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Can virtual water trade save water resources?

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Abstract

At times, certain areas of China suffering from water shortages. While China's government is spurring innovation and infrastructure to help head off such problems, it may be that some water conservation could help as well. It is well-known that water is embodied in traded goods—so called "virtual water trade" (VWT). In China, it seems that many water-poor areas are perversely engaged in VWT. Further, China is also engaging on the global trend of fragmentation in production, even as an interregional phenomenon. It seems some implications could be learned about conserving or reducing VWT, if we knew where and how it is practiced. From those implications, perhaps policies could be formulated. We employ China's multiregional input-output tables straddling two periods to trace the trade of a given region's three types of goods: local final goods, local intermediate goods, and goods that shipped to other regions and countries. We find that goods traded interregionally in China in 2012 embodied 30.4% of all water used nationwide. Nationwide, water use increased substantially over 2007-2012 due to greater shipment volumes of water-intensive products. In fact, as suspected, the rise in value chain-related trade was a major overall contributing factor. Coastal areas tended to be net receivers of VTW from interior provinces, although reasons differed, e.g. Shanghai received more to fulfill its final demand and Zhejiang for its value-chain related trade. In sum, the variety of our findings reveals an urgent need to consider trade types and water scarcity when developing water resource allocation and conservation policies.

Keywords: multi-regional input-output analysis; value chain; virtual water trade; national water savings; embodied water

1. Introduction

Due to the nature of watersheds, China's water resources are unevenly distributed; About 66% of water resources are located in South China (Ministry of Water Resources of the People's Republic of China, 2015). It is perhaps no wonder that many parts of China are suffering from severe water shortages as a result since it uses about 14% of the world's freshwater per capita (The World Bank, 2014). Moreover, the nation's demand for water is growing, exacerbating water scarcity issues (Distefano and Kelly, 2017; Sowers et al., 2010). Clearly, better management measures are needed to ensure a more sustainable China.

So, how can China make water resources more sustainable? Technological innovation is one approach. It should make more efficient use of water, And infrastructure projects such as the "South to North Water Diversion" should help mitigate some degree of water scarcity (Zhang et al., 2011). An alternative way to generate sustainable water use practices is by considering virtual trade of water. Oki and Kanae (2004) coined the term "virtual water trade" (VWT) to discuss water that is used as an input into the production of goods and services that are traded.

The re-allocation of water resources through international trade has more than doubled from 1986 to 2007 (Dalin et al., 2012). (Savenije, 2006) identifies global water saving benefits through international agricultural products trade. (Cazcarro et al., 2013; Masud et al., 2019; Mubako et al., 2013) focus on the regional water system; (Chouchane et al., 2018; Duarte et al., 2019) on proximate causes of VWT; (Lenzen et al., 2013) on water scarcity, and all, plus Hoekstra and Hung (2005), address effective management policies. VWT appears to be influenced by many factors: economic level, population, cultivated area, water endowments (Duarte et al., 2019). But VWT does not always seem to benefit the water-scarce regions (Kumar and Singh, 2005).

The scale and structure of VWT has received some attention at the municipal level, e.g. Beijing (Han et al., 2015; Han et al., 2014; Zhang et al., 2011); provincial and multi-provincial level, e.g., Hebei (Liu et al., 2018; Liu et al., 2017b) and Liaoning (Dong et al., 2013), and 30 provinces (Chen et al., 2017; Dong et al., 2014; Zhang and Anadon, 2014; Zhao et al., 2015); and watershed, e.g., Haihe River Basin (White et al., 2015; Zhao et al., 2010) and eight hydro-economic regions (Guan and Hubacek, 2007). (Zhao et al., 2019) summarizes much of the above literature and note that China's VWT runs from water-scarce north to south (from less-developed to more-developed areas); so VWT runs against water availability, which is greater to the south. Thus to alleviate water shortages in water scarce provinces, Feng et al. (2014) suggest incorporating a measure of water scarcity into subnational VWT analysis. Although, (Zhao et al., 2019) have since found that the relative productivity of land between agriculture and non-agriculture uses is the main indicator, not water availability.

We note from a 30 multi-provincial table of China for 2007 that 31% of interregional trade is due to the exchange of final goods, and 69% is due to intermediate inputs, which is related to value chains. This suggests a string amount of production fragmentation. That is, activities for producing a good cross multiple-borders, from the production of individual unfinished parts to assemblage of the final product (Athukorala and Yamashita, 2007). The fragmentation of production is increasing interregionally in China as well as internationally (Meng et al., 2014) , as observed in trade streams.

Due to the global financial crisis (2008-2009), international trade's share of total global production declined by three percentage points from 2007 to 2010. Meanwhile, the value of final goods and intermediate input trade increased substantially, by 67% and 22%, respectively. And trade increased further through 2012, by another 28%. This implies that trade in intermediate inputs is accelerating and that provinces are intensifying their specialization of production. At the same time this means that firms are getting more specific in targeting locations from which they buy intermediate products to support their domestic supply chains. These trade trends in intermediate inputs affect the locations in which water is used. In this vein, it is necessary for us to analyze how production fragmentation shapes trade types and, thereby, water use across provinces and nations. The effect of production fragmentation on VWT have been largely ignored.

We decompose interregional trade to learn how the fragmentation of domestic production is affecting the apparent availability of provincial and national water resources. To date, literature on the effects of production fragmentation have mostly focused on the virtual trade of carbon and particularly at an international scale, which tests the pollution haven hypothesis (Zhang et al., 2017). A few studies point out that China's west incurs higher environmental costs but provides lower value-added gains via its position in the domestic supply chains as well as industry mix compared to other regions (Liu et al., 2015; Meng et al., 2013).

Herein we evaluate VWT from 2007 to 2012. This enables an examination into how the economic crisis of 2008−2009 has altered interregional trade and its impact on the environment. Moreover, our distinction between the trade for goods in final versus intermediate uses is useful in testing the importance of VWT, e.g., as related to water efficiency policy. Existing studies discuss the necessity of improving supply-side perspective of efficiency in water use (Jiang et al., 2015), but our analysis is able to yield insight into the full supply-chain context. Another important environmental policy concentrates on the responsibility of water usage, for which, we could identify the responsibility for virtual water use from final goods or intermediate goods import in a supply chain context by incorporating multi-stakeholders. Further, for national water use, the effects (savings or losses) brought by existing VWT and production fragmentation is unclear, which is important to get a broader vision of VWT impacts on water resources in China.

For depicting the production fragmentation, we distinguish the different purposes of imports based on the production stages, e.g. final consumption, processing for final consumption, and processing for re-export. Accordingly, three different trade types emerge. The first two patterns are trade of final goods and trade of intermediate goods for the final stage of production. The traded goods are absorbed by the importers. The third trade type is associated with the production of intermediate goods, which are re-exported as inputs for further production in another region or nation. We call this "value chain-related trade". This type of trade determines whether a region or a nation receives intermediate products for processing and ships these intermediates for processing or final consumption to a different region or country (Borin and Mancini, 2015; Dean and Lovely, 2010; Wang et al., 2017b).

2. Materials and Methods

In prior studies, various methods have been employed. Some use a bottom-up, crop-by-crop accounting framework to trace VWT in agriculture products (Dalin et al., 2014; Ma et al., 2006; Zeng et al., 2012). Another popular method is the environmental extended input-output (IO) analysis with different spatial resolutions, e.g. single region or multi-regional (Deng et al., 2016; Lenzen, 2009; Liu et al., 2018; Llop, 2013; Rosa Duarte, 2002). The IO method expands the scope beyond agriculture products by involving industrial products and services. This enables a study of VWT by considering water-intensive products, like electric power, chemical manufacturing, and paper products, and food processing.

