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Trade heterogeneity and virtual water exports of China

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ABSTRACT

China is facing serious water scarcity, and the effects of international trade on its water resources have been widely examined. Processing exports account for nearly half of China's gross exports. Adopting China's multi-regional input–output table that captures processing exports, we enrich the literature on virtual water exports by accounting for trade heterogeneity. The results show that China's virtual water exports show a significant trade heterogeneity. Normal and processing exports are attributed to 86.7% and 13.3% of the Agriculture sector's water use induced by exports respectively. Conversely, normal and processing exports are attributed to 31.8% and 68.3% of the Communications Equipment, Computers sector's water use induced by exports respectively. In addition, a cross-regional compensation is needed to deal with the unequal regional distribution of water uses and economic benefits related to exports.

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KEYWORDS
Virtual water; processing exports; normal exports; input–output analysis

1. Introduction

Trade may alleviate or exacerbate a region's water shortage problem (Allan, 1993). As China leads global exports, the effects of international trade on China's water resources have been examined in several studies (Chen et al., 2018; Dalin et al., 2012; Haddad et al. 2020; Yang & Zehnder, 2001). However, the related literature fails to distinguish between processing and normal exports. The distinction is important because processing exports account for a significant share of China's gross exports. Processing exports mean that firms import all or part of the raw materials, parts and components from abroad, and assemble them for exports (Yang et al., 2015). Normal exports mean that firms directly use domestic intermediate inputs for production, and export finished products to international markets. In 2012, processing trade accounted for as much as 42.1% of China's

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gross international trade volume.[1] However, the country captured a smaller share of value added associated with processing trade compared with its consumption of natural and environmental resources (Dietzenbacher et al., 2012). Because processing exports account for a significant share of China's gross exports, the estimation of water resources embodied in exports may be biased without accounting for trade heterogeneity. To fill this gap, we evaluate the effects of exports on China's water resources by taking trade heterogeneity into account.

This paper is related to the literature on virtual water trade. When physical water is consumed in the production process, it turns into virtual water embodied in commodities between different regions (Zhang et al., 2019). The literature shows that the total volume of global virtual water trade has doubled between 1986 and 2007 (Dalin et al., 2012). The volume of virtual water flows within China is greater than that of physical water flows (Zhao et al., 2015). The literature also shows that net virtual water within China flows from the less-developed west to the developed coast (Liu et al., 2019; Zhao et al., 2015). This makes China a net exporter of virtual water (Lenzen et al., 2013), as the production of coastal regions' exported goods uses domestic intermediate inputs. However, previous studies fail to distinguish between virtual water embodied in normal and processing exports (Okadera et al., 2014; Zhang et al., 2016). The literature shows that the homogeneity assumption overestimated carbon emissions and air pollutants embodied in China's exports (Dietzenbacher et al., 2012; Du et al., 2020). The estimation of water resources embodied in exports would be biased if normal and processing exports were not distinguished. Therefore, in this paper, we focus on virtual water flows within China to support both processing and normal exports.

We apply an input–output (IO) model to calculate virtual water flows within China. The IO model is widely used in the discussion of global production networks' environmental effects (Koopman et al., 2014; Rodrigues et al. 2020; Sommer and Kratena 2020; Wang et al., 2017; Zhang et al., 2017). To deal with the problem of trade heterogeneity, relevant scholars split the IO table based on firm-level data. For instance, Tang et al. (2014) divided China's national IO table by firm size and ownership type, while Ma et al. (2015) divided each sector into four types based on trade regimes. However, they adopted the national IO table, and failed to capture the provincial trade heterogeneity. Liu et al. (2019) found that different provinces gained or lost water resources via their dominant trade types. Production fragmentation within China not only results in geospatial separations of production and consumption, but also results in regional mismatches between water uses and economic benefits associated with exports (Zhang et al., 2018). First, export-oriented processing firms are mainly concentrated in coastal provinces such as Guangdong and Jiangsu. Second, water resources of China are unequally distributed geographically. According to the National Bureau of Statistics, water resource of Guangdong is 1921 m^3 per capita, while water resource of Jiangsu is only 472 m^3 per capita. According to the water-stress index adopted by the United Nations, which is proposed by the Swedish hydrologist Malin Falkenmark, the areas with less than 500 m^3 of water per capita are labeled 'absolute' water scarcity. Third, different regions are connected with each other through China's domestic supply chains. As such, some water-deficient inland provinces are also involved in

[1] The data are obtained from the National Economic and Social Development Statistics Bulletin for 2012. http://www.stats.gov.cn/tjsj/tjgb/ndtjgb/qgndtjgb/201302/t20130221_30027.html.

China's processing exports indirectly, such as power transmission from the west to the east. Therefore, in this paper, we construct China's multi-regional input–output (MRIO) table that captures provincial normal and processing exports. The impacts of trade on provincial water resources and economic benefits are analyzed through China's MRIO table for 2012.

The contributions of this study are as follows. First, we enrich the literature on virtual water exports of China by taking trade heterogeneity into account. Processing exports, which consume a great volume of water resources to generate value added, account for almost half of the country's gross exports. Second, we consider not only the unequal geographical distribution of China's water resources, but also the geographical characteristic of exports. For instance, northern provinces face more serious water shortages than other regions, while coastal provinces benefit more from exports than other regions. Finally, we are the first to use the multi-regional input–output table that captures processing exports to analyze virtual water.

2. Methodology and data

2.1. Methodology

2.1.1. The IO model

Both bottom-up and top-down approaches have been applied to calculate virtual water flows (Feng et al., 2011). The bottom-up approach refers to process analysis, which mainly concentrates on agricultural products (Dalin et al., 2014, 2015; Zhuo et al., 2016; Zhuo et al., 2019). The top-down approach refers to input–output (IO) analysis, which follows the entire industrial supply chain (Bae & Dall'erba, 2018; Guan & Hubacek, 2007; Lenzen et al., 2013; Qian et al., 2018; Zhang & Anadon, 2014; Zhao et al., 2015, 2010). Feng et al. (2011) discussed advantages and limitations of these two approaches in details. The process-based approach fails to distinguish between intermediate and final demands. Therefore, in this study, we adopt the top-down IO approach.

The IO model was first proposed by Leontief (1936) to quantify structural interdependences among producing sectors. Since it was first applied to analyze environmental and social issues (Leontief, 1970) in the 1970s, the IO model has been subsequently widely used to map environmental and social impacts of international trade (Wiedmann & Lenzen, 2018). The traditional IO model is based on homogeneity assumption, and fails to capture different production structures of normal and processing exports. In this study, we construct China's MRIO table that captures provincial normal and processing exports. The structure of the MRIO table is presented in Appendix Table A1. The table shows economic relationships among different regions and sectors.

