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Virtual Scarce Water in China

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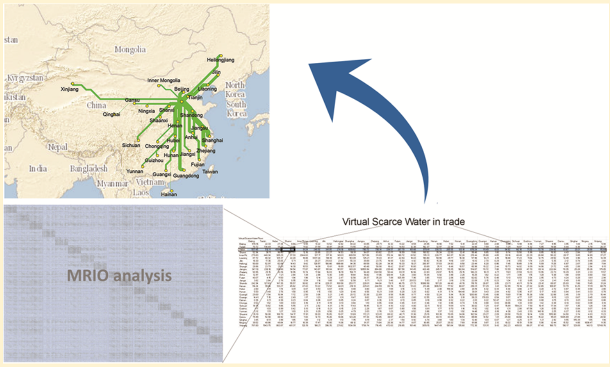
Supporting Information

ABSTRACT: Water footprints and virtual water flows have been promoted as important indicators to characterize human-induced water consumption. However, environmental impacts associated with water consumption are largely neglected in these analyses. Incorporating water scarcity into water consumption allows better understanding of what is causing water scarcity and which regions are suffering from it. In this study, we incorporate water scarcity and ecosystem impacts into multiregional input−output analysis to assess virtual water flows and associated impacts among 30 provinces in China. China, in particular its water-scarce regions, are facing a serious water crisis driven by rapid economic growth. Our findings show that inter-regional flows of virtual water reveal additional insights when water scarcity is taken into account. Consumption in highly developed coastal provinces is largely relying on water resources in the water-scarce northern provinces, such as Xinjiang, Hebei, and Inner Mongolia, thus significantly contributing to the water scarcity in these regions. In addition, many highly developed but water scarce regions, such as Shanghai, Beijing, and Tianjin, are already large importers of net virtual water at the expense of water resource depletion in other water scarce provinces. Thus, increasingly importing water-intensive goods from other water-scarce regions may just shift the pressure to other regions, but the overall water problems may still remain. Using the water footprint as a policy tool to alleviate water shortage may only work when water scarcity is taken into account and virtual water flows from water-poor regions are identified.



INTRODUCTION

China shows a huge disparity in distribution of water resources between the water-rich South and water-scarce North. With the fast growth of the economy and increasing water use for irrigation and industrial production, water scarcity has become a pressing issue. In particular, the water-scarce North China tends to produce water intensive goods for consumption in the South,[1] amplifying the serious water shortage in the North. To tackle this problem, the Chinese government initiated the gigantic South−North Water Transfer Project 12 years ago, aiming to divert water from the South to the North.[2] However, this project is estimated to cost more than 62 billion dollars with relocation of hundreds of thousands of people.[2] Although the water problem might be partially mitigated due to increasing water flows to the North, it is predicted to cause environmental impacts in southern China.[3] Directly using this water in the South to replace imports from the North would be more efficient from a water-saving and environmental point of view, but that might compete with the increasing comparative advantages for industrial production in the South.[4]

To provide information on allocation of water resources, the notions of virtual water flows have been introduced. With few exceptions,[5] virtual water studies mainly focus on water consumption without accounting for water scarcity. For example, by applying a multiregional input−output model, Zhang and Anadon (2014) calculated virtual water trade and water footprints at the provincial level in China.[6] However, their study focused on virtual water flow only, with all flows being treated equally without taking relative scarcity and environmental impacts of water flow into account. In reality, consuming the same amount of water in water-rich and water-scarce regions would have very different impacts on local water resources and ecosystems. Therefore, it is of fundamental importance to focus on virtual scarce water flows instead of the traditional virtual (neutral) water flows because what matters in water planning and management is the flow of virtual scarce water rather than neutral or abundant water. Consideration of water scarcity and environmental impacts is also required for a proper water footprint analysis as described in the draft and

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upcoming ISO standard on water footprint (ISO DIS 14046) and is a key factor for "Measuring Water use in a Green Economy" according to the corresponding UNEP report.[7] There are several other studies assessing water footprints in China. However, these studies either focus on a particular region[8−12] or on China as a whole.[13,14] In this study, we incorporate a water stress index (WSI) and an indicator for ecosystem damage[15] into the assessment of interregional virtual water flows across 30 Chinese provinces. By applying an economic trade model based on the multiregional input−output (MRIO) approach, we calculate both water footprints (WF) and scarce water footprints (SWF).

■ MATERIALS AND METHODS

There are two types of approaches which are frequently employed to calculate global virtual water flows. One is a bottom-up approach commonly used for Water Footprint accounting (e.g., Water Footprint Network[16]); the other is a top-down approach based on input−output analysis. The bottom-up approach estimates virtual water flows by calculating the virtual water content of goods (water used throughout the production process of a good) and associated international trade from detailed trade data.[17,18] It has become one of the most popular approaches in water footprint studies due to its relatively good data availability.[19−21] However, the bottom-up does not distinguish between intermediate and final users, in terms of water consumption. Therefore, it cannot comprehensively describe supply chain effects, which are crucial for allocating responsibility to the final consumer and identifying driving forces.[22] In addition, the bottom-up approach mainly concentrates on agricultural and food products but lacks detail on industrial and service products.[23,24] Environmental input−output analysis as a top-down approach calculates the water footprint through tracing the whole regional, national, or global supply chain depending on the accounting framework used. In the top-down approach, water consumed in production is allocated to final rather than intermediate consumers. However, a problem with the top-down approach is the aggregation of processes and products at the level of economic sectors and the relatively high aggregation level especially of different agricultural sectors due to the given data in national accounts.[22] In this study, we apply the top-down multiregional input−output approach to assess virtual water flows across 30 sectors and 30 Chinese provinces.