We employ a multiregional input-output (MRIO) approach to evaluate VWT along with water savings in the interprovincial trade over two periods, 2007-2010 and 2010-2012. We focus on the role of three different trade types: (i) the trade of final goods (TF), (ii) the trade of intermediate goods for the final stage of production (TI) and (iii) trade in value chain (TVC) (*SI Appendix, section 1 Equation(2)*). Our analyses focus on freshwater *use* (quantify of water distributed to users, part of which returns to the environment) instead of freshwater *consumption* (includes only water lost via evaporation, absorption by products, and/or any other losses). The former seems to better represent the broader impact of humans on local water resources and ecosystems and data accuracy, so we employed freshwater use to assess the resource losses in the goods production in specific provinces.

Some studies have considered how changes in the balance of VWT affects provincial water use considering provincial water scarcity (Feng et al., 2014; White et al., 2015). The water stress index is one of the main indicators of water scarcity and it is defined as the ratio of water demanded to total local water resources available, with a higher ratio indicating more severe water scarcity (Liu et al., 2017a; Pfister et al., 2009). These previous studies helped us better understand what was causing water scarcity and which region was suffering from it. In our study, we distinguish how water scarcity varies at the province level to reveal its influence on VWT under different trade types. Thus, our study identifies the impacts of both trade types and water scarcity and suggests how to improve water management policies. The analysis mainly include two parts:

2.1 Multiregional input-output analysis (MRIO)

The provincial virtual water trade under different trade types were calculated by using a MRIO analysis. In the MRIO framework, the total exports from region *s* to *r* (s, r=1,…, g), could be written as, $T^{sr}=Y^{sr}+Z^{sr}$, with Y^{sr} represents the final demand of region *r* for products from region *s*, Z^{sr} represents the intermediate use of products in region *r* from region *s*. We followed Zhang et al. (2017), and classified the trade between each pair of provinces *s* and *r*, T^{sr}, into three trade types as followed:

$$T^{sr} = \underbrace{Y^{sr}}_{TF^{sr}} + \underbrace{A^{sr}L^{rr}Y^{rr}}_{TI^{sr}} + \underbrace{\underbrace{A^{sr}L^{rr}\sum_{t\neq r}^{G} A^{rt}B^{tr}Y^{rr} + A^{sr}\sum_{t\neq r}^{G} B^{rt}Y^{tr} + A^{sr}\sum_{t}^{G} B^{rt}\sum_{u\neq r}^{G} Y^{tu}}_{T\_d^{sr}} + \underbrace{A^{sr}\sum_{t}^{G} B^{rt}EX^{t}}_{T\_g^{sr}}}_{TVC^{sr}} \quad (1)$$

where $L^{rr} = (I\text{-}A^{rr})^{-1}$, A^{sr} is the input coefficient matrix that represents the intermediate use in region *r* of goods produced in region *s*. B^{tr} is the Leontief inverse matrix, representing the quantity of the gross output of region *t* required to produce one-unit increase in the final demand of region *r*. EX^{t} is the exports to foreign countries from region *t*. TF^{sr} defines the trade in final products, where the trade partner would directly absorb the exported products, and the exporter was located in the final stage of production. TI^{sr} defines the trade in intermediate products for the final stage of production, where the products must be further processed by the trade partner before finally being absorbed by itself. TVC^{sr} defines the value chain-related trade, including domestic value chain-related trade (T_d^{sr}) and global value chain-related trade (T_g^{sr}). For TVC^{sr}, the traded products crossed the provincial border more than once. The products may be finally absorbed by a domestic region (T_d^{sr}) or further processed and exported to foreign counties (T_g^{sr}). Then, based on the balance of gross output of one province, it can be decomposed into five parts, i.e. the use for local economic activities, exports to foreign countries, and exports to other regions via trade in final products, trade in intermediate products for the final stage of production and the value chain-related trade. Similarly, the province's water uses embodied in five different output components were derived, which was obtained by multiplying the sector water use intensity by the corresponding output uses (*see SI Appendix, section 1*).

A province's net virtual inflow of water (or *balance of virtual water use* embodied in trade between regions, BVW) was the difference between its total virtual water inflows and outflows from and to all other provinces. The virtual water inflows or outflows can be further disaggregated into virtual water embodied in trade in final products, trade in intermediate products for the final stage of production and the value chain-related trade, so the BVW could be obtained as followed:

$$BVW^{sr}=VW^{sr}-VW^{rs}=(F^{s}L^{ss}TF^{sr}-F^{r}L^{rr}TF^{rs})+(F^{s}L^{ss}TI^{sr}-F^{r}L^{rr}TI^{rs})+(F^{s}L^{ss}TVC^{sr}-F^{r}L^{rr}TVC^{rs}) \quad (2)$$

where, the BVW^{sr} represents the net virtual water inflow of region *r* from region *s*, VW^{sr} (VW^{rs}) indicates the virtual water export from regions s (r) to region r (s). A positive net virtual water outflow (exporter) meant that the inter-provincial trade contributed to an increase in the province's water use and vice versa.

Furthermore, the effects of interprovincial trade on national water savings were evaluated by *balance of avoided water uses, BAW*. The BAW induced by the trade between two provinces can be obtained based on the difference between virtual water uses embodied in exports (VW) and virtual water uses avoided by imports (WAI), as shown in Equation (3):

$$BAW^{sr} = (VW^{sr} - WAI^{sr}) + (VW^{rs} - WAI^{rs})$$

$$= (F^sL^{ss} - F^rL^{rr})TF^{sr} + (F^sL^{ss} - F^rL^{rr})TI^{sr} + (F^sL^{ss} - F^rL^{rr})TVC^{sr}$$
$$+(F^rL^{rr} - F^sL^{ss})TF^{rs} + (F^rL^{rr} - F^sL^{ss})TI^{rs} + (F^rL^{rr} - F^sL^{ss})TVC^{rs} \quad (3)$$

The first three terms in Equation (3) explain the effects of national water savings from the perspective of the production structure and amount of water associated with the water savings in outflows of commodities from region *s* to *r*, which can be further divided into three trade types . The latter three terms explain the national water savings associated with the inflows of commodities to region *s* from *r* . Then province *s*' national water savings were evaluated by the average of water savings lying in its imports and exports, BAW^s=($\sum_{r\neq s}^{G} BAW^{sr}$)/2. The total interprovincial trade's national water savings were gained by aggregating all the provinces' national water saving effects, BAW=$\sum_{s}^{G} BAW^s$. A positive national water savings effect of a province meant that the interprovincial trade associated with the province contributed to an increase in the national water use and vice versa. Similarly, a positive national water savings effect of three trade types indicated that the three trade types contributed to an increase in the national water use and vice versa. Obviously, the national water uses could be "saved" if virtual flows of water from a relatively more water-efficient province were instead shipped to a less water-efficient province (Dalin et al., 2014).

2.2 Incorporating water scarcity into MRIO

We considered the provincial water scarcity to compare the provincial performance in terms of the virtual water trade. We use a *water stress index* (the ratio of water demanded to total local water resources available) as the weight by which we multiply *provincial water use* (defined as "scarce water use"). A higher value in the result this multiplication indicates that a province is consuming more water resources than expected, given its resource base. Similarly, we got the scarcity-weighted virtual water trade (virtual scarce water trade). We define a "scarce water importer" as a province with little available water that also has a net virtual inflow of water resources; Conversely, a "scarce water exporter" is a province with little available water that also has a net outflow of water resources. Further, the scarcity-weighted national water savings ("national scarce water savings") indicates the impact of interprovincial trade on the net use of water nationwide in water scarce areas. When water resources flow from a less water-stressed, more water-efficient province to a province that is more water-stressed, but less-efficient water user, the national water resources are "saved" through trade. (*SI Appendix, section 1*).