We assume that there are n regions, and each region has m sectors, where $r, s = 1, 2, \cdots n$ and $i, j = 1, 2, \cdots m$. The production of each sector is divided into production for normal exports and production for processing exports. We define the gross output vector of processing exports of region r $\boldsymbol{xp}_r = [xp_{r1} \cdots xp_{rj} \cdots xp_{rm}]^T$, where xp_{rj} is the gross output of processing exports of the j-th sector in region r, and the superscript T indicates the transpose of a vector or matrix. Similarly, we define the gross output vector of normal exports of region r $\boldsymbol{xo}_r = [xo_{r1} \cdots xo_{rj} \cdots xo_{rm}]^T$, where xo_{rj} is the gross output of normal exports of the j-th sector in region r. Then the gross output vector can be given by

$$\mathbf{x} = [\boldsymbol{xp}_1, \boldsymbol{xo}_1 \cdots \boldsymbol{xp}_r, \boldsymbol{xo}_r \cdots \boldsymbol{xp}_n, \boldsymbol{xo}_n]^T. \quad (1)$$

We define the intermediate input vector of the i-th sector $\boldsymbol{zop}_{rs,i} = [zop_{rs,i1} \cdots zop_{rs,ij} \cdots zop_{rs,im}]^T$, where $zop_{rs,ij}$ is the intermediate input of the i-th sector's normal exports of region r consumed by the j-th sector's processing exports of region s. The intermediate input matrix of normal exports of region r consumed by processing exports of region s is $\mathbf{ZOP}_{rs} = [\boldsymbol{zop}_{rs,1} \cdots \boldsymbol{zop}_{rs,i} \cdots \boldsymbol{zop}_{rs,m}]^T$. Similarly, we define the intermediate input matrix of normal exports of region r consumed by normal exports of region s $\mathbf{ZOO}_{rs} = [\boldsymbol{zoo}_{rs,1} \cdots \boldsymbol{zoo}_{rs,i} \cdots \boldsymbol{zoo}_{rs,m}]^T$. Then the total intermediate input matrix:

$$\mathbf{Z} = \begin{bmatrix} 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 \\ \mathbf{ZOP}_{11} & \mathbf{ZOO}_{11} & \cdots & \mathbf{ZOP}_{1s} & \mathbf{ZOO}_{1s} & \cdots & \mathbf{ZOP}_{1n} & \mathbf{ZOO}_{1n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \mathbf{ZOP}_{r1} & \mathbf{ZOO}_{r1} & \cdots & \mathbf{ZOP}_{rs} & \mathbf{ZOO}_{rs} & \cdots & \mathbf{ZOP}_{rn} & \mathbf{ZOO}_{rn} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \mathbf{ZOP}_{n1} & \mathbf{ZOO}_{n1} & \cdots & \mathbf{ZOP}_{ns} & \mathbf{ZOO}_{ns} & \cdots & \mathbf{ZOP}_{nn} & \mathbf{ZOO}_{nn} \end{bmatrix} \tag{2}$$

We define the final demand matrix

$$\mathbf{Y} = \begin{bmatrix} 0 & \cdots & 0 & \cdots & 0 \\ \boldsymbol{yo}_{11} & \cdots & \boldsymbol{yo}_{1s} & \cdots & \boldsymbol{yo}_{1n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 \\ \boldsymbol{yo}_{r1} & \cdots & \boldsymbol{yo}_{rs} & \cdots & \boldsymbol{yo}_{rn} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 \\ \boldsymbol{yo}_{n1} & \cdots & \boldsymbol{yo}_{ns} & \cdots & \boldsymbol{yo}_{nn} \end{bmatrix}, \tag{3}$$

where $\boldsymbol{yo}_{rs} = [yo_{rs,1} \cdots yo_{rs,i} \cdots yo_{rs,m}]^T$ is the final demand vector from region r to region s, $yo_{rs,i}$ is the final demand of the i-th sector in region r consumed by region s. The exports vector:

$$\mathbf{e} = [\boldsymbol{ep}_1, \boldsymbol{eo}_1 \cdots \boldsymbol{ep}_r, \boldsymbol{eo}_r \cdots \boldsymbol{ep}_n, \boldsymbol{eo}_n]^T, \tag{4}$$

where $\boldsymbol{ep}_r = [ep_{r,1} \cdots ep_{r,i} \cdots ep_{r,m}]^T$ and $\boldsymbol{eo}_r = [eo_{r,1} \cdots eo_{r,i} \cdots eo_{r,m}]^T$ are the processing exports vector and the normal exports vector of region r, $ep_{r,i}$ and $eo_{r,i}$ are processing exports and normal exports of the i-th sector in region r respectively. The value added vector:

$$\mathbf{v}' = [\boldsymbol{vp}'_1, \boldsymbol{vo}'_1 \cdots \boldsymbol{vp}'_r, \boldsymbol{vo}'_r \cdots \boldsymbol{vp}'_n, \boldsymbol{vo}'_n], \tag{5}$$

where $\boldsymbol{vp}'_r = [vp'_{r,1} \cdots vp'_{r,i} \cdots vp'_{r,m}]$ and $\boldsymbol{vo}'_r = [vo'_{r,1} \cdots vo'_{r,i} \cdots vo'_{r,m}]$ are the value added vectors of processing exports and normal exports of region r, $vp'_{r,i}$ and $vo'_{r,i}$ are value added of processing exports and normal exports of the i-th sector in region r respectively. The water consumption vector:

$$\mathbf{c} = [\boldsymbol{cp}_1, \boldsymbol{co}_1 \cdots \boldsymbol{cp}_r, \boldsymbol{co}_r \cdots \boldsymbol{cp}_n, \boldsymbol{co}_n], \tag{6}$$

where $\boldsymbol{cp}_r = [cp_{r,1} \cdots cp_{r,i} \cdots cp_{r,m}]$ and $\boldsymbol{co}_r = [co_{r,1} \cdots co_{r,i} \cdots co_{r,m}]$ are water consumption vectors of processing exports and normal exports of region r, $cp_{r,i}$ and $co_{r,i}$ are water consumption of processing exports and normal exports of the i-th sector in region r respectively. $cp_{r,i}$ is given by $cp_{r,i} = t_{r,i} \times (zop_{r,iw}/(zop_{r,iw} + zoo_{r,iw}))$, where $t_{r,i}$ is total water use of the i-th sector in region r, $zop_{r,iw}$ is intermediate input of the i-th sector to processing exports of the w-th sector (i.e. Water Production and Supply sector) in region r, $zoo_{r,iw}$ is intermediate input of the i-th sector to normal exports of the w-th sector (i.e. Water Production and Supply sector) in region r. Similarly, $co_{r,i}$ is given by $co_{r,i} = t_{r,i} \times (zoo_{r,iw}/(zop_{r,iw} + zoo_{r,iw}))$.