Water Stress Index and Ecosystem Impacts. Water stress is commonly defined as the ratio of total annual freshwater withdrawals to hydrological availability.[25,26] Pfister et al. (2009) advanced the water stress concept to calculate a water stress index, ranging from 0 (no stress) to 1 (maximum stress), following a logistic curve to represent commonly reported thresholds for water stress levels (see Pfister et al. (2009)[15] for a detailed description of the index). The WSI is used in many water footprint studies[27,28] following the draft ISO 14046 standard.[29] Other indicators for assessing water scarcity exist,[30] but they have lower spatial resolution or lack global coverage.

In addition, Pfister et al. (2009) calculated impacts on ecosystem quality in line with one of the most used Life Cycle Assessment (LCA) methods for impact assessment, the Eco-indicator 99 (EI99).[31] Depending on water resource availability, ecosystem type and climate conditions, the impacts of water consumption are reported as equivalents of land area loss for an ecosystem during a year (the area-time integral of the impact): the loss of ecosystem quality is quantified on the watershed level based on a conceptual framework accounting for vulnerability of the total ecosystem regarding water loss. For this purpose the share of net primary productivity (NPP) limited by water availability is used as a proxy for the share of ecosystem quality loss when depriving an area of its water. This proxy is consequently multiplied by the inverse of precipitation, which quantifies the area-time deprived of its water per volume of water consumed.

In this study, we applied Pfister et al.'s method to calculate WSI for each province in China. The WSI and ecosystem impact factors are obtained at ∼50 km grid cells (0.5 arc minutes resolution). To match the spatial detail of the MRIO table, the provincial WSI is calculated from the average value of the grid cells within the provincial boundary, weighted by the respective water consumption in each cell. The provincial fresh water consumption is then multiplied by the provincial WSI to derive provincial scarce water consumption.

Environmentally Extended Multiregional Input−Output Analysis. MRIO approach has been popular in water footprint studies.[5,22,32−38] In a MRIO framework, different regions are connected through inter-regional trade. The technical coefficient submatrix $A^{rs} = (a_{ij}^{rs})$ is given by $a_{ij}^{rs} = z_{ij}^{rs}/x_j^s$, in which z_{ij}^{rs} is the intersector monetary flow from sector i in region r to sector j in region s; x_j^s is the total output of sector j in region s. y^{rs} is a final demand vector of y_j^{rs} that reveals the final demand of region s for goods produced in region r. It is important to note that here the final demand is the sum of household consumption, government expenditure, capital formation, changes of inventory, and international export. Vector x represents total output of all economic sectors (x_j) in each region. Using matrix notation and dropping the subscripts, we have

$$A = \begin{bmatrix} A^{11} & A^{12} & \cdots & A^{1n} \\ A^{21} & A^{22} & \cdots & A^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A^{n1} & A^{n2} & \cdots & A^{nn} \end{bmatrix}$$

$$Y = \begin{bmatrix} Y^{11} & Y^{12} & \cdots & Y^{1k} \\ Y^{21} & Y^{22} & \cdots & Y^{2k} \\ \vdots & \vdots & \ddots & \vdots \\ Y^{n1} & Y^{n2} & \cdots & Y^{nk} \end{bmatrix} \quad x = \begin{bmatrix} x^1 \\ x^2 \\ \vdots \\ x^n \end{bmatrix}$$

Here, A is a 900 by 900 matrix; Y is a 900 by 30 matrix; x is a column vector with 900 cells. Consequently, the MRIO framework can be written as $x = Ax + Y$, and we have $x = (I - A)^{-1}Y$, where $(I - A)^{-1}$ is the Leontief inverse matrix which captures both direct and indirect inputs to satisfy one unit of final demand in monetary value; I is the identity matrix. To calculate the embodied water in the goods and services, we extend the MRIO table with environmental extensions by using water consumption and water scarcity. Consumptive water footprint (CWF) is calculated as

$$\mathrm{CWF} = k_c(I - A)^{-1}Y \tag{1}$$

where CWF is total water consumption or water footprint associated with the production of goods and services along the whole national supply chain triggered by final consumption; k_c is a row vector of water consumption per unit of economic