2.3 Data sources

The MRIO allows us to trace the water embodied in the goods transactions so that the water uses can be re-distributed from production processes to the consumers. The MRIO tables of China quantify economic transactions amongst 30 sectors across 30 provinces in 2007, 2010 and 2012. The MRIO tables in 2007, 2010 and 2012 were retrieved from School of International Development, University of East Anglia.

Our analysis focused mainly on the blue water uses to evaluate the impacts of the interprovincial trade on provincial and national water uses, similar to other studies (Zhao et al., 2015; Zhao et al., 2010). To link the MRIO table of China to data on freshwater use, first, the aggregated sector (primary, secondary and tertiary industries) water use values were mainly extracted from *Chinese Statistical Yearbook 2008, 2011 and 2013* (China National Bureau of Statistics, 2011) and *China Urban-Rural Construction Statistical Yearbook 2007, 2010 and 2012* (Ministry of Housing and Urban-Rural Development, 2011). The water used in the primary industry is mostly that used in agriculture, such as irrigating farming fields, grassland, forestry, orchards and fishing. The secondary industry's water use is that used in mining, manufacturing, electricity and construction. The tertiary industries use water to produce services, e.g. commerce, restaurants, posts, cargo transportation and telecommunications (China National Bureau of Statistics, 2011). Second, more details on water use data by secondary industries is available from *Chinese Economic Census Yearbook 2008* (The State Council 's second national economic census leading group office, 2010), from which we estimated water use by subsector for 2007, 2010 and 2012 by using fixed water use ratios over time via the 2008 data (Zhao et al., 2015). Third, the subsectoral tertiary sectoral water use is based on the share of intermediate inputs from the “water production and supply” by the different service sectors in the MRIO table (Zhang and Anadon, 2014). Further details about the data and sources, *see SI Appendix, section 2*.

3. Results

3.1 Water uses by trade type. The national water use increased continuously from 580.4 billion m^3/yr in 2007 to 613.8 billion m^3/yr in 2012, in which 30.4% (186.9 billion m^3/yr) was embodied in interprovincial trade within China. Our results for 2012 show that of this traded aspect, TI, TF and TVC composed relatively equal shares. (*Appendix Table S1*). Water embodied in international exports shows up as a negative impact brought by the financial crisis since it decreased by 13% over 2007-2010 and by 9% further over 2010-2012. Of course, part of the global value chain-related trade decreased too, by 23% over 2007-2010 and by 19% more over 2010-2012. Structural changes in interregional trade arose too. As a result they shifted from an orientation toward TVC (2007) toward TF (2010), then toward TI (2012). This suggests that the VWT has gained more of an interregional trade tilt over time.

The share of total provincial water use that was embodied in interregional trade ranged widely across China's 30 provinces—from 8.1% in Guangdong to 56.5% in Anhui in 2012. The main provinces involved in upstream processes tend to be located in the less-developed central, west and northeast parts of China, e.g. Anhui, Hainan, Heilongjiang, Xinjiang, Inner Mongolia, Henan and Hebei. These provinces have a dominant TI trade type that ranges from 14.3% to 20.1%, which indicates that they ship intermediate goods for further processing elsewhere domestically. Provinces with large amounts of water embodied in trade in the 2007-2010 period also tended to display a similar tendency on 2012, but with slight difference in the dominant trade type (TVC in 2007, TF in 2010). The dominant trade type even changed for a given province. For example, Heilongjiang (TVC in 2007, TI in 2012) shifted its mix of commodity outflows after the financial crisis, reducing international exports while increasing the domestically destined outflows of intermediate goods (*Appendix Figure S1, Table S2-S4*).

3.2 Interprovincial water flows by trade type. Comparing the difference of water embodied in outflows and inflows of provinces, net water transfers are obtained. We call this the "balance of virtual water embodied in trade" (BVW). Thus, a negative BVW implies the province is a net virtual importer of water. In aggregate, we identify critical virtual importers and exporters of water for three trade types, i.e. TF, TI and TVC (Figure 1, *Appendix Figure S2-S3, Table S5-S8*). Results show that the developed coastal provinces tend to rely on virtual imports of water from less-developed agricultural provinces. Major sectors and regions that virtual export or import water remain largely unchanged over the study period. Nonetheless, water flows became more dominant among the central provinces by 2012. Provinces located in the northwest, southwest, northeast, and Yangtze River regions, which feature agriculture as a major industry, were top virtual exporters of water. The virtual outflow of water declined in the west and northeast regions between 2007 and 2012. For example, Xinjiang's total water outflow ranked it first among the top ten flows under TF, TI and TVC over the three years. But the outflows from Xinjiang declined by 1.2 billion m^3/yr from 2007 to 2012. In contrast, the Yangtze River regions intensified their virtual outflows of water. For example, Anhui's outflows rose by 2.1 billion m^3/yr between 2007 and 2012, and its total virtual outflows of water ranked it within the top four flows in 2012. Top importers provinces consist were either populous, coastal, or both. Virtual inflows of water into coastal provinces declined from 2007 to 2012. For example, the east coast, particularly Shanghai, decreased its virtual imports of water via final goods by 3.1 billion m^3/yr from 2007 to 2012, though the inflows to Shanghai have always been among the largest flows under TF. In contrast, the Yellow River region increased it virtual imports of water, e.g. Inner Mongolia shifted from being a virtual water exporter via value chain-related goods to one for final goods.

Further, our results highlight the disparities among Chinese provinces due to different trade types of total virtual inflows/outflows of water. For example, as a virtual water importer, Shanghai mainly receives an inflow of goods for final consumption, indicating its down-stream position in domestic production chains. Shandong and Guangdong, meanwhile, mainly receive virtual inflows of water via goods that they further process before consumed by itself in the form of final goods; Zhejiang also obtains virtual imports of water for further processing but it mostly re-exports those processed goods. As a virtual exporter of water, for example, Xinjiang mainly ships goods elsewhere for final consumption; Heilongjiang, Guangxi and Anhui ship such goods, which are eventually consumed as final goods by the regions that receive them; Hubei, Guizhou, and Gansu virtually ship water for value chain-related trade. The water-intensive goods are largely agriculture commodities and electricity; the difference is that a province either directly consumes them as an imported good (direct trade) or as a good for further processing (indirect trade) and does so differently given its position within the domestic supply chain. (for further analysis about regional VWT, refer to *Appendix S3*).