The gross output's production balance can be written as:

$$\mathbf{x} = \mathbf{Zu} + \mathbf{Yt} + \mathbf{e}, \tag{7}$$

where $\mathbf{u} = (1, \cdots 1)_{2mn\times 1}$ and $\mathbf{t} = (1, \cdots 1)_{mn\times 1}$. $\mathbf{Zu}$ is the row sum of the $2mn$ by $2mn$ matrix $\mathbf{Z}$. $\mathbf{A} = \mathbf{Z}(\hat{\boldsymbol{x}})^{-1}$ is the intermediate input coefficient matrix, and $\hat{\boldsymbol{x}}$ indicates diagonalization of the gross output vector $\mathbf{x}$. The superscript -1 indicates matrix inversion. The Leontief inverse matrix is $\mathbf{B} = (\mathbf{I} - \mathbf{A})^{-1}$. Equation 7 can be expressed as:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}(\mathbf{Yt} + \mathbf{e}) = \mathbf{B}(\mathbf{Yt} + \mathbf{e}). \tag{8}$$

The Leontief inverse matrices of normal and processing exports are $\mathbf{BO} = [\boldsymbol{bo}_1 \cdots \boldsymbol{bo}_r \cdots \boldsymbol{bo}_n]$ and $\mathbf{BP} = [\boldsymbol{bp}_1 \cdots \boldsymbol{bp}_r \cdots \boldsymbol{bp}_n]$. The output vectors caused by normal and processing exports are $\mathbf{eo}$ and $\mathbf{ep}$ respectively. $\mathbf{fo} = \mathbf{co}(\widehat{\boldsymbol{xo}})^{-1}$and $\mathbf{fp} = \mathbf{cp}(\widehat{\boldsymbol{xp}})^{-1}$ are water coefficients vectors of normal and processing exports, where $\mathbf{co} = [\boldsymbol{co}_1 \cdots \boldsymbol{co}_r \cdots \boldsymbol{co}_n]$, $\mathbf{xo} = [\boldsymbol{xo}_1 \cdots \boldsymbol{xo}_r \cdots \boldsymbol{xo}_n]$, $\mathbf{cp} = [\boldsymbol{cp}_1 \cdots \boldsymbol{cp}_r \cdots \boldsymbol{cp}_n]$, $\mathbf{xp} = [\boldsymbol{xp}_1 \cdots \boldsymbol{xp}_r \cdots \boldsymbol{xp}_n]$. $\mathbf{vo} = \mathbf{vo}'(\widehat{\boldsymbol{xo}})^{-1}$ and $\mathbf{vp} = \mathbf{vp}'(\widehat{\boldsymbol{xp}})^{-1}$ are value added coefficients vectors of normal and processing exports, where $\mathbf{vo}' = [\boldsymbol{vo}'_1 \cdots \boldsymbol{vo}'_r \cdots \boldsymbol{vo}'_n]$, $\mathbf{vp}' = [\boldsymbol{vp}'_1 \cdots \boldsymbol{vp}'_r \cdots \boldsymbol{vp}'_n]$. Then, water resources embodied in normal exports (**weox**) and processing exports (**wepx**) and value added embodied in normal exports (**veox**) and processing exports (**vepx**) are:

$$\mathbf{weox} = \widehat{\boldsymbol{fo}} \times \mathbf{BO} \times \mathbf{eo}, \tag{9}$$

$$\mathbf{wepx} = \widehat{\boldsymbol{fp}} \times \mathbf{BP} \times \mathbf{ep}, \tag{10}$$

$$\mathbf{veox} = \widehat{\boldsymbol{vo}} \times \mathbf{BO} \times \mathbf{eo}, \tag{11}$$

$$\mathbf{vepx} = \widehat{\boldsymbol{vp}} \times \mathbf{BP} \times \mathbf{ep}. \tag{12}$$

We define water resources (value added) of region r induced by normal and processing exports of region s as $weox_{rs}$ and $wepx_{rs}$ ($veox_{rs}$ and $vepx_{rs}$), where $r, s = 1, 2, \cdots n$. We define water resources (value added) of sector i induced by normal and processing exports of sector j as $weox_{ij}$ and $wepx_{ij}$ ($veox_{ij}$ and $vepx_{ij}$), where $i, j = 1, 2, \cdots m$.

2.1.2. The balance between water use and economic benefit

China uses domestic water resources to produce exported products, and gains economic benefits simultaneously. However, there exists an unequal regional distribution of water uses and economic benefits related to exports (see Appendix Figure B3). The provinces' water stresses caused by exports are different because there exist significant differences of exports volumes and economic benefits in different provinces of China. In this study, we measure a region's economic benefit from exports by the ratio of its trade-related value added to its gross domestic product (GDP), and measure a region's water stress caused by exports by the ratio of its trade-related water use to its total renewable water resource. The renewable water resource data are derived from the China Statistical Yearbook of 2013.[2] We map the 31 provinces in four quadrants by the national water stress and economic benefit ratios. We decide the threshold of water stress according to the average water stress ratio, and we decide the threshold of economic benefit according to the average economic benefit ratio.

2.2. Data sources

2.2.1. China's MRIO table that captures processing exports

Adopting the MRIO table that captures processing exports, we trace China's virtual water flows to support exports. We construct China's MRIO table that captures processing exports. The databases include: (1) the MRIO table of China in 2012 constructed by the Development Research Center of the State Council (Pan et al., 2018), (2) the national input–output table that captures processing exports, (3) the trade data from China Customs Statistics (CCS). The benchmark MRIO table is composed of the exports vector, the imports vector, the value added vector, the final demand vector, the intermediate input matrix and the output vector (see Appendix Table A3). We split vectors and matrices in the benchmark table to construct China's MRIO table capturing processing trade.

According to the data from CCS, the exports vector is assigned to processing and normal exports vectors, and we aggregate the commodity level data into sector level. The output vectors of normal and processing exports are estimated based on the normal exports vector and domestic demand for products from foreign-invested enterprises. According to the data for foreign-invested enterprises, the value added vector is assigned to value added vectors of normal exports and processing exports. The final demand vector of normal exports is estimated based on the ratio of foreign-invested enterprises' products that are used to satisfy domestic demand to all enterprises' products that are used to satisfy domestic demand.

Finally, based on differences between the output vector of processing exports and the value added vector of processing exports, we obtain the gross intermediate input vector of processing exports for each sector. Subtracting the imports vector from the gross intermediate input vector of processing exports, we obtain the intermediate input vector of processing exports for each sector. Then the intermediate input matrix of normal exports is estimated by subtracting the intermediate input matrix of processing exports from the intermediate input matrix in the benchmark input–output table.

2.2.2. Water consumption data

The original water consumption inventory is from the China Statistical Yearbook of 2013, including water use by agriculture, water use by industry and water use by living consumption. The mapping of sector classification between the water consumption inventory and China's MRIO table is presented below.