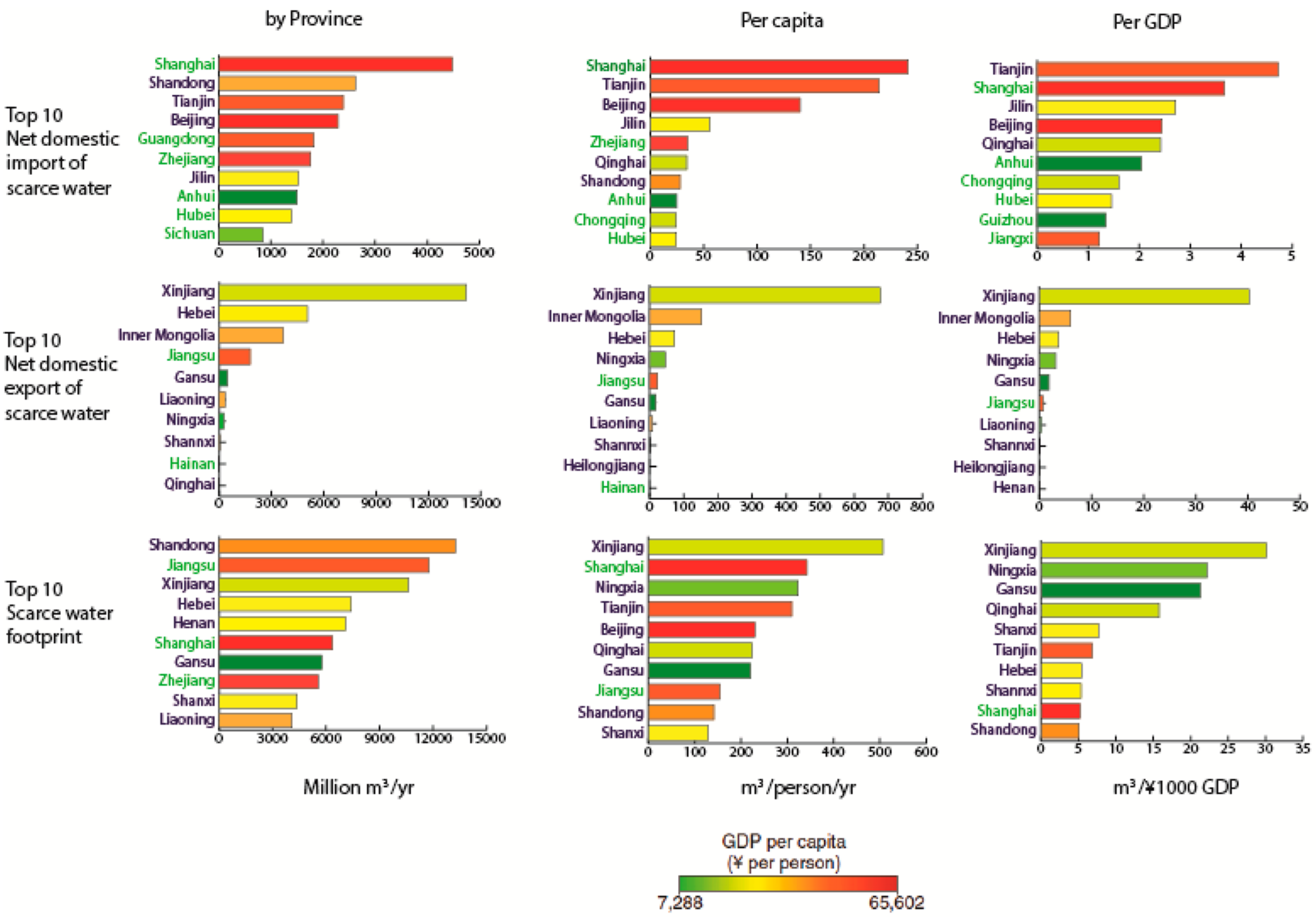

Figure 1. Top 10 provinces by net domestic import of scarce water (row 1), net domestic export of scarce water (row 2), and domestic scarce water footprint (row 3), all presented as regional totals (left column), per capita (center column), and per GDP (right column). Dark blue names indicate provinces in north China, whereas light green indicates provinces in south China. The colors of the bars reflect GDP per capita in each region.

output for all economic sectors in all regions. Similar to the calculation for CWF, the scarce water footprint (SWF) is calculated by

$$\mathrm{SWF} = k_s(I - A)^{-1}Y \quad (2)$$

where k_s is a vector of scarce water consumption per unit of economic output for all economic sectors in all regions. In this paper, we also calculate the impacts of water consumption on ecosystem quality by eq 3

$$\mathrm{EI} = k_e(I - A)^{-1}Y \quad (3)$$

where k_e is a vector of ecosystem impacts of water consumption per unit of economic output for all sectors.

Virtual Water in Trade. Although eq 1 captures the total direct and indirect water consumption associated with the final demand of a region, it may not be able to make a distinction between the water for final consumption from the local and virtual water import. To calculate the import of virtual water from region r to region s, we modify eq 1 to

$$\mathrm{VW}^{rs} = \tilde{k}^{r}(I - A)^{-1}y^{\cdot s} \quad (4)$$

where VW^{rs} represents the total virtual water flows from region r to region s to satisfy the final consumption of regions s; $\tilde{k}^{r}$ is a vector of the corresponding sectoral water coefficients with the sectoral water coefficients for region r but zeros for all other regions; $y^{\cdot s}$ is the final demand vector of region s. Here, we use the same method to calculate the embodied scarce water and ecosystem impacts in inter-regional trade.

Data Sources. In this study, the 2007 China MRIO tables, which include 26 provinces and 4 city-regions, excluding Tibet and Taiwan, are used.[39] For convenience, we use province as a general term of a Chinese region. The MRIO tables were constructed based on 30 provincial input−output tables and estimated inter-regional trade flows. The inter-regional trade flow matrix for 30 sectors and 30 provinces was estimated using the well-known gravity model of Leontief and Strout (1963)[40] and augmented in line with LeSage and Pace (2008)[41] and Sargento (2009).[42] The 30 regions multiregional input−output table was provided by Liu (2012).[39]

Provincial water withdrawal at sector level was collected from China Economic Census Yearbook 2008.[43] However, note that the water withdrawal can be much larger than water consumption (referred to as blue water[44]) because the latter includes only water that cannot directly return back to the local ecosystem and consequently becomes unavailable for other users within a given time period (e.g., one year).[9] In this study, water consumption was estimated based on an observed ratio of water consumption to water withdrawal in each river basin and for each sector: To estimate sectoral water consumption for each province, we multiply the sectoral water withdrawal of each province by the ratio of water withdrawal to water consumption in the agricultural, industrial, service and domestic