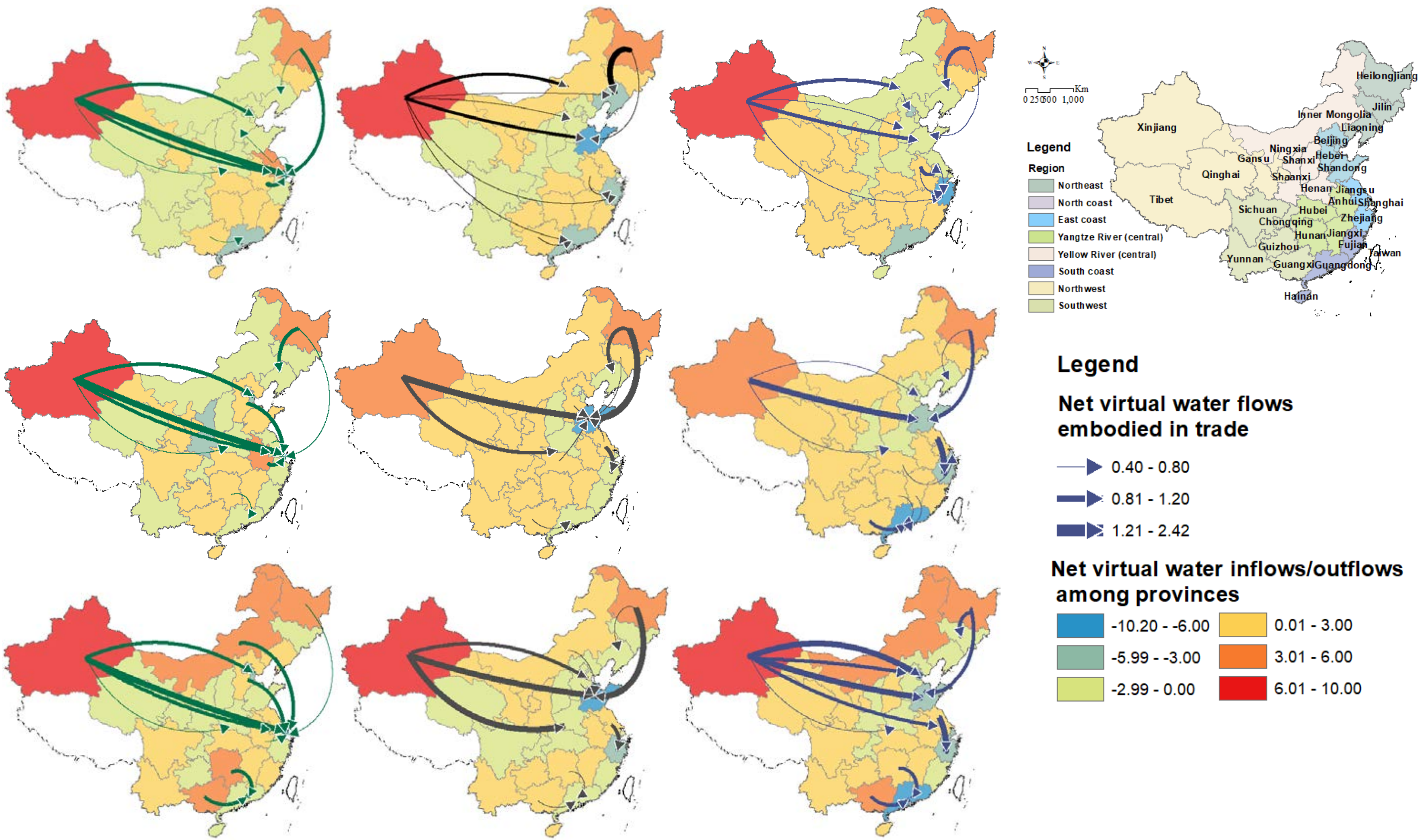
Km
0 250 500 1,000
Legend
Region
Northeast
North coast
East coast
Yangtze River (central)
Yellow River (central)
South coast
Northwest
Southwest
Heilongjiang
Jilin
Inner Mongolia
Liaoning
Xinjiang
Beijing
Ningxia
Hebei
Gansu
Shanxi
Shandong
Qinghai
Shaanxi
Henan
Jiangsu
Tibet
Anhui
Shanghai
Sichuan
Hubei
Chongqing
Zhejiang
Hunan
Jiangxi
Guizhou
Fujian
Taiwan
Yunnan
Guangxi
Guangdong
Hainan
Legend
Net virtual water flows embodied in trade
0.40 - 0.80
0.81 - 1.20
1.21 - 2.42
Net virtual water inflows/outflows among provinces
-10.20 - -6.00
-5.99 - -3.00
-2.99 - 0.00
0.01 - 3.00
3.01 - 6.00
6.01 - 10.00

Figure 1. The 10 largest net water flows in interprovincial trade for three trade types in 2007-2012

Notes: The units are billion m^3/yr. The rows indicates 2012, 2010 and 2007 from top to down. The columns indicate the trade types from left to right, final goods trade, intermediate goods trade and value chain-related trade.

3.3 Water savings. National water uses could be "saved" if virtual flows of water from a relatively more water-efficient province were instead shipping to a less water-efficient province (Dalin et al., 2014). We found interprovincial trade activities led to a progressive rise in national water uses by 28.0, 13.6 and 20.3 billion m^3/yr in 2007, 2010 and 2012, respectively. We find the proximate cause to be the rising fragmentation of production, with value chain-related trade being the biggest contributor (*Appendix Table S5, S9-S10*). The TVC dominated the increase of national water use by 13.7, 9.4 and 7.6 billion m^3/yr in 2007, 2010 and 2012, i.e. more than 37% of the total increase Similarly, TI generated a slight increase of 6.5, 5.1 and 5.9 billion m^3/yr in 2007, 2010 and 2012, respectively.

~~The national water savings of a province was evaluated by the difference between water use linked to exports and water use avoided by imports, which we call the balance of avoided water use (BAW). A negative BAW implies that national water uses are decreasing.~~ Trade activities in around two thirds of those 30 provinces led to the increase of national water uses. Further, we observe different performances in terms of BAW and BVW for provinces, which was classified into four categories (Figure 2, *Appendix Table S5*). The most desirable scenario for provinces located in the third quadrant, where both provincial and national water were saved. The third quadrant includes Shanxi, Chongqing and Shaanxi, resulting total provincial and national water savings by 8.2 and 1.2 billion m^3/yr.

For provinces in the first quadrant, both provincial and national water uses increased, resulting in the increase of the total provincial and national water by 62.6 and 13.2 billion m^3/yr, respectively. The provinces in the first quadrant were with larger water saving potential from both provincial and national perspectives. Crucial trade type and sectors varied according to provinces. For the trade type, for example, Xinjiang should pay attention to products export in both TF and TI, as the major contributor to the provincial and national water uses increase (37.9% of BVW, 30.5% of BAW; 33.5% of BVW, 36.7% of BAW). For Heilongjiang and Guangxi, the TI should be further examined, as a significant driver to the growth in provincial and national water uses (38.3% of BVW, 42.6% of BAW; 36.0% of BVW, 35.1% of BAW). In terms of sectors, the agriculture sector was most crucial for water savings, accounting for more than 50% in the water uses for trade in most provinces, e.g., Guangxi (89.0% in TF), Heilongjiang (89.4% in TI) and Xinjiang (95.9% in TF). Meanwhile, the electricity sector accounted for about 20% of the water uses for trade in several provinces, e.g. Jiangsu, Anhui, Fujian, Jiangxi, Hunan, Guizhou and Yunnan. Similarly, more attention should be paid to the chemical industry in Sichuan and textile, wearing apparel and leather production in Fujian for water resource savings. It is to be noticed that, for the main provinces to be targeted by an effort to save national and provincial water use should include Xinjiang, Heilongjiang and Guangxi. They have trade types that remain more or less the same over the study period.

