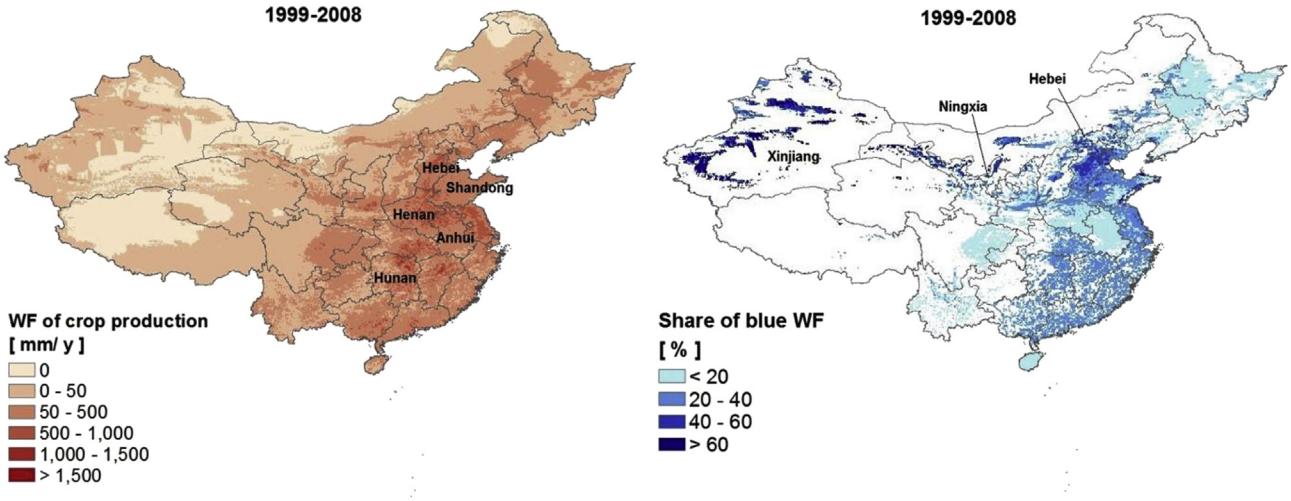

Fig. 8. Spatial distribution of consumptive WFs (mm y^{-1}) of crop production (left) and the share of the blue WF in the total (right) in China. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

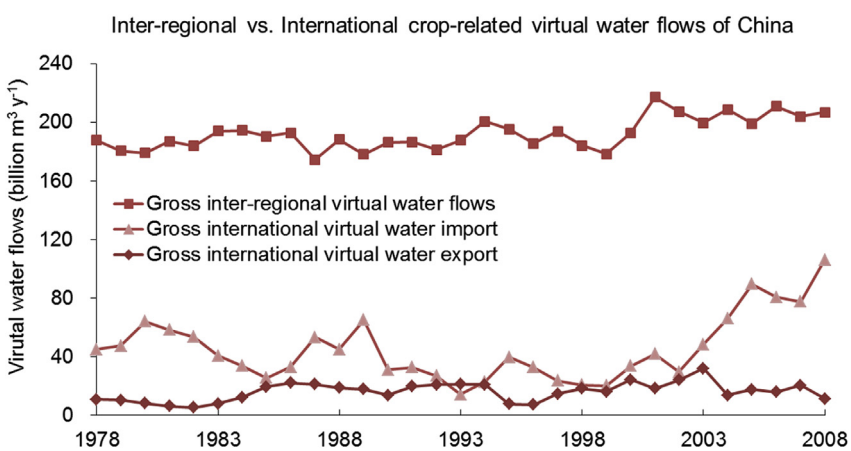

Fig. 9. China's inter-regional and international VW flows.

but over time the size of this flow declined and since the year 2000 the VW flow – related to the 22 crops studied here – goes from North to South (Fig. 10). In 2008, the North-to-South VW flow is related to twelve of the twenty-two considered crops (wheat, maize, sorghum, millet, barley, soybean, cotton, sugar beet, groundnuts, sunflower seed, apples and grapes). Still, other crops, most prominently rice, go from South to North. The main driving factor of the reversed VW flow is the faster increase of production in the North and the faster increase of consumption in the South. By 2008, the crop-related net VW flow from North to South has reached 27 billion m^3 y^{-1}, equal to 7% of the total consumptive WF of crop production in the North.

Fig. 11 presents the net VW trade balances of all provinces for the years 1978 and 2008, for total VW trade as well as for blue and

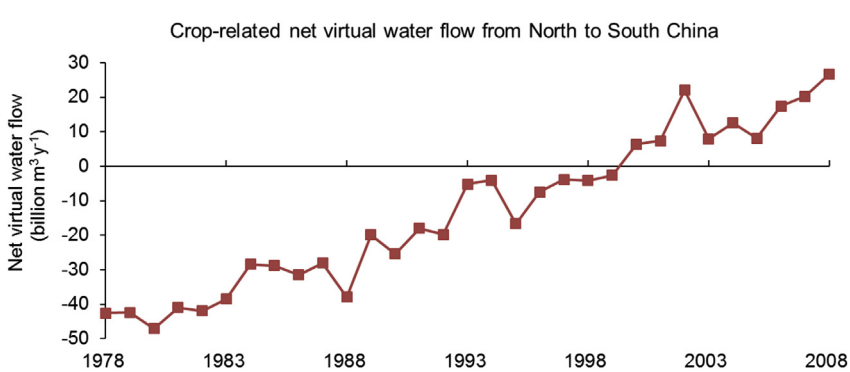

Fig. 10. Net VW transfer from North to South China resulting from inter-regional crop trade.