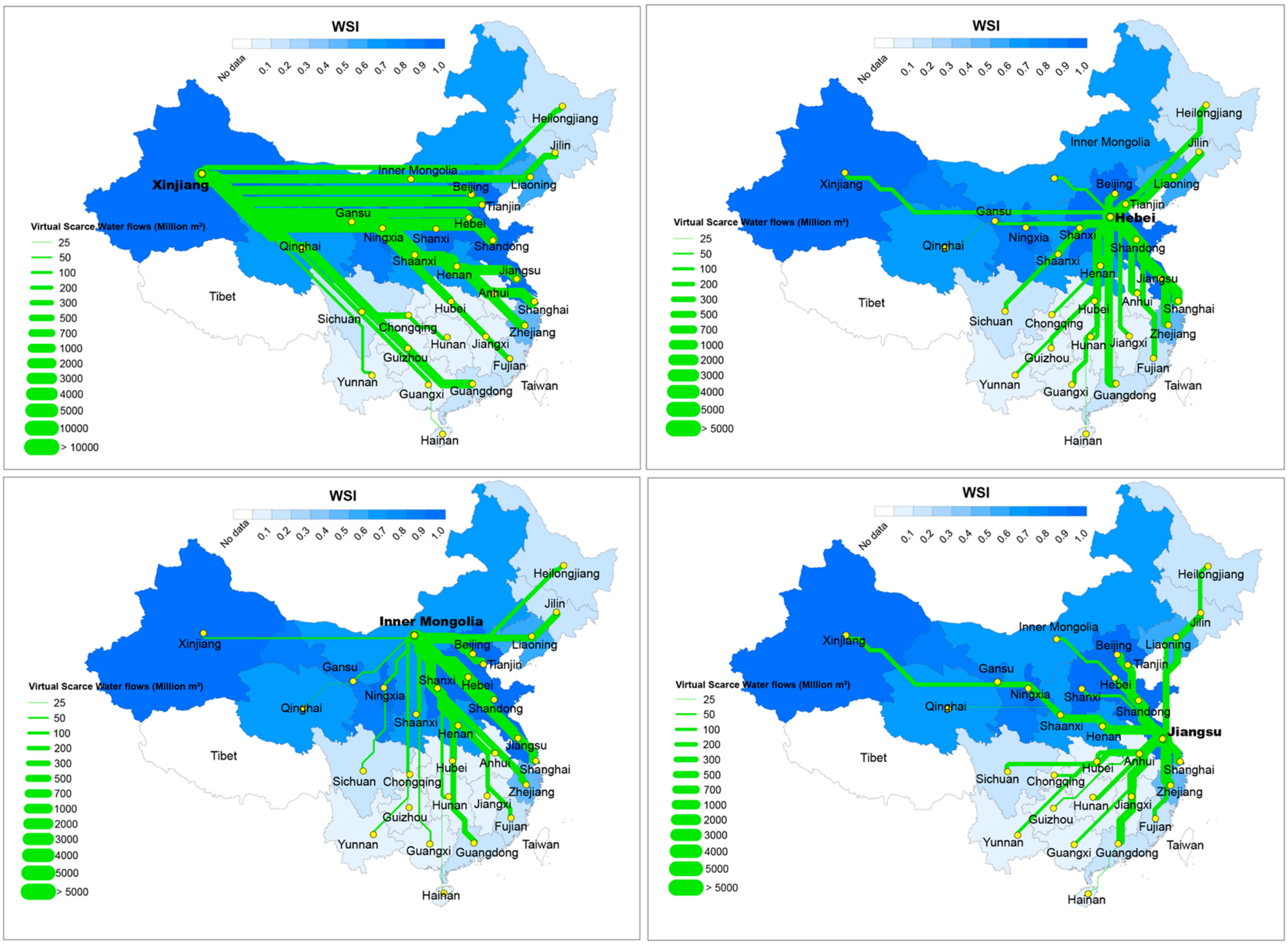

Figure 2. Virtual scarce water flows from top four virtual water exporting provinces Xinjiang, Hebei, Inner Mongolia and Jiangsu (in million m^3).

sectors of that province, thereby assuming that the ratio of the specific sector is the same as for the aggregate sector (see Supporting Information Table S1 for details on the share of water consumption by aggregate sectors). The ratios were estimated based on Water Resource Bulletins of different river basins (e.g., Yellow River Water Resource Bulletin[45]) and provincial Water Resource Bulletins (e.g., Liaoning Water Resource Bulletin[46]). Watersheds ratios have been attributed to provinces by overlapping the provincial maps and the river basin maps. We directly adopted the water consumption ratios of a river basin if the province is largely located within the basin. However, for the provinces overlapped with more than one basin, we weighted the ratios based on the overlapping areas.

Shortcomings. There are some shortcomings in our approach for virtual water flow analysis. Our approach is limited to administrative boundaries rather than catchment boundaries because of data availability. In addition, our analysis shares a particular shortcoming with virtually every input–output analysis referred to as sectoral aggregation error. For example, all agricultural products, such as rice, wheat, corn, and others, are aggregated into one agricultural sector. Water requirements for different crops are clearly different, and averaging out all crops in terms of water use may under- or overestimate the water requirements and, thus, the virtual water flows via inter-regional trade. Therefore, improving sectoral resolution in the MRIO table would lead to more accurate estimation of virtual water flows.

■ RESULTS

In 2007, 109 billion m^3 of virtual water were traded across Chinese provinces, which accounted for about 40% of total water consumption. Rich provinces with large populations, such as Jiangsu, Guangdong, Shandong, Zhejiang, and Shanghai, are ranked at the top in terms of consumptive water footprint (CWF) mainly due to the large quantity of goods and services imported from other provinces for local consumption, and more strikingly, their CWF is much larger than their local water consumption. However, in terms of scarce water footprint (SWF), the majority of high-ranking provinces are in the water scarce North. For example, Xinjiang is ranked as the third largest province in terms of SWF, as it is one of the most water-scarce provinces in China. Many provinces in the south of China, such as Guangdong, Fujian, Hunan and Jiangxi, have large CWF, but their SWF is relatively small due to their relative abundant water resources and compensating imports from water scarce regions (see Supporting Information Figure S1).