[2] Source: http://www.stats.gov.cn/tjsj/ndsj/2013/indexch.htm.

Water use of the first sector (S01 in Appendix Table B1) in China's MRIO table is derived from water use by agriculture released by the China Statistical Yearbook. Based on the water consumption data of key enterprises of different sectors from the Chinese Academy for Environmental Planning, we obtain the water consumption coefficient of each industrial sector (from S02 to S27 in Appendix Table B1). Then, based on the total water use by industry and the proportion of each industrial sector's water consumption, we obtain water uses of different industrial sectors (from S02 to S27 in Appendix Table B1).

Based on the total water use of living consumption (*fwl*) released by the China Statistical Yearbook, we obtain water uses of the Construction sector (S28 in Appendix Table B1) and tertiary industrial sectors (from S29 to S42 in Appendix Table B1) in China's MRIO table. The total water use of living consumption is composed of household use and public use (including tertiary industry and construction). First, we obtain the proportion of water use by the Construction sector (*pcon*) and the proportion of total water use by tertiary industrial sectors (*ptid*) according to water consumption data from the First National Water Census Bulletin. The First National Water Census Bulletin publishes water uses of construction (*wcon*), tertiary industry (*wtid*) and household (*whou*) in 2011. The proportion of water use by the Construction sector in 2011 is $pcon = wcon/(wcon + wtid + whou)$. Similarly, the proportion of total water use by tertiary industrial sectors in 2011 is $ptid = wtid/(wcon + wtid + whou)$. We assume that the proportion of water use by the Construction sector (*pcon*) and the proportion of total water use by tertiary industrial sectors (*ptid*) in 2012 are the same as that in 2011. Second, we obtain water use of the Construction sector (S28 in Appendix Table B1) by $fwcon = fwl \times pcon$ and total water use of tertiary industrial sectors by $fwtid = fwl \times ptid$. Finally, water use of the i-th tertiary industrial sector is obtained by $wtid_i = fwtid \times \left(z_{iw} / \sum_{i=29}^{42} z_{iw} \right)$, where z_{iw} is intermediate input of the i-th tertiary industrial sector to the w-th sector (i.e. Water Production and Supply sector).

3. Results

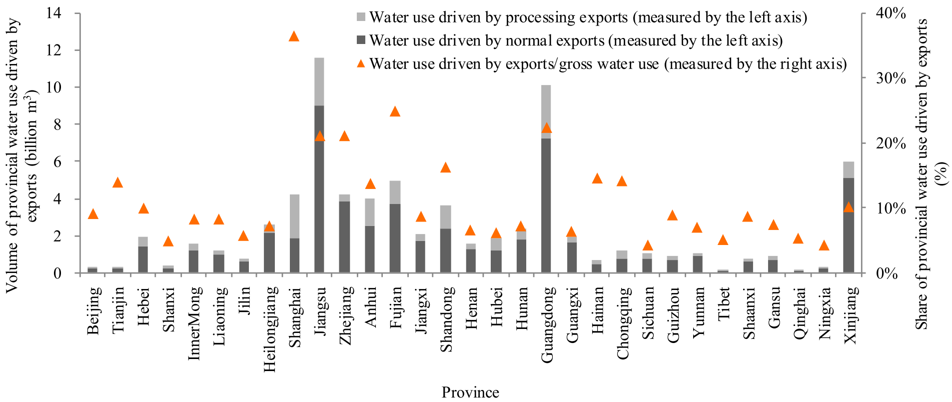
3.1. Provincial water uses induced by exports

Adopting the MRIO table that captures processing exports, we calculate provincial water uses induced by China's exports. Results are presented in Figure 1.

Coastal provinces consume more water resources to support China's exports than inland ones. Jiangsu uses the largest volume of water resource to support China's exports (11.62 billion m^3), followed by Guangdong (10.12 billion m^3) and Xinjiang (6.01 billion m^3). The first two provinces are coastal ones, and directly export products to foreign countries on a large scale. Xinjiang is an inland province, and has abundant water resources. It uses a large amount of local water resources to support production of other provinces' exported commodities, although the volume of its direct exports is small. The water use of Shanghai that supports China's exports accounts for 36.5% of its gross water use, followed by that of Fujian (24.9%) and Guangdong (22.4%). Conversely, western regions' water uses to support China's exports account for smaller shares of their gross water uses than that of coastal regions.

In Figure 1, we distinguish between water uses induced by normal and processing exports. Processing exports mainly drive water uses of Guangdong (2.84 billion m^3),

Figure 1. Provincial water uses driven by normal and processing exports.



Jiangsu (2.63 billion m^3) and Shanghai (2.36 billion m^3). Generally, processing exports drive proportionally less water use compared with normal ones. For instance, processing exports account for more than half of Jiangsu's gross exports (Appendix Figure B1), yet the water use of Jiangsu induced by processing exports only accounts for 22.6% of Jiangsu's gross water use induced by exports.

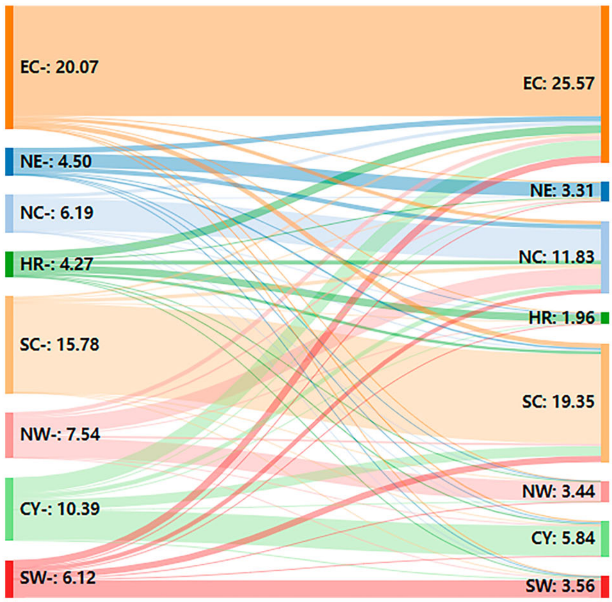
As previously mentioned, through domestic industrial linkages, a region's water resource sometimes is used to support exports of other regions. We further analyze virtual water flows within China to support gross, normal and processing exports. The 31 provinces are divided into eight regions according to the 'Eight Economic Regions' proposed by the Development Research Center of the State Council. The detailed information of the division is shown in Appendix Table A2. Figure 2 presents the eight regions' virtual water flows to support China's exports.