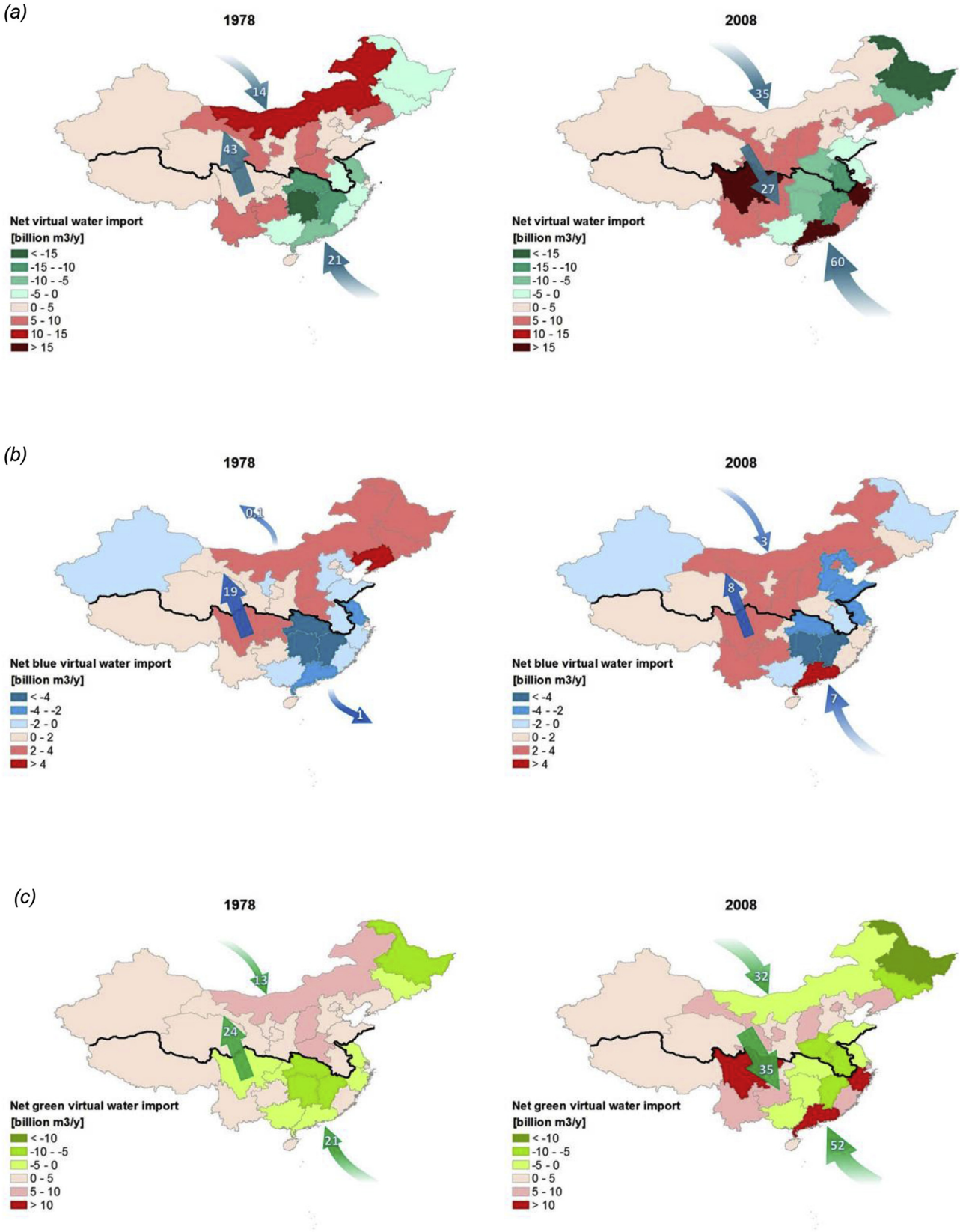

Fig. 11. China's provincial crop-related total (a), green (b) and blue (c) net VW imports for 1978 (left) and 2008 (right). The net VW flows between North and South and the international net VW flows of North and South are shown by arrows, with the numbers indicating the size of net VW flows in billion $m^3\ y^{-1}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

green VW trade separately, with positive balances reflecting net VW import and negative balances indicating net VW export. The figure also shows total, blue and green net VW flows between North and South and the international net VW flows towards the North and South. International net VW imports to both North and South increased. With regard to blue water, China was a net VW exporter to other countries in the 1978, which was mainly from the South and mostly related to rice exports. With the increased crop consumption of the Chinese population, China as a whole became a net blue VW importer in 1990 and remained since.