Figure 1 shows that the rich coastal provinces, such as Shanghai, Shandong, Guangdong, Tianjin, Beijing, and Zhejiang, are ranked at the top in terms of net scarce water import. Jiangsu is one of the richest coastal provinces in China

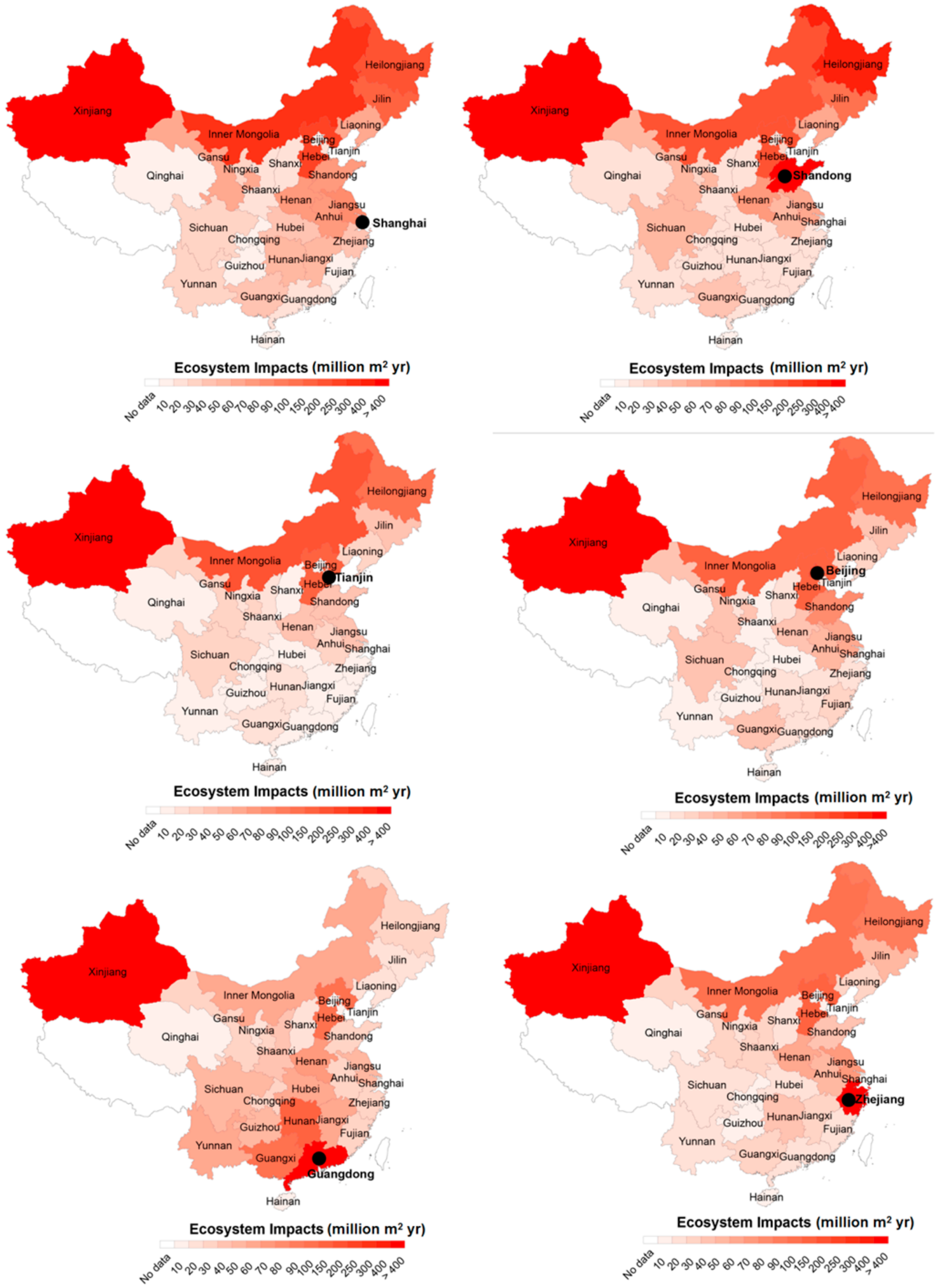

Figure 3. Distribution of ecosystem impacts of domestic consumption by the top six net scarce water importers Shanghai, Shandong, Tianjin, Beijing, Guangdong, and Zhejiang (in million m^2 per year).

with large net imports of water. However, in terms of virtual scarce water (VSW), the province becomes one of the largest net exporters. In contrast, the less developed but water scarce provinces, such as Xinjiang, Hebei, and Inner Mongolia, are ranked as the top three net VSW exporters.

In the per-capita and per-GDP analysis, the three mega cities, Tianjin, Shanghai, and Beijing, are the top net importers of scarce water. The water scarce provinces, Xinjiang, Inner Mongolia, and Ningxia are the top three in terms of the net domestic exports of scarce water, per capita, and per GDP. Of the top ten regions concerning scarce water footprints, eight are provinces in the water-scarce North, the other two, Jiangsu and Shanghai, are in the South but are also facing serious water scarcity.