When the exports volume of a country in a specific year is greater than its imports volume, the country is under trade surplus. In 2012, China's international trade surplus reached 230.58 billion dollars, and processing trade accounted for 42.1% of China's gross international trade volume.[3] Figure 2 shows that 74.5% of China's virtual water use is induced by normal exports, while the remaining 25.5% is induced by processing exports. Therefore, processing exports use proportionally less water resources than normal exports. The water use induced by normal exports (3.24 billion m^3) in the northwest is 18 times of that induced by processing exports (0.18 billion m^3). The East Coast's normal and processing exports drive the most water use among all regions, followed by the South Coast.

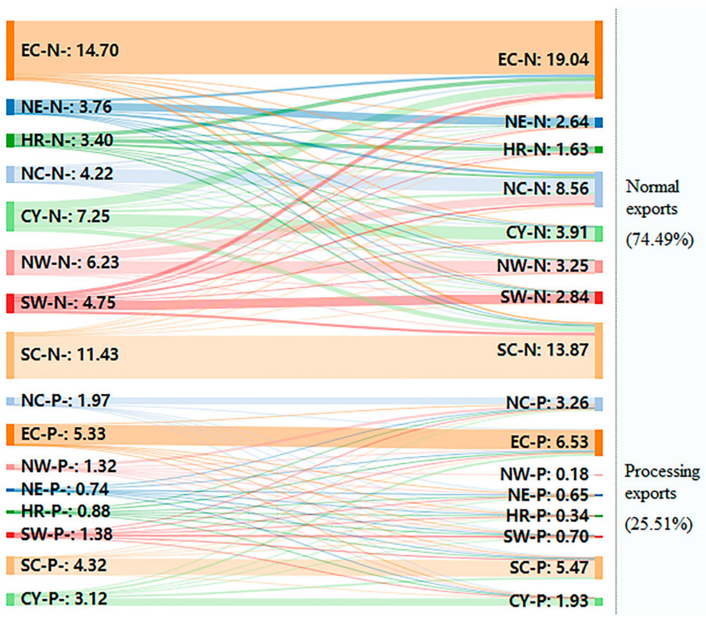
Export-oriented enterprises of China are mainly concentrated in coastal provinces. Therefore, trade-related water uses are mainly driven by exports of coastal regions. As shown in Figure 2, a large quantity of trade-related water uses in inland regions, such as Southwest, Northwest and Middle Yangtze River, are induced by exports of coastal regions such as East Coast and North Coast. Except for the Middle Yellow River region, other seven regions' trade-related water uses are mainly driven by their direct exports. The Middle Yellow River region is composed of coal resource-intensive provinces. Coal mining consumes

[3] The data are obtained from the National Economic and Social Development Statistics Bulletin for 2012. http://www.stats.gov.cn/tjsj/tjgb/ndtjgb/qgndtjgb/201302/t20130221_30027.html.

Figure 2. Virtual water flows within China to support exports (billion m^3). Notes: The detailed division of regions is shown in Appendix Table A2.



(a) Virtual water flows within China that support gross exports



(b) Virtual water flows within China that support normal and processing exports a large quantity of water resources. A great quantity of coal in the Middle Yellow River region is transferred to other regions to support their production of exported commodities. Therefore, a large quantity of the Middle Yellow River region's water uses are driven by other regions' exports.

We then focus on virtual water induced by a certain province's exports. Guangdong has the largest exports volume among all provinces, followed by Jiangsu (see Appendix Figure B1). A detailed analysis on each province's water use to support Guangdong and Jiangsu's exports is provided, and the results are shown in Figure 3.

Compared with processing exports, normal exports of Guangdong and Jiangsu drive more water uses of other regions. For instance, other regions in China use 17.88 and 7.56 billion m^3 of water resources to support Jiangsu's normal and processing exports respectively. Overall, Guangdong's exports mainly drive water uses of southern regions. Hunan uses 6.14 and 2.39 billion m^3 of domestic water resources to support Guangdong's normal and processing exports. Conversely, Jiangsu's exports mainly drive water uses of northern regions that face serious water shortage problems. As the largest virtual water supplier for Jiangsu's exports, Anhui uses 2.85 and 1.13 billion m^3 of domestic water resources to support Jiangsu's normal and processing exports, respectively. Jiangsu's exports put additional pressure on China's water resources.

3.2. *Sectoral water uses induced by exports*

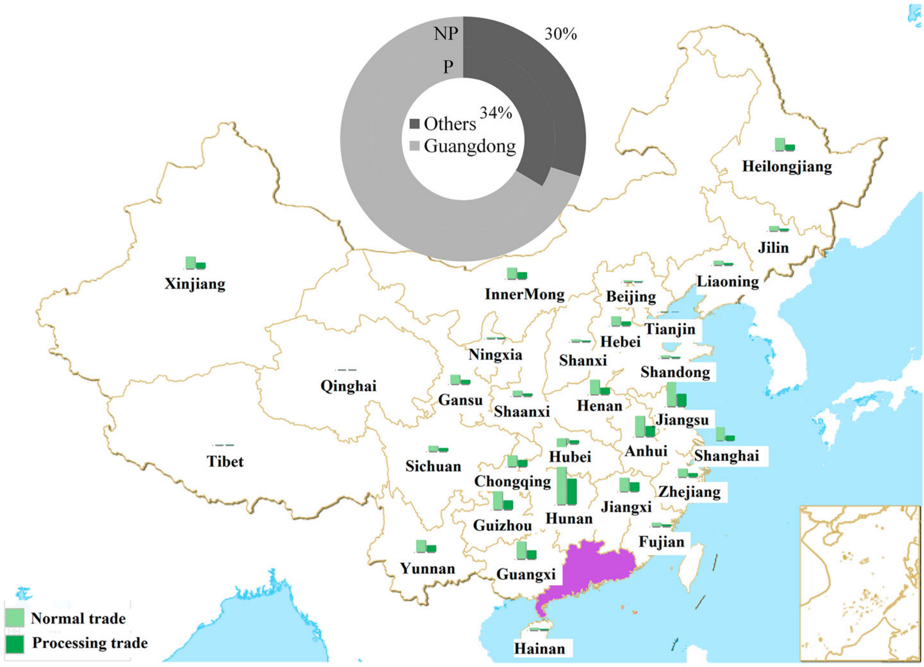
In this study, we calculate sectoral water uses induced by China's exports. Table 1 shows the top 10 sectors of water uses induced by gross exports, normal exports, and processing exports.

The top 10 sectors' water uses account for 90.4% of China's total water use induced by gross exports. The Agriculture sector consumes the largest volume of water resource among all sectors (36.06 billion m^3), followed by the Production and Supply of Electric Power and Heat Power sector (7.76 billion m^3) and the Chemical Products sector (5.97 billion m^3). Hence, improving water use efficiency of agriculture is important for reducing China's virtual water exports. This is consistent with the literature (Chen et al., 2018; Dalin et al., 2012; Yang & Zehnder, 2001), in which China can reduce domestic water use through virtual water imports associated with agricultural products.