Over the whole study period, we find a blue VW flow from South to North. It is the green VW flow, and with that the total VW flow, that reversed direction in the study period. This is the first study that shows this, because previous studies didn't distinguish between the green and blue components in the VW flow between North and South. The reason for the continued blue VW flow from South to North is the continued trade of rice in this direction.

The provinces Zhejiang, Guangdong and Fujian, all located in the South, have changed from net VW exporters to net VW importers, in the years 1999, 1987 and 1981, respectively. By 2008, Guangdong was the largest net VW importing province (36 billion m^3 y^{-1}), followed by Sichuan (18 billion m^3 y^{-1}) and Zhejiang (15 billion m^3 y^{-1}). In the meantime, the provinces Henan and Shandong in the North became net VW exporters, in 1993 and 1983, respectively. In 2008, the three largest crop-related net VW exporters were Heilongjiang (21 billion m^3 y^{-1}), Jiangxi (12 billion m^3 y^{-1}) and Anhui (10 billion m^3 y^{-1}).

The inter-regional VW network related to crop trade has changed significantly over the study period (Fig. 12). The Jing-Jin, Northwest, and Southwest regions were all-time net VW importers. The net VW import of Jing-Jin, where Beijing is located, from other regions has more than doubled, from 4.5 to 9.7 billion m^3 y^{-1}, which can be explained by the 84% growth of its population. Central was net VW exporter over the whole study period, with a net VW export increasing from 28 to 52 billion m^3 y^{-1}. East Coast and South Coast have changed from net VW exporter in 1978 to net VW importer in 2008, while North Coast reversed in the other direction. The direction of the net VW flow from South Coast to Northeast has been reversed during the study period due to a reversed direction of rice trade between the two regions. While Northeast shifted from a net importer of rice to a net exporter, the reverse happened in South Coast.

3.4. National water saving related to international and inter-regional crop trade

As shown in Fig. 13, China's total national water saving as a result of international crop trade highly fluctuated, amounting to 41 billion m^3 y^{-1} (6% of total national WF of crop production) in 1978 and 108 billion m^3 y^{-1} (15% of total national WF of crop production) in 2008. From 1981 onwards, inter-regional crop trade in China started to save increasing amounts of water for the country in total, reaching to 121 billion m^3 y^{-1} (17% of the total national WF of crop production) by 2008. Inter-regional crop trade in China did not lead to an overall saving of blue water; instead, the trade pattern increased the blue WF in China as a whole, due to the fact that blue WFs per tonne of crop in the exporting regions were often larger than in the importing regions. The blue water loss resulting from inter-regional trade was 20 billion m^3 y^{-1} (13% of national blue WF of crop production) in 1978 and 9 billion m^3 y^{-1} (6% of national blue WF of crop production) in 2008. The decrease was the result of the increased blue water productivity over the years.

Table 4 lists the national water saving related to international and inter-regional trade of China, per crop, for both 1978 and 2008. In recent years, soybean plays the biggest role in the national water saving of China through international crop trade, which confirms earlier findings (Liu et al., 2007; Shi et al., 2014; Chapagain et al., 2006; Dalin et al., 2014). We found that before 1997 the largest national water saving related to international trade was for wheat trade. In 2008, international trade of only four of the 22 crops considered (soybean, rapeseed, cotton and barley) resulted in national water saving for China. The international export of tea led to the greatest national water loss in 2008.