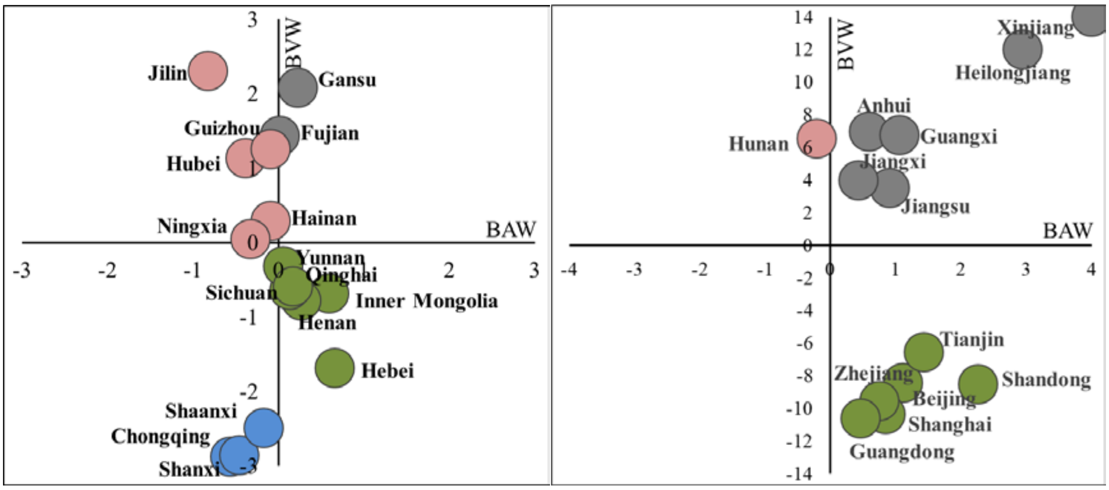

Figure 2. The distribution of total BVW and BAW in 30 provinces in China in 2012

Note: The units are billion m^3/yr. Each circle indicates one province. The left figure shows BVW and BAW smaller than 3 m^3/yr, the right figure shows values that larger than 3 m^3/yr, for figure display, we change Xinjiang (7, 26) to (4, 14) in the figure.

3.4 Re-mapping VWT with consideration of water scarcity. ~~As Feng et al., (2014) argued, consuming a pre-specified amount of water necessarily has different impacts on water-rich versus water-poor regions. Incorporating water scarcity into the virtual water trade analysis could help better identify which province is suffering from water scarcity and what has caused the water scarcity. Thus~~, we remap the virtual water trade by developing a scarcity-weighted virtual water trade network, which we call the virtual scarce water trade (Lenzen et al., 2013). We found there was 281.5 billion m^3/yr scarce water in 2012, accounting for 45.9% of the total water uses of China. The provinces with higher water–stress level became the major users of scarce water, mainly located in northern regions (*Appendix Table S12*). For example, Hebei, Shandong and Henan was ranked 3rd, 5th and 6th in terms total scarce water use, but ranked 15th, 12th, and 11th in terms of the total water uses. Jiangsu, Xinjiang and Heilongjiang retained the top ranking in total scarce water use because of the large amount of water use and relatively higher level of water-stress.

In 2012, 92.0 billion m^3/yr of scarce water was associated with interprovincial trade within China, of which, 31.8, 30.7 and 29.5 billion m^3/yr was induced by TF, TI and TVC, respectively. ~~For provinces, similar to BVW, the balance of virtual scarce water embodied in trade (BVWs) could be obtained. A negative BVWs implies the province is a net virtual scarce water importer and vice versa.~~ Based on the net scarce water transfer and water scarcity, a unique type of province was identified, i.e. "stressed water resources and net water outflow" (Figure 3, *Appendix Table S13*). Xinjiang, Jiangsu, Heilongjiang, Hebei, Anhui, Gansu, Ningxia, and Jilin fell into this category, which were suffering from water scarcity by shipping scarce water to other regions or countries.

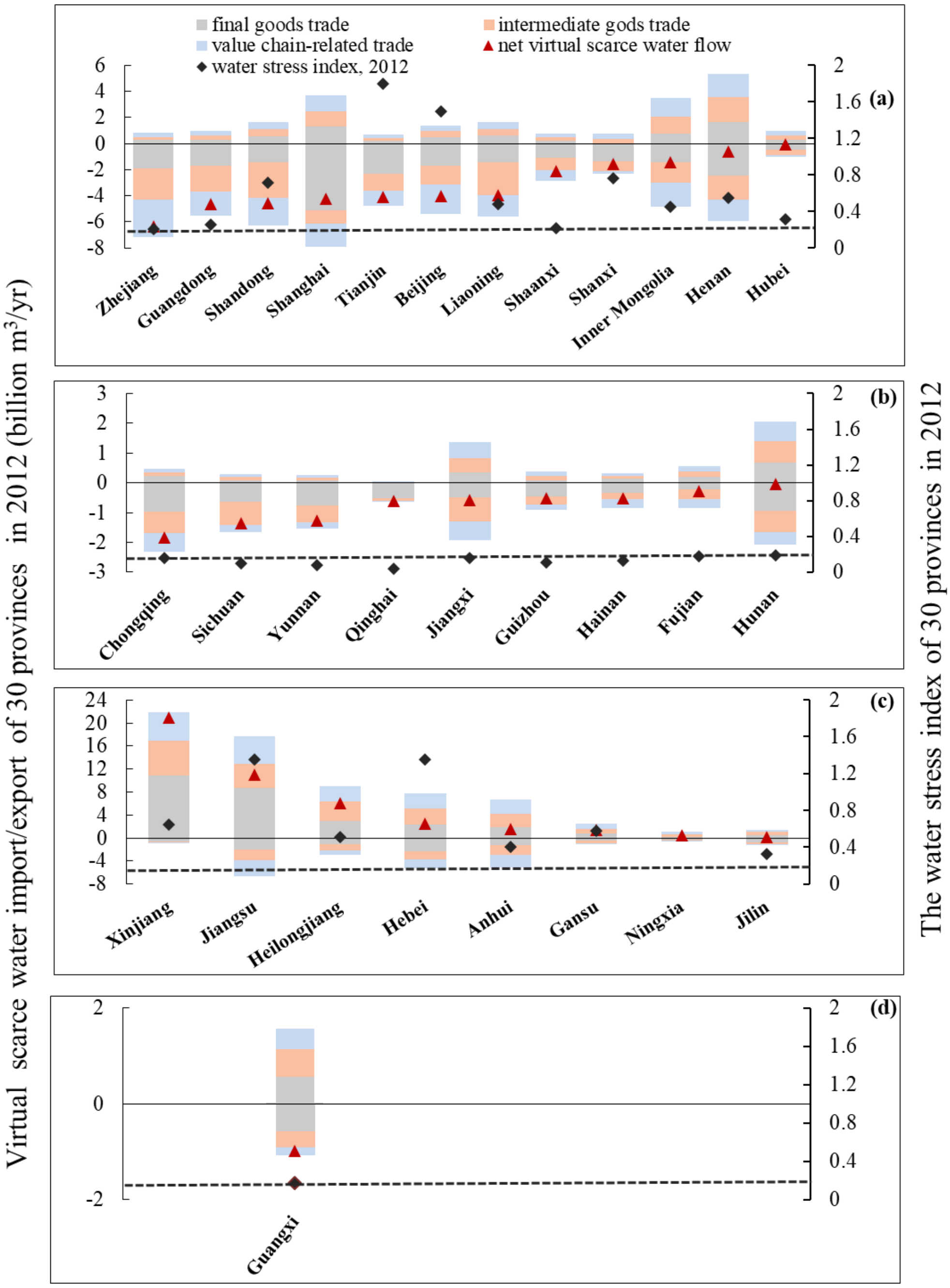

Figure 3. The classification of 30 provinces into 4 types based on net scarce water transfer and water scarcity, i.e. (a) stressed water resources and net water importer, (b) abundant water resources and net water importer, (c) stressed water resources and net water exporter, and (d) abundant water resources and net water exporter.