There are significant differences in contributions of normal and processing exports to the total water use of each sector. For example, normal and processing exports are attributed to 86.7% and 13.3% of the Agriculture sector's water use induced by exports respectively. Conversely, normal and processing exports are attributed to 31.8% and 68.3% of the Communications Equipment, Computers sector's water use induced by exports respectively. The contributions of normal exports (52.5%) and processing exports (47.5%) to the Chemical Products sector's water use induced by exports are similar.

The top 10 sectors' water uses account for 91.4% and 88.3% of China's water uses induced by normal and processing exports, respectively. Water use of the Agriculture sector accounts for 56.1% of China's total water use induced by normal exports. Following the Agriculture sector, water uses of the Production and Supply of Electric Power and Heat Power sector and the Textile sector account for 11.0% and 6.4% of China's total water use induced by normal exports, respectively. Water use of the Agriculture sector accounts for

Figure 3. Regional water use to support Guangdong and Jiangsu's exports.



(a) Regional water use to support Guangdong's exports

(b) Regional water use to support Jiangsu's exports

Table 1. Sectoral water uses induced by China's exports.

Sectors	Volume	Share	Normal share	Processing share
(a) Top 10 sectors of water uses induced by gross exports (billion m^3)				
Agriculture	36.06	48.20%	86.73%	13.27%
Production and Supply of Electric Power and Heat Power	7.67	10.25%	79.97%	20.03%
Chemical Products	5.97	7.97%	52.51%	47.49%
Textile	4.79	6.39%	74.54%	25.46%
Paper Printing and Educational and Sports Goods	3.48	4.65%	54.15%	45.85%
Smelting and Pressing of Metal Ores	3.24	4.33%	53.10%	46.90%
Food and Tobacco	1.91	2.55%	50.67%	49.33%
Communications Equipment, Computers	1.89	2.53%	31.75%	68.25%
Petroleum, Coking, and Nuclear Fuel Processed Products	1.71	2.28%	59.74%	40.26%
Wearing Apparel, Footwear, Leather and Related Products	0.91	1.22%	59.70%	40.30%
Others	7.20	9.63%	67.87%	47.34%

Sectors	Volume	Share
(b) Top 10 sectors of water uses induced by normal exports (billion m^3)		
Agriculture	31.27	56.12%
Production and Supply of Electric Power and Heat Power	6.13	11.01%
Textile	3.57	6.40%
Chemical Products	3.13	5.62%
Paper Printing and Educational and Sports Goods	1.89	3.38%
Smelting and Pressing of Metal Ores	1.72	3.08%
Petroleum, Coking, and Nuclear Fuel Processed Products	1.02	1.83%
Food and Tobacco	0.97	1.74%
Metal Mining Products	0.63	1.13%
Accommodation and Catering	0.62	1.12%
Others	4.78	8.58%

Sectors	Volume	Share
(c) Top 10 sectors of water uses induced by processing exports (billion m^3)		
Agriculture	4.78	25.06%
Chemical Products	2.83	14.84%
Paper Printing and Educational and Sports Goods	1.60	8.37%
Production and Supply of Electric Power and Heat Power	1.54	8.05%
Smelting and Pressing of Metal Ores	1.52	7.95%
Communications Equipment, Computers	1.29	6.76%
Textile	1.22	6.38%
Food and Tobacco	0.94	4.94%
Petroleum, Coking, and Nuclear Fuel Processed Products	0.69	3.60%
Transportation Equipment	0.45	2.38%
Others	2.23	11.67%

Table 2. The Agriculture sector's water use induced by other sectors' exports.

Sectors	Volume	Share
(a) The Agriculture sector's water use induced by other sectors' normal exports (billion m^3)		
Food and Tobacco	6.89	22.03%
Textile	4.76	15.23%
Manufacture of Textile Wearing Apparel, Footwear	4.26	13.63%
Agriculture	4.16	13.31%
Chemical Products	2.53	8.07%
Sectors	Volume	Share
(b) The Agriculture sector's water use induced by other sectors' processing exports (billion m^3)		
Food and Tobacco	1.24	25.93%
Communication Equipment, Computers	0.81	16.90%
Chemical Products	0.51	10.73%
Paper Printing and Educational and Sports Goods	0.43	9.03%
Textile	0.36	7.44%

25.1% of China's total water use induced by processing exports, followed by the Chemical Products sector (14.8%) and the Paper Printing and Educational and Sports Goods sector (8.4%).

In Table 2, we further investigate the Agriculture sector's water use induced by other sectors' normal and processing exports.

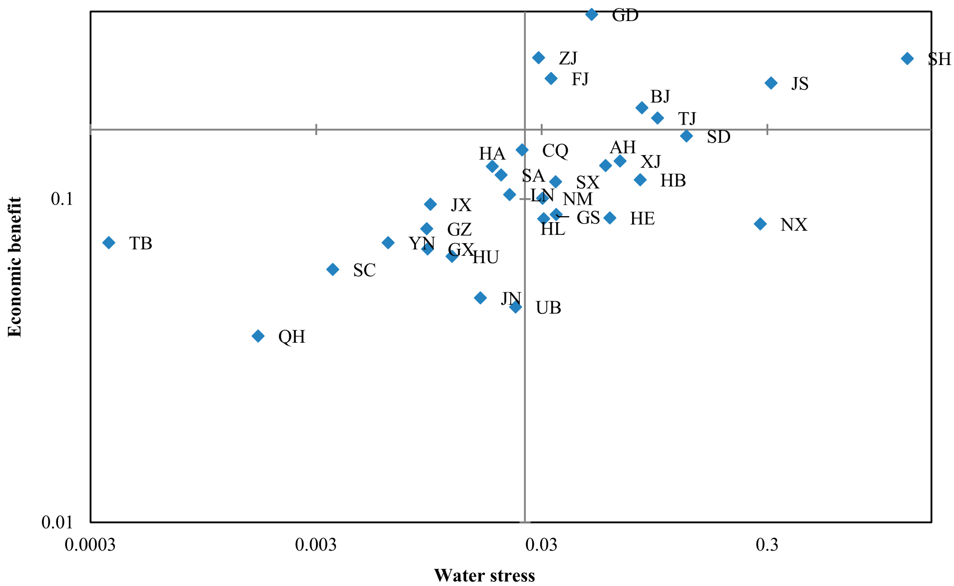
The Agriculture sector consumes the largest volume of water resource among all sectors to support both normal and processing exports. This is because agricultural products have high water use coefficients, and are usually used as intermediate inputs in the production of other sectors' exported products (Chen et al., 2018). The Agriculture sector's water consumption embodied in normal exports is mainly induced by the Food and Tobacco sector (22.0%) and the Textile sector (15.2%). The Agriculture sector's water consumption embodied in processing exports is mainly induced by the Food and Tobacco sector (25.9%) and the Communication Equipment, Computers sector (16.9%). In addition, 13.3% of the Agriculture sector's water consumption is related to its own normal exports.