Most of the national water saving related to inter-regional crop

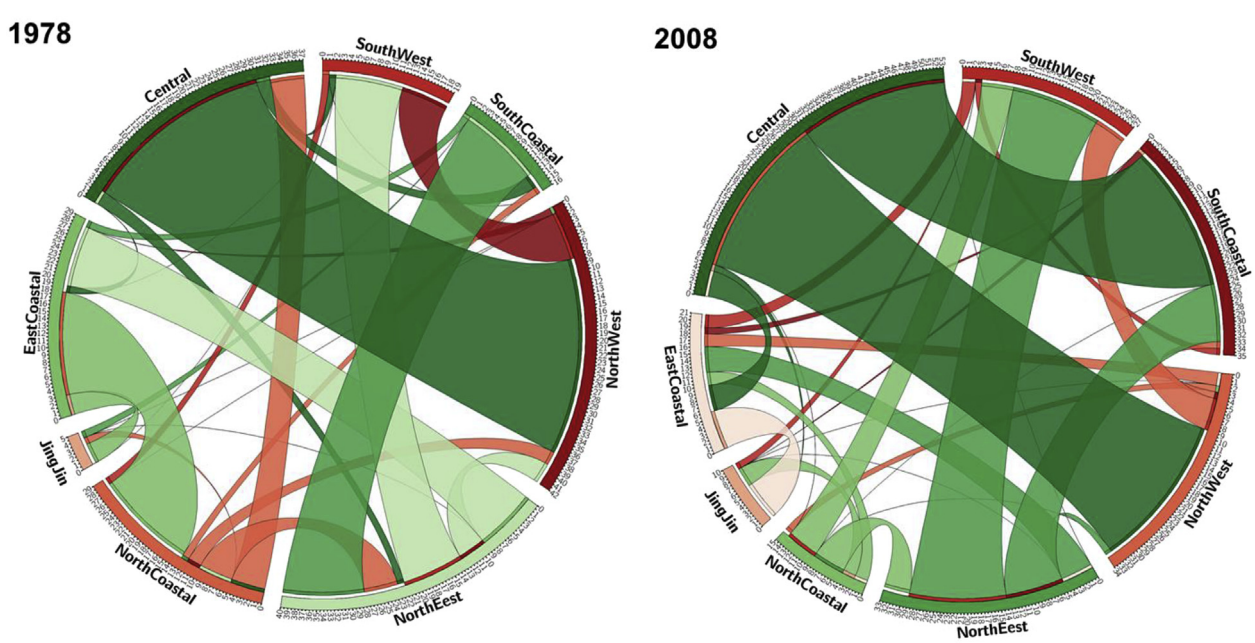

Fig. 12. Inter-regional VW flows in China as a result of the trade in 22 crops for 1978 and 2008. The widths of the ribbons are scaled by the volume of the VW flow. The colour of each ribbon corresponds to the export region. The net VW exporters are shown in green segments, the net VW importers are shown in red segments. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

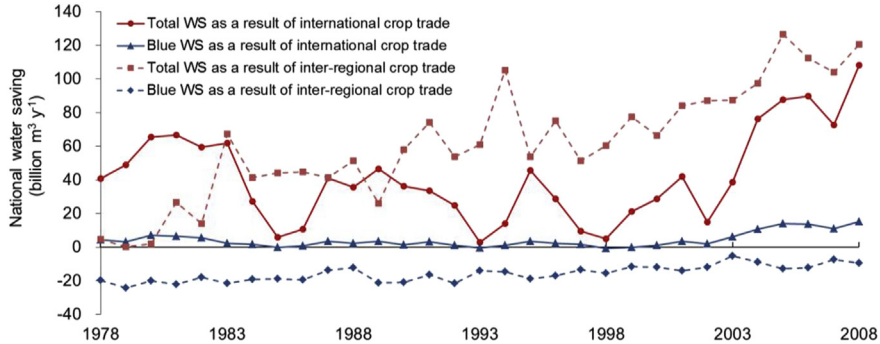

Fig. 13. National water saving (WS) as a result of China's international and inter-regional crop trade.

Table 4
National water saving (WS) through international and inter-regional crop trade of China.

	National WS through international crop trade (billion m^3 y^{-1})		National WS through inter-regional crop trade (billion m^3 y^{-1})		Blue WS through inter-regional crop trade (billion m^3 y^{-1})	
	1978	2008	1978	2008	1978	2008
Wheat	33.8	−0.6	23.9	59.6	−10.4	−3.2
Maize	1.6	−0.9	13.2	3.5	3.6	−0.6
Rice	−4.9	−1.6	−55.7	−28.9	−17.2	−10.7
Sorghum	0.0	−0.1	−1.1	0.0	0.2	0.1
Barley	−0.0	0.3	0.0	−0.0	−0.0	−0.0
Millets	−0.1	−0.0	3.7	0.7	1.2	0.3
Potatoes	−0.0	−0.1	0.7	0.2	0.2	0.1
Sweet potatoes	−0.0	−0.0	0.3	0.2	−0.5	0.1
Soybean	0.4	86.1	1.7	−1.3	1.0	0.7
Groundnuts	−0.1	−0.9	3.5	10.2	1.8	4.3
Sunflower	−0.0	−0.2	0.1	0.1	0.1	0.1
Rapeseed	−0.0	20.4	13.7	64.9	0.0	0.0
Sugar beet	0.0	−0.0	−0.1	0.2	−0.0	−0.0
Sugar cane	0.0	0.0	−0.0	3.0	0.1	0.3
Cotton	12.9	9.4	0.1	0.0	0.2	−0.3
Spinach	−0.0	−0.0	0.0	0.1	0.0	0.0
Tomatoes	−0.0	−0.0	0.8	7.3	0.0	0.1
Cabbages	−0.0	−0.1	−0.0	−0.0	−0.0	−0.0
Apples	−0.1	−0.9	−0.4	0.6	−0.0	−0.1
Grapes	−0.0	−0.0	−0.0	−0.2	−0.0	−0.5
Tea	−2.7	−2.5	−0.0	0.3	0.0	0.0
Tobacco	−0.0	−0.2	0.4	0.2	0.1	0.1
Total	40.7	108.1	4.6	120.6	−19.6	−9.3

trade in 2008 was due to trade in rapeseed, wheat and groundnuts. Due to the increasing inter-regional trade of rapeseed (from 0.8 million t y^{-1} in 1978 to 5 million t y^{-1} in 2008), the generated water saving increased by a factor 4.5 over the study period. The biggest contributor to the national water loss through inter-regional crop trade was rice, with a national water loss of 29 billion m^3 y^{-1} (11% of total consumptive WF of rice production) in 2008. Particularly inter-regional trade in rice and wheat led to blue water losses.