To further trace to what locations scarce water is virtually exported, we present the maps of VSW flows via inter-regional

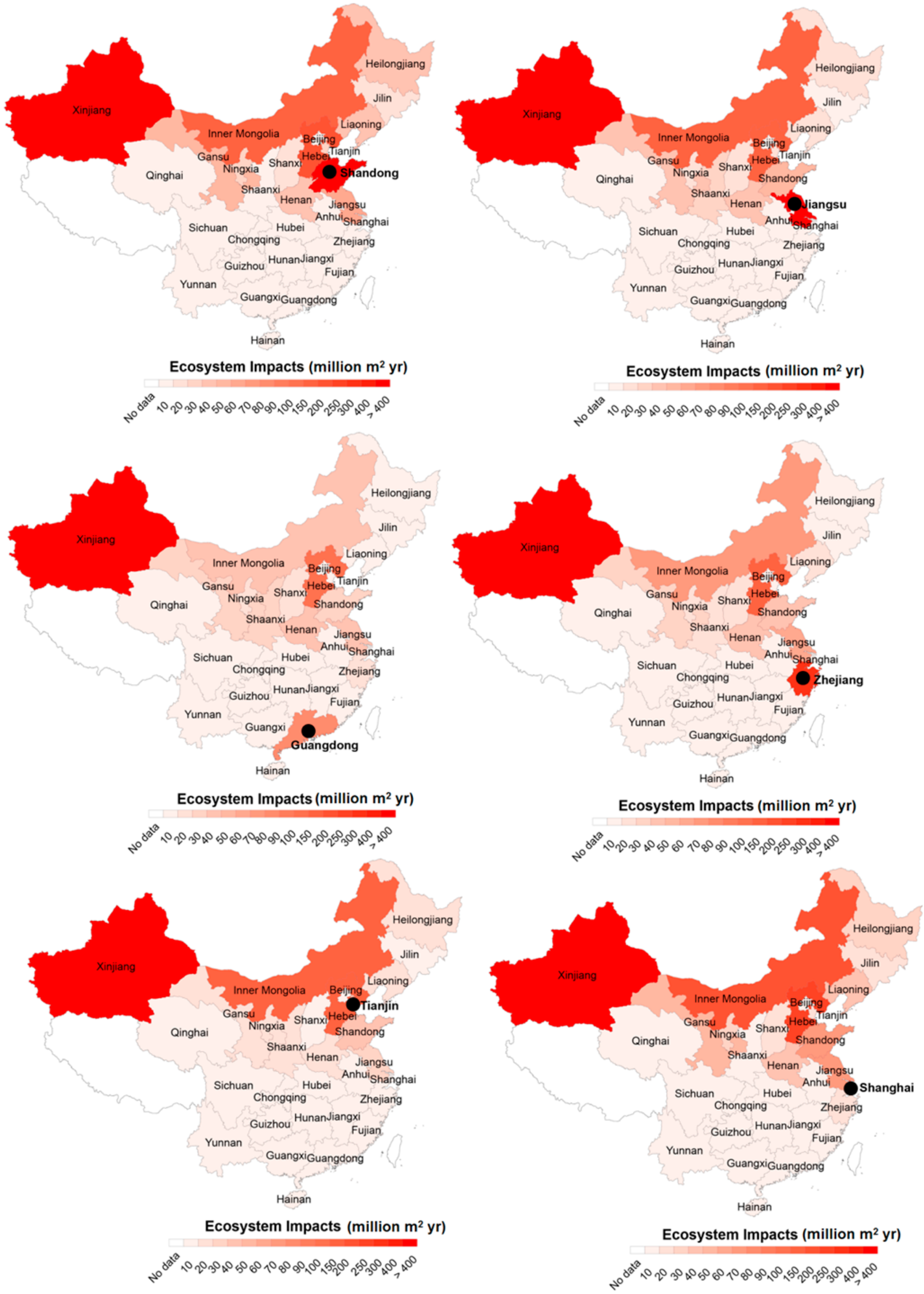

Figure 4. Distribution of ecosystem impacts of international exports by the top six international exporters Shandong, Jiangsu, Guangdong, Zhejiang, Tianjin and Shanghai (in million m^2 per year).

trade from the top four net VSW exporters, Xinjiang, Hebei, Inner Mongolia, and Jiangsu in Figure 2. We can see that water scarce northern provinces, such as Xinjing, Hebei, and Inner Mongolia, export a large amount of VSW to other provinces, in particular the eastern coastal provinces, such as Shandong, Shanghai, Tianjin, and Zhejiang. In addition, Jiangsu, the fourth largest VSW exporter located in the South, not only exports a large amount of VSW to the eastern coastal provinces, such as Shandong, Shanghai, Tianjin, and Zhejiang, but also supports the economic growth in the southern coastal provinces, such as Guangdong, at expense of its domestic water resources depletion.

In addition to mapping virtual water flows across Chinese provinces, we also map the spatial distribution of ecosystem