Note: The left vertical axis is scarce water inflow/outflow under final goods, intermediate goods trade for the final stage of production, and value chain-related trade, with the positive value indicating the province's virtual scarce water outflow and vice versa. Net virtual scarce water flow>0 represents net virtual scarce water outflow and vice versa. The right vertical axis is the water stress index. The black diamonds are water stress index of 30 provinces in 2012. Water scarcity can be classified into four categories: a value below 20% is regarded as "no or low stress", a value between 20% and 40% is considered as "moderate stress", a value between 40% and 100% is "serve stress", and a value above 100% is regarded as "extreme stress". The dotted line indicates the water stress index of 20% in (a), (b), (c) and (d). The water stress index for Shanghai (3.7) and Ningxia (7.1) was missing for their high value.

The VWT is more efficient in saving scarce water than in saving national water use. The VWT led to the increase of national scarce water by 11.9 billion m^3/yr, which is significantly lower than the increase of national water use (20.2 billion m^3/yr) in 2012. ~~The balance of avoided water use (BAWs) of provinces could be obtained similar to BAW, while a negative BAWs implies that national scarce water uses are decreasing due to interprovincial trade.~~ As Figure 4 shows, more provinces (about half) reduced the national water scarcity because of VWT. As a result, the national scarce water use was saved by 3.9 billion m^3/yr, higher than that without considering water scarcity (3.5 billion m^3/yr) (*Appendix Table S14*). Provinces in the third quadrant are ideal where interprovincial trade resulted in both provincial and national scarce water savings (9.9 and 2.4 billion m^3/yr). On the contrary, provinces in the first quadrant is least ideal, resulting in increase in both provincial and national scarce water uses (41.9 and 9.5

billion m^3/yr). It is worth noting that provinces located in the first quadrant, including Xinjiang, Heilongjiang, Jiangsu, Gansu and Hebei have large potential in scarce water savings. In particular, more attention should be paid to Xinjiang and Heilongjiang as the most critical trade type remained the same no matter water scarcity is considered or not.

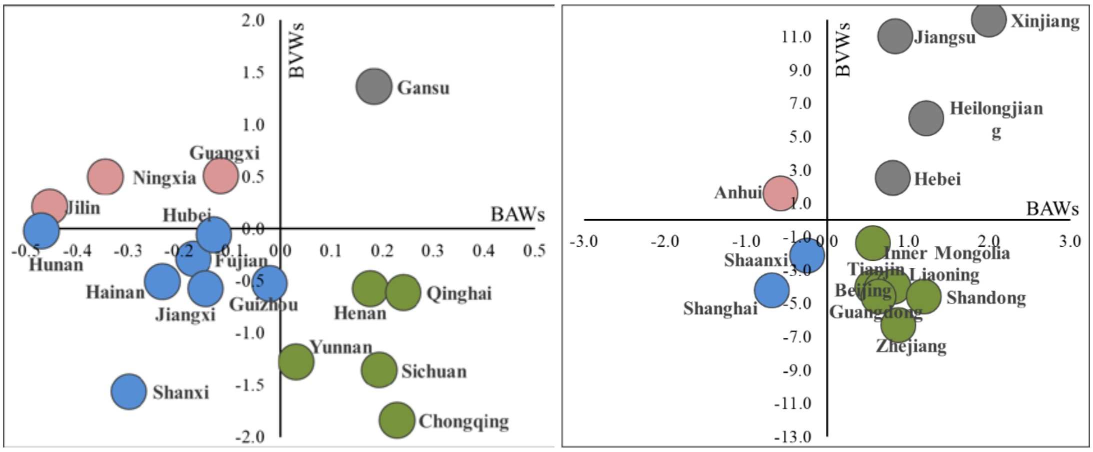

Figure 4. The distribution of total BVWs and BAWs in 30 provinces in China in 2012 when considering water scarcity

Note: The units are billion m^3/yr. Each circle indicates one province. The left figure shows BVW and BAW smaller than 0.5 and 2.0 m^3/yr, respectively; the right figure shows values that larger than 0.5 and 2.0 m^3/yr, respectively; for figure display, we change Xinjiang (6, 21) to (2, 12) in the figure.

4. Discussion

4.1 Establishing the water compensation scheme for interprovincial trade

Our results suggested that the present domestic production network results in virtual water flows from western to coastal regions, from less developed to more developed economies via different trade types. Thus, the environmental externalities of virtual water transfer should be considered when designing water conservation policies. A virtual water compensation scheme may be a practical solution to distributing the ecological burdens equally among provinces. Wang et al. (2017a) proposed a compensation mechanism for crop virtual water trade that follows the “who benefits, will compensate” principle. Their proposal only considered direct bilateral trade partners.

However, our study revealed that VWT is related to economic structure, production technology, trade policies and the position in domestic supply chain (Wichelns, 2004; Zhang and Anadon, 2014). We distinguish trade types, i.e. direct and indirect trade to see how it affects VWT, and observe provincial disparity. Results show that the value chain-related trade accounts for 32.7% of VWT. For example, Zhejiang mainly involved value chain-related trade with other provinces (e.g. Jiangsu, Anhui), accounting for 40.2% of the total import, followed by final goods trade (24.4%) and intermediate goods trade for the final stage of production (35.5%). Therefore, the water use responsibility for 40.2% of the virtual water import of Zhejiang should not be simply assigned to Zhejiang. Rather, third-party importers from Zhejiang should be considered. Thus, built on the prior research on a consumption-based allocation for water-use responsibility, we propose that those provinces mainly involve in interprovincial trade indirect trade (value chain-related trade)—exporters, importers, and a third player, the final consumer—should be responsible for compensating for indirect water use. This parallels a popular, but somewhat less elaborate, theory of responsibility principle applied in the field of climate change. Here, the value gains in the domestic supply chain, the environmental impacts, **and** *water resource utilization* should all be considered in the compensation framework.

4.2 Alleviating water scarcity under the rising fragmentation of production

Although VWT helps meet the water demand in coastal provinces, it has negative impacts: (1) the existing VWT is potentially increasing the scarcity of water those provinces in which water is especially scarce, such as Xinjiang, Jiangsu, Heilongjiang, Hebei, Gansu, Ningxia, Jilin, Anhui and Hubei. For example, Heilongjiang, had virtual outflows of water to Liaoning, Shandong, and other provinces, mainly via intermediate goods trade. Such a strategy relieves the water use shortage in Shandong, but aggravate the water stress condition in Heilongjiang, as Zhao et al. (2015) discussed. Our analysis has enriched Zhao et al. (2015)'s study by identifying the effects of different trade types.

Based on our calculation focusing on different trade types , we can devise other ways to reduce water scarcity, e.g. by conserving water related to the trade in intermediate goods. It is important to attempt to monitor and control water use throughout each supply chain. Important initiatives include more adoption of intermediate products with hither water efficiency, more efficient use and more recycling rate of intermediate products. *A good example* is the green supply chain, which aims to minimize the environmental impacts of a product throughout the life cycle, including green design, resource saving, production recycling, etc. (Ahi and Searcy, 2015). Including the water resource use in the metrics for evaluation of green supply chain performance would be useful for water savings in direct and indirect trades.

Another option, the market-based instrument, variation of water prices to reflect water scarcity, especially in arid regions, may be a promising way to reduce water scarcity in drier regions. The water pricing is argued to be relatively low for the major water user, irrigation water, resulting the farmers with less incentive to conserve water resources (Yang et al., 2003). Thus, taking the ongoing household multistep water pricing as a good attempt, the water pricing system should be reformed in agriculture, industry and household sector, To better address the water conservation goal, together with the water pricing system reform, appropriate and clear water rights allocation is essential (Webber et al., 2008).