3.5. Discussion

We compared the national average WF of each crop (in m^3 t^{-1}) as estimated in the current study with three previous studies that gave average values for different periods: Mekonnen and Hoekstra (2011) for 1996–2005, Liu et al. (2007) for 1999–2007 and Shi et al. (2014) for 1986–2008. Our estimates match well with previous reported values, with R-square values of 0.96, 0.89 and 0.98 for the three studies, respectively.

A number of limitations should be taken into account when interpreting the results of this study. First, in simulating WFs of crops, a number of crop parameters, such as harvest index, cropping calendar and the maximum root depth for each type of crop, were taken constant over the whole period of analysis. Second, the annual variation of the initial soil water content for each crop (at the beginning of the growing season) in each grid cell was not taken into consideration. Third, we assumed, per crop, that the changes in cropping area over the study period only happened in grid cells where a harvested area for that crop existed around the year 2000 according to the database used (Monfreda et al., 2008; Portmann et al., 2010). Fourth, in estimating WFs of crop consumption, the spatial variation of per capita crop consumption levels (e.g. urban vs. rural) was ignored due to lack of data. Finally, the specific trade flows between crop surplus and crop deficit regions were estimated assuming static multi-regional input–output tables as explained in the method section.

The various assumptions that have been taken by lack of more accurate data translate to uncertainties in the results. The assumptions on harvest indexes and maximum root depths mainly affect the magnitude of modelled crop yield levels; the effect of uncertainties in these model parameters has been minimized by the fact that we calibrated the simulated yields in order to match provincial yield statistics. Regarding assumed cropping calendars and initial soil water content values, a detailed sensitivity analysis to these two variables has been carried out by Zhuo et al. (2014) for the Yellow River basin, the core of Chinese crop production, and by Tuninetti et al. (2015) at global level. By varying the crop planting date by ±30 days, Zhuo et al. (2014) found that the consumptive WF of crops generally decreased by less than 10% with late planting date due to decreased crop ET and that crop yields hardly changed. By changing the initial soil water content by ±1 mm m^{-1}, Tuninetti et al. (2015) showed that an increment in the initial soil water content resulted in decreases in consumptive WF due to higher yield. Again, the effects on yield simulations were diminished by calibration to fit yield statistics. Since none of the factors mentioned can influence the order of magnitude of the outcomes, the broad conclusions with respect to declining WFs of crops (m^3 t^{-1}), declining WFs per capita (m^3 y^{-1} cap^{-1}), increasing total WFs of consumption and production (m^3 y^{-1}) and the reversing of the VW flow between South and North China, are solid.

The volumetric WF as applied in the current study appears to be useful to understand (spatial and temporal variability of) water usage for different crops, inter-regional virtual water flows and water dependences between regions. For the purpose of life cycle assessment studies for products, it has been suggested that a water-scarcity weighted water footprint metric would be better to understand potential local environmental impacts of water use (Ridoutt and Pfister, 2010), an approach recently adopted by ISO

standard 14046. The methods of water footprint assessment (WFA) and life cycle assessment (LCA) share commonalities (Boulay et al., 2013; Manzardo et al., 2016), but the two methods differ in terms of objective and scope (Gu et al., 2014). In the current study we show that WFA focusses on understanding both blue and green water usage and virtual water flows rather than potential local environmental impacts of blue water use. As shown in Zhuo et al. (2016), volumetric blue WFs can be put in the context of local water availability in order to assess water scarcity and thus potential environmental impacts of water use as well, the focus area of LCA studies.

4. Conclusions

For China as a whole, even though the per capita consumption of considered crops grew by a factor of 1.4 over the study period, China's average WF per capita (m^3 cap^{-1} y^{-1}) related to crop consumption decreased by 23%, owing to improved yields. Due to the population growth (37%), the total consumptive WF (m^3 y^{-1}) of Chinese crop consumption increased by 6%, with a tripled net VW import as a result of importing crops from other countries. The production of the 22 crops considered doubled, while the harvested area increased only marginally (4%). The increased crop yields in China have led to significant reductions in the WF of crops (e.g. halving the WF per tonne of cereals), resulting in a slight increase (7%) in the total consumptive WF of crop production. About 28% of total consumptive water use in crop fields in China serves the production of crops for export to other regions. About 35% of the crop-related WF of a Chinese consumer is outside its own province. By 2000, the North has become net VW exporter through crops to the South. This is in line with the findings in earlier studies (e.g. Ma et al., 2006; Cao et al., 2011; Dalin et al., 2014), but we add the nuance that the North-South VW flow concerns green water. There is still a blue VW flow from the South to the North, although this flow more than halved over the study period.