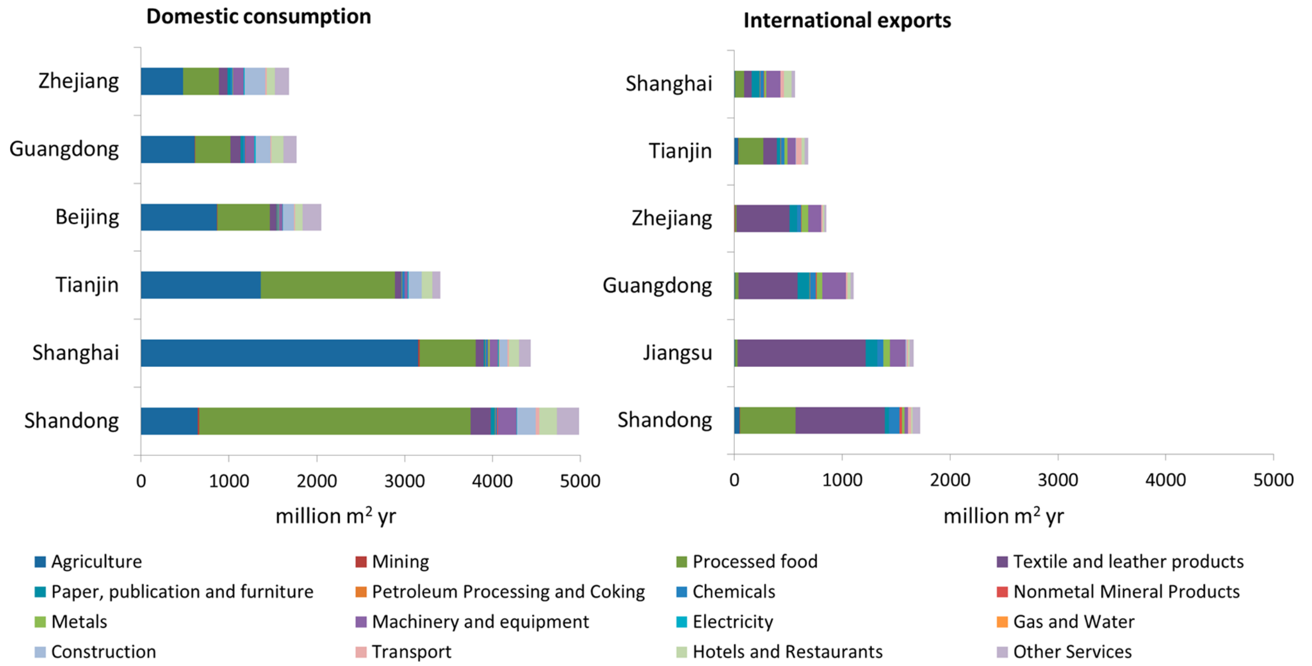

Figure 5. Ecosystem impacts embedded in inter-regional trade triggered by regional domestic consumption and international export (in million m^2 per year). Bar chart on the left shows the top six provinces in terms of ecosystem impacts in other Chinese provinces induced by regional domestic consumption. The bar chart on the right shows the top six regions in terms of ecosystem impacts in other Chinese provinces induced by regions' international export. The colors of the bar indicate the products for domestic final consumption which triggered imports and ecosystem impacts in other regions (left) and the products for international export which triggered imports and ecosystem impacts in other regions (right).

impacts associated with CWF. Figure 3 presents the spatial distribution of ecosystem impacts as a consequence of consumption of the top six importers of net scarce water (Shanghai, Shandong, Guangdong, Tianjin, Beijing, and Zhejiang). Consumption in northern China, such as Shandong, Tianjin, and Beijing, mainly causes impacts on ecosystems in the northern provinces, such as Xinjiang, Inner Mongolia, Hebei, Heilongjiang, and Jilin. Although Heilongjiang and Jilin are not considered as being water scarce regions, the large amount of water exported to other regions via inter-regional trade still leads to serious impacts on domestic ecosystems of these two provinces. The consumption in Shanghai and Zhejiang exerts also significant impacts on some provinces in Central China, such as Anhui and Hunan besides those highlighted in north China. The ecosystem impacts of consumption in the southern coastal province Guangdong affects mainly the south and southwest provinces, such as Guangxi, Hunan, Yunnan, and Guizhou, due to their strong trade ties with Guangdong. Xinjiang is largely affected in terms of ecosystem impacts caused by production for consumption in the highly developed provinces.

A large proportion of ecosystem impacts in the coastal provinces are caused by production for international exports. Figure 4 shows the distribution of ecosystem impacts of international exports by the top six international exporters. All top international exporting provinces trigger significant ecosystem impacts on the northern provinces through importing goods from these provinces for re-export. For example, international export in Guangdong, which is located in the far south, results in significant ecosystem impacts in the northern provinces but to a lesser extent in the surrounding provinces. However, in terms of value added triggered by its international exports, Guangdong received 72% of the total value added, but Xinjiang and Inner Mongolia received less than 1% of the total.

To better understand the ecosystem impacts associated with inter-regional trade patterns, we further distinguish the ecosystem impacts in inter-regional trade for domestic consumption and international export by products. Figure 5 shows the extent at which the consumption of different products in the rich coastal provinces causes ecosystem impacts in other provinces via inter-regional supply chains. For example, we see that to meet domestic consumption, Shanghai imports a large amount of agricultural products (thus outsourcing the associated ecosystem impacts) due to the very limited agricultural production within Shanghai but imports a relatively small proportion of processed food due to its own high capacity of food processing. In contrast, Shandong imports a large amount of processed food, which outsources the associated ecosystem impacts. It is worth noting that although Shandong is one of the major crop production provinces in China, its food processing capacity is insufficient and furthermore it still needs large imports to meet the consumption of its huge population. All other top importing provinces, Tianjin, Beijing, Guangdong, and Zhejiang, have a relatively equal share of ecosystem impacts embedded in the imports of agricultural and processed food products. Ecosystem impacts associated with the imports of nonagricultural products for domestic consumption is relatively small. In contrast to the above patterns, ecosystem impacts embedded in inter-regional trade triggered by international exports looks very differently. For example, the top sector becomes textile and leather products in Jiangsu, Guangdong, Zhejiang, and Shandong because these provinces are the major textile and leather exporters to foreign countries, such as the U. S., Europe, and other developed countries. Therefore, these provinces import a large amount of goods from other provinces to produce products for their international exports, thus causing ecosystem impacts in other provinces. For example, international exports in Shandong contribute to 26% of its total consumption-based ecosystem impacts and the corresponding percentage share is 39% in Guangdong. In Tianjin, international exports of processed food, textiles, and leather products create the higher impacts on ecosystems outside Tianjin, whereas in Shanghai, the export of machinery and equipment are the dominant drivers of ecosystem impacts outside Shanghai.