4.3 Saving national and provincial water under production fragmentation

(2) The existing VWT network did not benefit national water use due to the water intensive products flows from less water efficient places, e.g. Xinjiang, Guangxi, Heilongjiang. Due to VWT, national water use has risen by 20.3 billion m^3/yr in 2012. An example of such flow is Xinjiang's virtual water export to Shandong or Inner Mongolia. Further, as we stated before, the virtual water embodied in the trade of intermediate goods (value chain-related trade) contributed more to the increase. That is, the production fragmentation aggregates the national water use, leading the national water stress into a higher level. This is a major concern for China, as blue water resources are becoming increasingly polluted or scarce (Liu et al., 2013). But if the production fragmentation continues to increase in China regions without production technology improvement and trade network shifts, the national water resources would generate more lose. For alleviating the situation, possible measures (not limited to)

could be considered, the first is the reorganization of trade (especially crop trade) into a more water efficient system, i.e. trade flows from a more water efficient to less efficient province (Dalin et al., 2014). The second is the improvements in local water productivity, helping decrease the national water use and increase the supply (e.g. food).

More specifically, target policy for water conservation would be in provincial scale, thus, our results identify large interregional and intersectoral flows. We identify provinces that are with virtual outflows of water are exporting relatively large volumes of water-intensive products, e.g. Xinjiang and Heilongjiang. Our results also identify different trade flows that can be targeted to reduce water use. For example, attention should be paid to the intermediate goods that are traded from Heilongjiang for importer's final stage of production. Further, the water conservation awareness should be focused upon both final goods and intermediate goods traded from Xinjiang in preparation for a final stage of production.

At the sectorial level, our findings support those found elsewhere: agriculture is a main water user, followed by electric power and chemicals industries. (*Appendix Figure S5).* For improving the agricultural water use efficiency, direct potential measures included technological innovation, enhanced awareness of water-saving practices, and the production of less-water demanding crops. Meanwhile, improving the crop yields would also be useful. (Foley et al., 2011). For electricity sector, the cooling system shifts to air cooling and utilizing the renewables especially wind and solar are effective ways (Zhang and Anadon, 2013). However, the production technology may lack of incentive to improve water use efficiency due to cost increment and other reasons, the demand side management could lead to the water saving options. One example is the eco-labelling scheme, which provides final consumers and the industries that importing the inputs with additional information regarding environmental responsibility (Banerjee and Solomon, 2003), particularly the coastal developed regions.

4.4 Limitations

As with other studies using the MRIO approach, there are limitations associated with this study. (1) Our results are aggregated at the sector level, and thus lack all variation that can exist at the product level, neglecting differences industrial processes. (2) We ignore heterogeneity of industrial process within a region, but acknowledge they exist and can influence estimates on the virtual water transfer embodied in different trade types. More product differentiation of industrial processes should be a future research goal.

Apart from the water use, water consumption is also used by others to evaluate the impacts of virtual water transfers (Hollanda et al., 2015). The latter represents evaporation and water loss. Future research could be conducted to consider both indicators to gain a better understanding of the virtual water transfers under various trade types.

5. Conclusions

This paper introduces a quantitative framework to trace the embodied water resources in the different trade types among regions and uses it to track how production fragmentation shapes water resource use at both regional and national level. Our findings reveal that the developed coastal region outsource virtual water from inland less developed regions, but with provincial disparity in terms of the dominate trade type. For example, the largest source of water import to Shanghai and Zhejiang is from final goods trade (67.8%) and value chain-related trade (40.2%). We further found that national water use increases in 2007, 2010 and 2012 due to interprovincial trade activities flowing from a less water-efficient province to a more efficient one, in which the value chain-related trade was the biggest contributor. In addition, for addressing the large water saving potential in terms of both national and provincial level, some dominate provinces (e.g. Xinjiang, Heilongjiang), trade types (e.g. intermediate goods trade for the final stage of production), and sectors (e.g. agriculture, electricity) should take the priority for water saving actions. The scarcity virtual water trade network highlights the risk of aggravating water stress driven by trade activities in northern provinces like Xinjiang, Jiangsu, Heilongjiang, Hebei, Anhui, etc., but the national scarce water would not be increased so much as the national water use induced by the regional trade activities. Our findings highlight the urgent need to consider trade types and water scarcity when it comes to developing water resource allocation policies.

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Supporting Information. Additional details on methodologies, data sources, additional results analysis, figures and tables.

References

Ahi, P., Searcy, C., 2015. An analysis of metrics used to measure performance in green and sustainable supply chains. Journal of Cleaner Production 86, 360-377.

Athukorala, P.-c., Yamashita, N., 2007. Production fragmentation in manufacturing trade: The role of East Asia in cross-border production networks. Working Papers Series No. 003.

Banerjee, A., Solomon, B.D., 2003. Eco-labeling for energy efficiency and sustainability: a meta-evaluation of US programs. Energy policy 31, 109-123.

Borin, A., Mancini, M., 2015. Follow the value added bilateral gross export accounting, Social Science Electronic Publishing, pp. 5-44.

Cazcarro, I., Duarte, R., Chóliz, J., 2013. Multiregional input-output model for the evaluation of Spanish water flows. Environ Sci Technol 47, 12275−12283.

Chen, W., Wu, S., Lei, Y., Li, S., 2017. China's water footprint by province, and inter-provincial transfer of virtual water. Ecological indicators 74, 321-333.

China National Bureau of Statistics, 2011. China Statistical Yearbook. China Statistics Press, Beijing.

Chouchane, H., Krol, M.S., Hoekstra, A.Y., 2018. Virtual water trade patterns in relation to environmental and socioeconomic factors: A case study for Tunisia. Sci Total Environ 613-614, 287-297.

Dalin, C., Hanasaki, N., Qiu, H., Mauzerall, D., Rodrigueziturbe, I., 2014. Water resources transfers through Chinese interprovincial and foreign food trade. Proc Natl Acad Sci USA 111, 9774-9779.

Dalin, C., Konar, M., Hanasaki, N., Rinaldo, A., Rodriguez-Iturbe, I., 2012. Evolution of the global virtual water trade network. Proc Natl Acad Sci USA 109, 5989-5994.

Dean, J., Lovely, M., 2010. Trade growth, production fragmentation, and China's environment, China's Growing roleinWorldTrade. University of Chicago Press and NBER, Chicago, pp. 429-469.

Deng, G., Ma, Y., Li, X., 2016. Regional water footprint evaluation and trend analysis of China—based on interregional input–output model. J Clean Prod 112, 4674-4682.

Distefano, T., Kelly, S., 2017. Are we in deep water? Water scarcity and its limits to economic growth. Ecol. Econ. 142, 130-147.

Dong, H., Geng, Y., Fujita, T., Fujii, M., Hao, D., Yu, X., 2014. Uncovering regional disparity of China's water footprint and inter-provincial virtual water flows. Sci Total Environ 500-501, 120-130.

Dong, H.J., Geng, Y., Sarkis, J., Fujita, T., Okadera, T., Xue, B., 2013. Regional water footprint evaluation in China: A case of Liaoning. Sci. Total Environ. 442, 215-224.

Duarte, R., Pinilla, V., Serrano, A., 2019. Long Term Drivers of Global Virtual Water Trade: A Trade Gravity Approach for 1965–2010. Ecol. Econ. 156, 318-326.