If these trends continue, this will put an increasing pressure on the North's already limited water resources. The on-going South-North Water Transfer Project (SNWTP) may alleviate this pressure to a certain extent, but might be insufficient (Barnett et al., 2015). The Middle Route of the South-North Water Transfer project, which is operational since late 2014, is transferring 3 billion m^3 of blue water per year to support agriculture, with the aim to increase irrigated land by 0.6 million ha in the drier North (SCPRC, 2014). The Government's plan to expand irrigated agriculture by using the transferred water for irrigation will stimulate crop export from the North and thus further increase the blue VW transfer from North to South. The blue water supply through the SNWTP will thus not significantly reduce the pressure on water resources in the North, but rather support agricultural expansion. Efforts to reduce water demand will be needed to address the growing water problems in China.

Crop yield improvements have led to a drop in the WF of crops (m^3 t^{-1}), but further reduction in the WF is possible. Setting WF benchmark values for the different crops, taking into account the agro-ecological conditions of the different regions, formulating targets to reduce the WFs of crops to benchmark levels and making proper investments to reach these targets will be important steps toward further reduction of the WF (Hoekstra, 2013). As the economy grows, the per capita consumption of water-intensive goods such as animal products and oil crops will increase, putting further pressure on China's already scarce water resources (Liu and Savenije, 2008). Thus, efforts are necessary to influence the food preferences of the population in order to curb the increasing consumption of meat, dairy and water-intensive crops, which is useful from a health perspective as well (Du et al., 2004).

The case of China shows that domestic trade, as governed by economics and governmental policies rather than by regional differences in water endowments, determines inter-regional water dependencies and may worsen rather than relieve the water scarcity in a country.

Acknowledgements

Zhuo is grateful for the scholarship under the China Scholarship Council (CSC No. 2011630181). The work was partially developed within the framework of the Panta Rhei Research Initiative of the International Association of Hydrological Sciences (IAHS).

References

Barnett, J., Rogers, S., Webber, M., Finlayson, B., Wang, M., 2015. Sustainability: transfer project cannot meet China's water needs. Nature 527 (7578), 295–297.
Batjes, N.H., 2012. ISRIC-WISE Global Data Set of Derived Soil Properties on a 5 by 5 Arc-minutes Grid (Version 1.2). Report 2012/01. ISRIC World Soil Information, Wageningen, the Netherlands.
Boulay, A.M., Hoekstra, A.Y., Vionnet, S., 2013. Complementarities of water-focused Life Cycle Assessment and water footprint assessment. Environ. Sci. Technol. 47 (21), 11926–11927.
Cao, X., Wu, P., Wang, Y., Zhao, X., Li, S., 2011. Application of virtual water trade theory in inter-regional grain allocation and transportation in China. Afr. J. Biotechnol. 10 (80), 18463–18471.
Cao, X., Wu, P., Wang, Y., Zhao, X., 2015. Challenge of water sources in urbanizing China: an analysis of agricultural water footprint. Pol. J. Environ. Stud. 24 (1), 9–18.
Cao, X.C., Wu, P.T., Wang, Y.B., Zhao, X.N., 2014a. Water footprint of grain product in irrigated farmland of China. Water Resour. Manag. 28 (8), 2213–2227.
Cao, X.C., Wu, P.T., Wang, Y.B., Zhao, X.N., 2014b. Assessing blue and green water utilisation in wheat production of China from the perspectives of water footprint and total water use. Hydrol. Earth Syst. Sci. 18, 3165–3178.
Chapagain, A.K., Hoekstra, A.Y., Savenije, H.H.G., 2006. Water saving through international trade of agricultural products. Hydrol. Earth Syst. Sci. 10, 455–468.
Chen, Z.M., Chen, G.Q., 2013. Virtual water accounting for the globalized world economy: national water footprint and international virtual water trade. Ecol. Indic. 28, 142–149.
Chilonda, P., Otte, J., 2006. Indicators to monitor trends in livestock production at national, regional and international levels. Livest. Res. Rural Dev. 18 (8), 117.
Chukalla, A.D., Krol, M.S., Hoekstra, A.Y., 2015. Green and blue water footprint reduction in irrigated agriculture: effect of irrigation techniques, irrigation strategies and mulching. Hydrol. Earth Syst. Sci. 19 (12), 4877–4891.
Dalin, C., Konar, M., Hanasaki, N., Rinaldo, A., Rodriguez-Iturbe, I., 2012. Evolution of the global virtual water trade network. Proc. Natl. Acad. Sci. 109 (16), 5989–5994.
Dalin, C., Hanasaki, N., Qiu, H., Mauzerall, D.L., Rodriguez-Iturbe, I., 2014. Water resources transfer through Chinese interprovincial and foreign food trade. Proc. Natl. Acad. Sci. 111 (27), 9774–9779.
Dijkshoorn, J.A., van Engelen, V.W.P., Huting, J.R.M., 2008. Soil and Landform Properties for LADA Partner Countries (Argentina, China, Cuba, Senegal and the Gambia, South Africa and Tunisia). ISRIC report 2008/06. ISRIC World Soil Information, Wageningen, the Netherlands.
Du, S., Mroz, T.A., Zhai, F., Popkin, B.M., 2004. Rapid income growth adversely affects diet quality in China—particularly for the poor! Soc. Sci. Med. 59 (7), 1505–1515.
Fader, M., Rost, S., Müller, C., Bondeau, A., Gerten, D., 2010. Virtual water content of temperate cereals and maize: present and potential future patterns. J. Hydrol. 384, 218–231.
Fader, M., Gerten, D., Thammer, M., Heinke, J., Lotze-Campen, H., Lucht, W., Cramer, W., 2011. Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade. Hydrol. Earth Syst. Sci. 15 (5), 1641–1660.
Falkenmark, M., Rockström, J., 2004. Balancing Water for Humans and Nature: the New Approach in Ecohydrology. Earthscan, London, UK.
Fang, D.L., Chen, B., 2015. Ecological network analysis for a virtual water network. Environ. Sci. Technol. 49, 6722–6730.
FAO, 2005. Livestock, Environment and Development Initiative 2005. Food and Agricultural Organization, Rome, Italy.
FAO, 2014. FAOSTAT. Food and Agriculture Organization, Rome, Italy.
Feng, K., Hubacek, K., Pfister, S., Yu, Y., Sun, L., 2014. Virtual scarce water in China. Environ. Sci. Technol. 48, 7704–7713.
Ge, L., Xie, G., Zhang, C., Li, S., Qi, Y., Cao, S., He, T., 2011. An evaluation of China's water footprint. Water Resour. Manag. 25, 2633–2647.
Gong, P., Yin, Y., Yu, C., 2011. China: invest wisely in sustainable water use. Science 331, 1264.
Gu, Y., Xu, J., Wang, H., Li, F., 2014. Industrial water footprint assessment: methodologies in need of improvement. Environ. Sci. Technol. 48 (12), 6531–6532.
Guan, D., Hubacek, K., 2007. Assessment of regional trade and virtual water flows in