Our results are consistent with similar studies that focus on virtual water driven by exports. The findings indicate that the Agriculture sector is an important water user, and its water consumption is mainly induced by the Food and Tobacco sector's exports, thus lowering exports of products from the Food and Tobacco sector can save water resources (Chen et al., 2018; Huang et al., 2017). Moreover, studies about virtual water driven by domestic production networks also suggest that the Agriculture sector is the largest water user (Chen et al., 2018; Dalin et al., 2012; Yang & Zehnder, 2001). Therefore, improving water use efficiency of the Agriculture sector helps save water uses induced by domestic and international trade.

3.3. The effects of exports on provincial water uses and economic benefits

In order to investigate the effects of exports on provincial water uses and economic benefits, we map the 31 provinces in four quadrants by the national economic benefit and water stress ratios according to the criteria in Section 2.1.2. The threshold of water stress is decided by the average water stress ratio, and the threshold of economic benefit is decided by the average economic benefit ratio. The results are depicted in Figure 4.

Figure 4. The effects of gross exports on provincial water uses and economic benefits. Notes: The names of all regions are shown in Table A2.

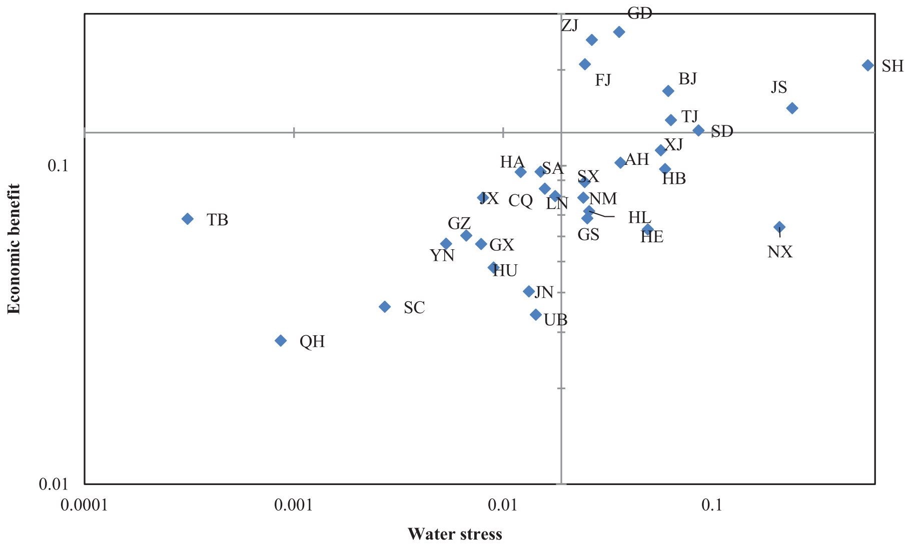


The national average economic benefit ratio is 0.164, and the national average water stress ratio is 0.025. According to the effects of China's gross exports on their water resources and economic benefits, the 31 provinces are divided into three groups. The first group is located in the first quadrant. Provinces in this group, namely Shanghai, Jiangsu, Guangdong, Zhejiang, Fujian, Beijing, and Tianjin, are all coastal provinces. Economic growth of these provinces is largely induced by China's exports. Exports-related water uses of these provinces account for greater shares of gross water resources than that of other regions, as these provinces are actively participating in the country's international exports. Conversely, provinces in the second group are mainly western provinces, corresponding to smaller scales of international exports than coastal provinces. These provinces, such as Tibet, Qinghai, and Sichuan, obtain relatively low value added from exports. Meanwhile, exports put relatively low pressures on these provinces' water resources. The third group is located in the fourth quadrant. Provinces in this group are mainly inland ones, and face water shortage problems. These provinces use local water resources to support China's exports but gain limited economic benefits from exports. China's exports thus result in more serious water shortage problems in these provinces.

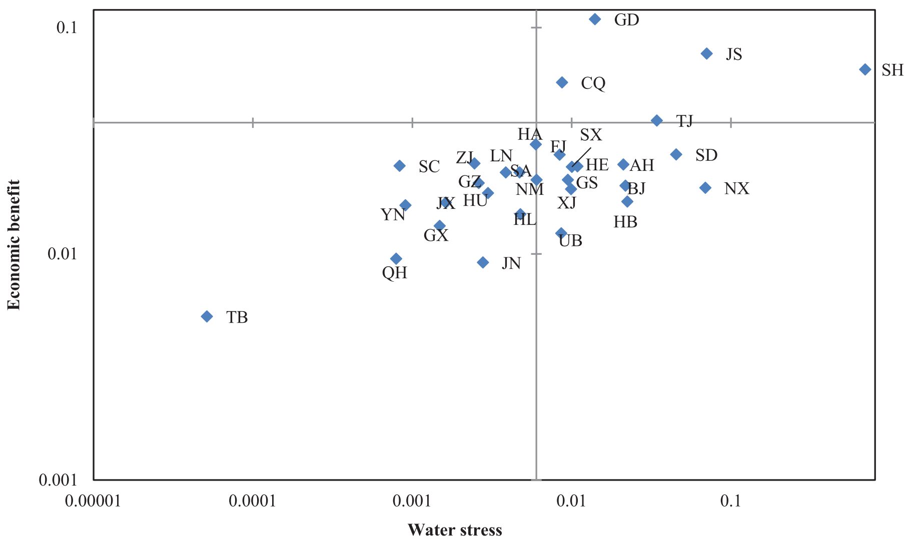
We further analyze the effects of normal and processing exports on provincial water uses and economic benefits. The national average economic benefit ratio and water stress ratio of normal exports are 0.127 and 0.019. The national average economic benefit ratio and water stress ratio of processing exports are 0.038 and 0.006. Figure 5 shows the 31 provinces in four quadrants by normal and processing exports' economic benefit and water stress ratios. The threshold of water stress is decided by the average water stress ratio, and the threshold of economic benefit is decided by the average economic benefit ratio.

Similar with gross exports, according to the effects of China's normal and processing exports on their water resources and economic benefits, the 31 provinces are divided into

Figure 5. The effects of normal and processing exports on provincial water uses and economic benefits. Notes: The names of all regions are shown in Table A2.