Feng, K., Hubacek, K., Pfister, S., Yu, Y., Sun, L., 2014. Virtual scarce water in China. Environ Sci Technol 48, 7704-7713.
Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., 2011. Solutions for a cultivated planet. Nature 478, 337.
Guan, D., Hubacek, K., 2007. Assessment of regional trade and virtual water flows in China. Ecol. Econ. 61, 159-170.
Han, M.Y., Chen, G.Q., Mustafa, M.T., Hayat, T., Shao, L., Li, J.S., Xia, X.H., Ji, X., 2015. Embodied water for urban economy: A three-scale input–output analysis for Beijing 2010. Ecol. Modell. 318, 19-25.
Han, M.Y., Guo, S., Chen, H., Ji, X., Li, J.S., 2014. Local-scale systems input-output analysis of embodied water for the Beijing economy in 2007. Front. Earth Sci. 8, 414-426.
Hollanda, R.A., Scott, K.A., Flörke, M., Brown, G., 2015. Global impacts of energy demand on the freshwater resources of nations. Proc Natl Acad Sci USA, E6707-6716.
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.
Kumar, M.D., Singh, O.P., 2005. Virtual Water in Global Food and Water Policy Making: Is There a Need for Rethinking? Water Resour. Manage. 19, 759-789.
Lenzen, M., 2009. Understanding virtual water flows: A multiregion input-output case study of Victoria. Water Resources Research 45, 11.
Lenzen, M., Moran, D., Bhaduri, A., Kanemoto, K., Bekchanov, M., Geschke, A., Foran, B., 2013. International trade of scarce water. Ecol. Econ. 94, 78-85.
Liu, H., Liu, W., Fan, X., Liu, Z., 2015. Carbon emissions embodied in value added chains in China. Journal of Cleaner Production 103, 362-370.
Liu, J., Wang, Y., Yu, Z., Cao, X., Tian, L., Sun, S., Wu, P., 2017a. A comprehensive analysis of blue water scarcity from the production, consumption, and water transfer perspectives. Ecological Indicators 72, 870-880.
Liu, J., Zang, C., Tian, S., Liu, J., Yang, H., Jia, S., You, L., Liu, B., Zhang, M., 2013. Water conservancy projects in China: Achievements, challenges and way forward. Global Environmental Change 23, 633-643.
Liu, S.Y., Han, M.Y., Wu, X.D., Wu, X.F., Li, Z., Xia, X.H., Ji, X., 2018. Embodied water analysis for Hebei Province, China by input-output modelling. Front. Earth Sci. 12, 72-85.
Liu, S.Y., Wu, X.D., Han, M.Y., Zhang, J.J., Chen, B., Wu, X.F., Wei, W.D., Li, Z., 2017b. A three-scale input-output analysis of water use in a regional economy: Hebei province in China. Journal of Cleaner Production 156, 962-974.
Llop, M., 2013. Water reallocation in the input–output model. Ecol. Econ. 86, 21-27.
Ma, J., Hoekstra, A., Wang, H., Chapagain, A., Wang, D., 2006. Virtual versus real water transfers within China. Philosophical Transactions of the Royal Society of London 361, 835–842.
Masud, M.B., Wada, Y., Goss, G., Faramarzi, M., 2019. Global implications of regional grain production through virtual water trade. Sci. Total Environ. 659, 807-820.
Meng, B., Peters, G., Wang, Z., 2014. Tracing CO2 Emissions in Global Value Chains, Social Science Electronic Publishing, pp. 1-76.
Meng, B., Xue, J., Feng, K., Guan, D., Fu, X., 2013. China's inter-regional spillover of carbon emissions and domestic supply chains. Energy Policy 61, 1305-1321.
Ministry of Housing and Urban-Rural Development, P.s.R.o.C., 2011. China Urban-Rural Construction Statistical Yearbook 2010. China Planning Press, Beijing, pp. 1-215.

Ministry of Water Resources of the People's Republic of China, 2015. China Water Resources Bulletin. China Water Power Press, Beijing.
Mubako, S., Lahiri, S., Lant, C., 2013. Input–output analysis of virtual water transfers: Case study of California and Illinois. Ecol. Econ. 93, 230-238.
Oki, T., Kanae, S., 2004. Virtual water trade and world water resources. Water Sci. Technol. 49, 203-209.
Pfister, S., Koehler, A., Hellweg, S., 2009. Assessing the Environmental Impacts of Freshwater Consumption in LCA. Environ. Sci. Technol. 43.
Rosa Duarte, J.S.n.-C.l., Jorge Bielsa, 2002. water use in Spanish economy- an input-output approach. Ecol. Econ.
Savenije, A.K.C.A.Y.H.H.H.G., 2006. Water saving through international trade of agricultural products.
Sowers, J., Vengosh, A., Weinthal, E., 2010. Climate change, water resources, and the politics of adaptation in the Middle East and North Africa. Clim. Change 104, 599-627.
The State Council 's second national economic census leading group office, 2010. Chinese Economic Census Yearbook 2008. China Statistics Press, Beijing.
The World Bank, 2014. The World Development Indicators. The World Bank.
Wang, Y.B., Liu, D., Cao, X.C., Yang, Z.Y., Song, J.F., Chen, D.Y., Sun, S.K., 2017a. Agricultural water rights trading and virtual water export compensation coupling model: A case study of an irrigation district in China. Agric. Water Manage. 180, 99-106.
Wang, Z., Wei, S., Yu, X., Zhu, K., 2017b. Characterizing global and regional manufacturing value chains: stable and evolving features, in: Centro Studi Luca D'Agliano, W.D.U.I. (Ed.), pp. 1-76.
Webber, M., Barnett, J., Finlayson, B., Wang, M., 2008. Pricing China's irrigation water. Global Environmental Change 18, 617-625.
White, D.J., Feng, K., Sun, L., Hubacek, K., 2015. A hydro-economic MRIO analysis of the Haihe River Basin's water footprint and water stress. Ecol. Modell. 318, 157-167.
Wichelns, D., 2004. The policy relevance of virtual water can be enhanced by considering comparative advantages. Agric. Water Manage. 66, 49-63.
Yang, H., Zhang, X., Zehnder, A.J., 2003. Water scarcity, pricing mechanism and institutional reform in northern China irrigated agriculture. Agric. Water Manage. 61, 143-161.
Zeng, Z., Liu, J., Koeneman, P., Zarate, E., Hoekstra, A.Y., 2012. Assessing water footprint at river basin level: a case study for the Heihe River Basin in northwest China. Hydrology and Earth System Sciences 16, 2771-2781.
Zhang, C., Anadon, L.D., 2013. Life cycle water use of energy production and its environmental impacts in China. Environ Sci Technol 47, 14459-14467.
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, Z., Zhu, K., Hewings, G.J.D., 2017. A multi-regional input–output analysis of the pollution haven hypothesis from the perspective of global production fragmentation. Energy Econ. 64, 13-23.
Zhang, Z.Y., Yang, H., Shi, M.J., 2011. Analyses of water footprint of Beijing in an interregional input-output framework. Ecol. Econ. 70, 2494-2502.
Zhao, D., Hubacek, K., Feng, K., Sun, L., Liu, J., 2019. Explaining virtual water trade: A spatial-temporal analysis of the comparative advantage of land, labor and water in China. Water Res. 153, 304-314.
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 USA 112, 1031-1035.
Zhao, X., Yang, H., Yang, Z., Chen, B., Qin, Y., 2010. Applying the input-output method to account for

water footprint and virtual water trade in the Haihe River basin in China. Environ. Sci. Technol. 44, 9150-9156.