China. Ecol. Econ. 61, 159–170.
Han, X., Sun, C., 2013. Virtual water flow patterns embedded in major crops in China. Resour. Sci. 35 (8), 1567–1576 (in Chinese).
Harris, I., Jones, P.D., Osborn, T.J., Lister, D.H., 2014. Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 dataset. Int. J. Climatol. 34 (3), 623–642.
Hsiao, T.C., Heng, L., Steduto, P., Rojas-Lara, B., Raes, D., Fereres, E., 2009. AquaCrop—The FAO crop model to simulate yield response to water. III. Parameterization and testing for maize. Agron. J. 101 (3), 448–459.
Virtual water trade. In: Hoekstra, A.Y. (Ed.), 2003. Proceedings of the International Expert Meeting on Virtual Water Trade. IHE Delft, the Netherlands, 12–13 December 2002. Value of Water Research Report Series No. 12. UNESCO-IHE, Delft, the Netherlands.
Hoekstra, A.Y., 2013. The Water Footprint of Modern Consumer Society. Routledge, London, UK.
Hoekstra, A.Y., Chapagain, A.K., 2007. Water footprints of nations: water use by people as a function of their consumption pattern. Water Resour. Manag. 21 (1), 35–48.
Hoekstra, A.Y., Chapagain, A.K., 2008. Globalization of Water: Sharing the Planet's Freshwater Resources. Blackwell, Oxford, UK.
Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M., 2011. The Water Footprint Assessment Manual: Setting the Global Standard. Earthscan, London, UK.
Hoekstra, A.Y., Hung, P.Q., 2005. Globalisation of water resources: international virtual water flows in relation to crop trade. Glob. Environ. Change 15 (1), 45–56.
Hoekstra, A.Y., Mekonnen, M.M., 2012. The water footprint of humanity. Proc. Natl. Acad. Sci. 109 (9), 3232–3237.
Hoekstra, A.Y., Mekonnen, M.M., Chapagain, A.K., Mathews, R.E., Richter, B.D., 2012. Global monthly water scarcity: blue water footprints versus blue water availability. PLoS ONE 7 (2), e32688.
Jiang, Y., 2009. China's water scarcity. J. Environ. Manag. 90 (11), 3185–3196.
Jiang, Y., Cai, W., Du, P., Pan, W., Wang, C., 2015. Virtual water in interprovincial trade with implications for China's water policy. J. Clean. Prod. 87, 655–665.
Liu, J., Savenije, H.H.G., 2008. Food consumption patterns and their effect on water requirement in China. Hydrol. Earth Syst. Sci. 12, 887–898.
Liu, J., Yang, H., 2010. Spatially explicit assessment of global consumptive water uses in cropland: green and blue water. J. Hydrol. 384, 187–197.
Liu, J., Zehnder, A.J.B., Yang, H., 2007. Historical trends in China's virtual water trade. Water Int. 32 (1), 78–90.
Ma, J., Hoekstra, A.Y., Wang, H., Chapagain, A.K., Wang, D., 2006. Virtual versus real water transfers within China. Philos. Trans. R. Soc. B 361 (1469), 835–842.
Manzardo, A., Mazzi, A., Loss, A., Butler, M., Williamson, A., Scipioni, A., 2016. Lessons learned from the application of different water footprint approaches to compare different food packaging alternatives. J. Clean. Prod. 112 (5), 4657–4666.
Mekonnen, M.M., Hoekstra, A.Y., 2011. The green, blue and grey water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci. 15 (5), 1577–1600.
Mekonnen, M.M., Hoekstra, A.Y., 2016. Four billion people facing severe water scarcity. Sci. Adv. 2 (2), e1500323.
Monfreda, C., Ramankutty, N., Foley, J.A., 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Glob. Biogeochem. Cycles 22, GB1022.
MWR, 2014. Water Resources Bulletin of China 2013. Ministry of Water Resources, Beijing, China.
NASMG, 2010. Surveying and Mapping Data Sharing Network. National Administration of Surveying, Mapping and Geo-information, China.
NBSC, 2013. National Data. National Bureau of Statistics of China.