■ DISCUSSION

To mitigate the pressing issue of water scarcity in the northern provinces of China, a theoretically consistent and practically accurate accounting of virtual scarce water flows is of fundamental importance to informing water management. However, such an important accounting assessment has largely been missing in the literature. In this study, we incorporated water consumption, water scarcity and ecosystem impacts into the MRIO analysis to identify the routes conveying pressures on water resources and ecosystems from centers of consumption to regions of water scarcity. This adds value to the literature on virtual water research and allows tracking flows from consumption to production to impacts within supply chains across provinces and watersheds. Our results show that inter-regional flows of virtual water look significantly different when water scarcity is taken into account. This demonstrates the importance of considering water scarcity in assessing virtual water flows. From a water management perspective, water scarce regions might want to consider virtual water imports to mitigate local water scarcity.

Several studies have highlighted that water-scarce regions could decrease their production of water intensive food commodities to alleviate their water scarcity problems by producing instead goods and services with higher value added per unit of water consumed.[47−49] In this study, our findings reveal that many developed but water-scarce provinces, such as Shanghai, Shandong, Beijing, and Tianjin, are already large net virtual water importers but at the expense of water resource depletion in other water-scarce provinces, such as Xinjiang, Inner Mongolia, and Hebei. Therefore, increasing virtual water flows across these water scarce regions would not mitigate the problem of water shortage in Northern China but simply shift the problem from the coastal to inland regions. Instead, these less-developed but water scarce regions could limit their exports of scarce water by reducing export of water intensive goods, such as agricultural products and processed food. In this way, the overall pressure on water resources in water-scarce Northern China could be reduced. The above discussion indicates that using virtual water as a policy tool to alleviate water shortage may only work when water scarcity is taken into account and virtual water flows from water-rich regions are identified and quantified. Finally, local integrated water resource management needs to be applied to evaluate the most promising options, combining local circumstances and the big picture provided by scarce virtual water flows.

Our findings also show that the consumption in developed coastal provinces is heavily dependent on water resources in the water scarce northern provinces, and this dependence further aggravates water scarcity in these inland regions. With the continuing fast growth of China's economy and large scale urbanization, consumption in the developed coastal provinces is most likely to keep increasing in the next few decades. In a business-as-usual scenario, this trend would exert additional pressure on water resources in Northern China. For example, although water scarcity in the northeast provinces, such as Heilongjiang and Jilin, is not as serious as in other northern provinces, the large and increasing demand from other regions for water-intensive goods produced in these two provinces have caused considerable impacts on local ecosystems (see Figure 4). Future increasing demand for virtual water exports may push the northeast regions toward higher levels of water scarcity. In fact, Heilongjiang has become one of the largest virtual water exporters and its exports of water intensive goods, such as rice, to satisfy the demand of other provinces have increased enormously in recent decades. This has put unprecedented pressure on local water resources and ecosystems. Thus, environmental policies should aim not only to reduce water consumption in water scarce regions but also to prevent water-rich regions becoming water scarce by limiting their water withdrawal to a sustainable level.

The overuse of water resources typically has severe consequences on ecosystem quality. The rich coastal provinces gain economic profits from international exports at the expense of ecosystem quality in the less developed regions, such as Xinjiang, Hebei, and Inner Mongolia. For example, the international exports of Zhejiang induced only 20% of the total ecosystem impacts on its local ecosystem but outsourced the rest to other regions, in particular to Northern China, such as Xinjiang (40% of the total ecosystem impacts), Hebei (7%), and Inner Mongolia (5%). However, in terms of the share of value added triggered by international exports, Zhejiang received 68% of the total value added but Xinjiang and Inner Mongolia only received about 1% of the total, respectively. Without local awareness and forceful policy support from China's central government, the ecosystem quality in the water scarce regions would be further degraded, and this would result in problems to human health and potentially to social stability. A uniform environmental tax across Chinese provinces on the impacts of ecosystem quality, and giving special consideration to ensuing social equity issues, may help because it relocates profits from rich regions to the poor regions for local environmental protection. In this way, the cost of mitigating ecosystem degradation would be shared by affluent consumers in coastal China who would pay more for goods and services imported from less-developed regions and consequently pay for part of the external costs.

Wichelns (2010) pointed out that the virtual water perspective cannot be used alone without considering the "comparative advantages" of other factors, such as production technologies and opportunity costs.[50] Our results show that the water scarce northern provinces export water intensive goods to the water rich South despite a comparative disadvantage in terms of water availability. However, this trend was largely driven by the increased comparative advantage for industrial production in the South, which increased the opportunity costs of agricultural production in the South and pushed agricultural production to the North. This northward movement was facilitated by the progress in irrigation technologies, which allowed the North to better mine underground reservoirs for agriculture use at low cost. For example, the groundwater abstraction ratio is higher than 67% in the northern basins, whereas this ratio is only about 8% in the southern basins.[51] Such heavy dependence on groundwater withdrawn to some extent reduced the disadvantages of water shortage in the North over the short-term but will cause severe water scarcity and ecosystem damage in the long term. Therefore, governmental development policies are advised to carefully consider the trade-off of water availability between the short-term and long-term, and again the notions of virtual water and water stress may serve as suitable tools to balance such trade-offs.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Additional figures for local water consumption and consumptive water footprint and net virtual water flows. This material is available free of charge via the Internet at http://pubs.acs.org."

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Notes

The authors declare no competing financial interest.

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