(a) The effects of normal exports on provincial water uses and economic benefits



(b) The effects processing exports on provincial water uses and economic benefits

three groups. Differently, the grouping of regions has changed according to the effects of processing exports on provincial water uses and economic benefits. Some provinces such as Beijing, Tianjin and Fujian change from the first quadrant to the fourth quadrant, implying that economic growth of these regions induced by exports is mainly from normal exports instead of processing exports. Zhejiang changes from the first quadrant to the third quadrant. This is related to the scale of Zhejiang's processing exports (see Appendix Figure B1). Different from other coastal provinces such as Guangdong and Jiangsu, the scale of processing exports (196 billion dollars) in Zhejiang is much less than that of normal exports (1290 billion dollars). Therefore, processing exports of Zhejiang have lower economic benefit and water stress ratios than normal exports. The average economic benefit ratio of normal exports (0.127) is approximately 3 times of that of processing exports (0.038). Similarly, the average water stress ratio of normal exports (0.019) is approximately 3 times of that of processing exports (0.006). As normal exports of most provinces usually correspond to larger quantities of value added and water uses than processing exports, the estimation of water resources embodied in exports will be biased without distinguishing between normal and processing exports.

4. Conclusions

We add to the literature on China's virtual water exports by accounting for trade heterogeneity from a provincial perspective. To this end, we use China's MRIO table that captures processing exports to assess the effects of exports on the country's water resources. To our knowledge, this is the first study to distinguish between normal and processing exports in virtual water analysis.

Coastal provinces consume more water resources to support China's exports than inland provinces because export-oriented enterprises are mainly concentrated in coastal provinces. Generally, processing exports use proportionally less water resources than normal exports. Processing exports account for 42.1% of China's gross exports, while only 25.5% of virtual water exports are induced by processing exports. Other related studies show that virtual water flows within China to support domestic final demand are also from less developed inland provinces to more developed coastal provinces (Liu et al., 2019; Zhao et al., 2015). It means that inland provinces consume much local water resources to support not only coastal provinces' consumption demands but also their exports. Through the findings, we give recommendations on alleviating water shortage problems of specific regions. Anhui and Henan are the two largest virtual water suppliers for Jiangsu's exports, which consume massive water resources to support Jiangsu's exports. According to the China Statistical Yearbook, water uses of Anhui and Henan account for 41.7% and 89.9% of their total water resources respectively. Virtual water flows from Henan to Jiangsu exacerbate the water shortage problem of Henan. According to the results, virtual water exports of Henan are mainly induced by water-intensive industries such as steel and electric power. The water consumption coefficient of the Production and Supply of Electric Power and Heat Power sector in Henan is 40.29 m^3/yuan, while the water consumption coefficient of the Production and Supply of Electric Power and Heat Power sector in Shandong is only 13.83 m^3/yuan. Therefore, we suggest that Henan introduces advanced technology from Shandong in the production of commodities, thereby reducing the volume of virtual water flows from Henan to Jiangsu and alleviating the water shortage problem of Henan. A regional guiding catalogue of industrial technology introduction is needed to promote the advanced technology introduction in Henan. Because the country's guiding catalogue of industrial structure adjustment is promulgated by the National Development and Reform

Commission, we suggest that the Henan Provincial Development and Reform Commission promulgates the local guiding catalogue of industrial technology introduction. The guiding catalogue needs to regard Shandong as a key area for technology introduction of electric power enterprises in Henan, thereby reducing the water consumption coefficient of the Production and Supply of Electric Power and Heat Power sector in Henan. We think the guiding catalogue will be effective because the catalog of commodities prohibited from processing trade has been proven to work. The proportion of processing exports volume to gross exports volume decreased from 42.1% in 2012 to 33.5% in 2017 since the government supplemented the catalog of commodities prohibited from processing trade.

Results reveal that the Agriculture sector consumes the largest volume of water resource among all sectors to support China's exports. This is because agricultural products have high water use coefficients, and are usually used as intermediate inputs in the production of other sectors' exported products. We find that the Agriculture sector's water consumption embodied in exports is mainly induced by the Food and Tobacco sector. This is related to the Food and Tobacco sector's high demand on the Agriculture sector since agricultural products such as rice, wheat and corn are usually used as raw materials of processed foods. Except for saving water through traditional methods such as promoting water-saving irrigation technologies and equipment, our results provide a reference for saving water through adjusting the export structure. The General Customs Administration is suggested to levy export tariff on tobacco and food products, thereby controlling water-intensive products' exports and reducing their dependence on the Agriculture sector.

Finally, there exists an unequal regional distribution of water uses and economic benefits related to exports. Regions in the upstream of supply chain such as Hunan and Anhui consume local water resources to meet demands of regions in the downstream of supply chain such as Guangdong and Jiangsu, but they gain lower proportions of economic benefits from exports compared with proportions of water consumptions. A cross-regional compensation is needed to deal with the unequal regional distribution of water uses and economic benefits related to exports. Previous water resources related compensation mainly focuses on physical water flows, which the downstream area provides economic compensation for the upstream area's efforts on pollution control. Based on this study, we provide a reference for the construction of water resources related compensation from the consumption perspective. According to our results, Hunan consumes 3.4% of total water resource driven by exports to meet the consumption demand of Guangdong, while it only gains 1.9% of total exports-related value added from Guangdong. Therefore, Guangdong should compensate for Hunan's deficient economic benefit. A cross-regional coordination institution is needed to perform the compensation between Guangdong and Hunan. We think the compensation between different regions is feasible because similar compensation policies have been applied in the field of air pollution and achieved good results. Zhong and Wang (2020) found that the annual average concentrations of major air pollutants in Hubei province had decreased since the region implemented the compensation for air quality. The process includes charging the air polluter, and compensating the victims who suffer from loss caused by the air pollution. We think the experience can be transferred to the virtual water domain because a similar compensation policy has been applied in the physical water domain (Cheng et al., 2020). The downstream government pays for the upstream government to compensate the upstream government's economic loss due to protecting water quality. In the field of air pollution and physical water, the provincial government is responsible for the payment and distribution of compensation funds between different cities. Applying the compensation policy to virtual water, we suggest that the central government establishes the cross-regional institution, and is responsible for the payment and distribution of compensation funds between Guangdong and Hunan. Meanwhile, the Water Conservancy Bureau is suggested to be responsible for the calculation of compensation funds between different regions.

This study has several limitations that can be improved in future research. First, we provide a static analysis of China's virtual water exports due to constraint of data. With restrictions on processing trade and the trade dispute in recent years, the export structure of China has changed. A temporal comparison of virtual water exports can be conducted in future research to identify the changes and their drivers. Second, as developed countries continue to move processing production from China to other developing countries, processing exports are playing increasingly important roles in other developing countries. The methodology presented in this paper is also suitable to analyze effects of trade heterogeneity on virtual water exports of other countries facing similar conditions. Third, the inter-regional trade not only influences water uses of different regions, but also influences other indicators such as carbon emissions and air pollutant emissions. The method in this study can be used to estimate effects of exports on other indicators such as carbon dioxide, air pollutants and energy. Finally, China uses domestic water resources to produce exported products. Meanwhile, China can save domestic water use by importing virtual water from other countries. In this paper, we focus on virtual water exports of China. A comparison of water resources embodied in exports and imports in future research can provide more comprehensive understandings of virtual water in China.

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