Portmann, F.T., Siebert, S., Döll, P., 2010. MIRCA2000 – global monthly irrigated and rain-fed crop areas around the year 2000: a new high-resolution data set for agricultural and hydrological modelling. Glob. Biogeochem. Cycles 24, GB1011.
Raes, D., Steduto, P., Hsiao, T.C., Fereres, E., 2009. AquaCrop – the FAO crop model to simulate yield response to water. II. Main algorithms and software description. Agron. J. 101 (3), 438–477.
Ridoutt, B.G., Pfister, S., 2010. A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. Glob. Environ. Change 20, 113–120.
SCPRC, 2010. No.1 Document of 2011. State Council of the P.R. China, Beijing, China.
SCPRC, 2014. Middle Route Project (MRP), Office of the South-to-North Water Diversion Project Commission. State Council of the P.R. China, Beijing, China.
Shi, J., Liu, J., Pinter, L., 2014. Recent evolution of China's virtual water trade: analysis of selected crops and considerations for policy. Hydrol. Earth Syst. Sci. 18, 1349–1357.
SIC (State Information Center), 2005. Multi-regional Input-output Model for China (1997). Social Sciences Academic Press, Beijing, China (in Chinese).
Siebert, S., Döll, P., 2010. Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. J. Hydrol. 384, 198–217.
Steduto, P., Hsiao, T.C., Raes, D., Fereres, E., 2009. AquaCrop – the FAO crop model to simulate yield response to water. I. Concepts and underlying principles. Agron. J. 101 (3), 426–437.
Sun, S.K., Wu, P.T., Wang, Y.B., Zhao, X.N., 2013. The virtual water content of major grain crops and virtual water flows between regions in China. J. Sci. Food Agric. 93 (6), 1427–1437.
Tuninetti, M., Tamea, S., D'Odorico, P., Laio, F., Ridolfi, L., 2015. Global sensitivity of high-resolution estimates of crop water footprint. Water Resour. Res. 51 (7), 8257–8272.
Wang, Y.B., Wu, P.T., Zhao, X.N., Engel, B.A., 2014. Virtual water flows of grain within China and its impact on water resource and grain security in 2010. Ecol. Eng. 69, 255–264.
Wu, P., Zhao, X., Cao, X., Hao, S., 2010. Status and thoughts of Chinese “agricultural north-to-south water diversion virtual engineering”. Trans. CSAE 26 (6), 1–6 (in Chinese).
Yu, C., 2011. China's water crisis needs more than words. Nature 470, 307.
Zhang, C., Anadon, L.D., 2014. A multi-regional input–output analysis of domestic virtual water trade and provincial water footprint in China. Ecol. Econ. 100, 159–172.
Zhang, L., Xia, J., Hu, Z., 2009. Situation and problem analysis of water resource security in China. Resour. Environ. Yangtze Basin 18 (2), 116–120.
Zhang, Y., Qi, S., 2011. China multi-regional Input-output Models (2002, 2007). China Statistics Press, Beijing (in Chinese).
Zhang, Z., Yang, H., Shi, M., 2011. Analyses of water footprint of Beijing in an interregional input-output framework. Ecol. Econ. 70, 2494–2502.
Zhao, C.F., Chen, B., 2014. Driving force analysis of the agricultural water footprint in China based on the LMDI method. Environ. Sci. Technol. 48, 12723–12731.
Zhao, X., Liu, J., Liu, Q., Tillotson, M.R., Guan, D., Hubacek, K., 2015. Physical and virtual water transfers for regional water stress alleviation in China. Proc. Natl. Acad. Sci. 112 (4), 1031–1035.
Zhu, X., Li, Y., Li, M., Pan, Y., Shi, P., 2013. Agricultural irrigation in China. J. Soil Water Conserv. 68 (6), 147A–154A.
Zhuo, L., Mekonnen, M.M., Hoekstra, A.Y., 2014. Sensitivity and uncertainty in crop water footprint accounting: a case study for the Yellow River Basin. Hydrol. Earth Syst. Sci. 18, 2219–2234.
Zhuo, L., Mekonnen, M.M., Hoekstra, A.Y., Wada, Y., 2016. Inter- and intra-annual variation of water footprint of crops and blue water scarcity in the Yellow River Basin (1961-2009). Adv. Water Resour. 87, 21–41.