Article Type: Research and Analysis

Title: Identifying Sectoral Impacts on Global Scarce Water Uses from Multiple Perspectives

Authors: Xuechun Yang [1], Sai Liang [2,*], Jianchuan Qi [2], Cuiyang Feng [1], Shen Qu [3,4], Ming Xu [5,6]

Institutions:

[1] School of Environment, Beijing Normal University, Beijing 100875, People's Republic of China.

[2] Key Laboratory for City Cluster Environmental Safety and Green Development of the Ministry of Education, Institute of Environmental and Ecological Engineering, Guangdong University of Technology, Guangzhou, Guangdong 510006, People's Republic of China.

[3] School of Management and Economics, Beijing Institute of Technology, Beijing 100081, People's Republic of China.

[4] Center for Energy & Environmental Policy Research, Beijing Institute of Technology, Beijing 100081, People's Republic of China.

[5] School for Environment and Sustainability, University of Michigan, Ann Arbor, Michigan 48109-1041, United States.

[6] Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, Michigan 48109-2125, United States.

* **Corresponding author**:

This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1111/jiec.13171.

Sai Liang, Key Laboratory for City Cluster Environmental Safety and Green Development of the Ministry of Education, Institute of Environmental and Ecological Engineering, Guangdong University of Technology, Guangzhou, Guangdong 510006, People's Republic of China.

Email: liangsai@gdut.edu.cn

Conflict of Interest Statement: The authors declare no conflict of interest.

Abstract:

Scarce water uses driven by hotspots in production and consumption stages of global supply chains have been well studied. However, hotspots in primary inputs and intermediate transmission stages also leading to large amounts of global scarce water uses are overlooked. This gap can lead to the underestimation of the impacts of certain nation sectors on global scarce water uses. This study identifies critical primary suppliers and transmission centers in global supply chains contributing to scarce water uses, based on environmentally extended multi-regional input-output (EE-MRIO) model and complex network analysis methods. Results show that some critical primary suppliers (e.g., the *service auxiliary to financial intermediation* sector in the U.S. and the *financial intermediation services* sector in India) and transmission centers (e.g., the *raw milk* sector in the U.S. and the *transmission services of electricity* sector in China) are unidentifiable in previous studies. These findings provide hotspots for supply-side measures (e.g., optimization of primary input and product allocation behaviors) and productivity improvement measures. The critical inter-sectoral transactions (mainly involving the agricultural and food products sectors in India, China, and the U.S.) further provide explicit directions for these measures. Moreover, this study conducts a

community detection, which identifies communities (i.e., the clusters of nation sectors closely interconnected) leading to global scarce water uses. Most of the communities involve sectors from different nations, providing foundations for international cooperation strategies.

Keywords: Scarce water use, primary input, betweenness, multi-regional input-output analysis, network analysis, industrial ecology

1. INTRODUCTION

Water is an essential resource to human beings and ecosystems (Baron et al., 2002). The increasing population and intensified human activities have resulted in large amounts of water uses and induced water scarcity (Mekonnen & Hoekstra, 2016; Veldkamp et al., 2017; Vorosmarty et al., 2000). Water scarcity is threatening the health of ecosystems and economic systems, and is receiving more and more attention (Hoekstra, 2014). It is crucial to identify critical human activities for policy decisions on mitigating water scarcity. This identification can provide more explicit directions for water policies, thereby strengthening the policy effects.

Water scarcity reflects the environmental impacts of water uses (Lenzen et al., 2013; Pfister et al., 2011; Pfister et al., 2009). Water scarcity also considers the regional heterogeneity, given that the climate conditions of various geographical regions are different. Therefore, the environmental impacts of equal amounts of water uses in different regions are distinctly different (Pfister et al., 2011). The global water scarcity is considered as the sum of scarce water uses of nations around the world. Scholars have developed various metrics to describe water scarcity of nations and regions, such as basic human water requirements (Gleick, 1996) and water stress index (FAO, 2016; Pfister et al., 2009). These metrics have been further applied in quantifying direct scarce water uses (Lenzen et al., 2013; Veldkamp et al., 2017; Wang et al., 2020). Direct scarce water uses can identify critical nation sectors with high water scarcity. They can support the cleaner production measures (e.g., restricting water consumption and improving water use efficiency) on the mitigation of water scarcity (a.k.a. production-side measures).

International trade of goods and services leads to the flows of scarce water embodied in traded commodities. Local scarce water uses are not only influenced by local production and consumption activities but also driven by distant consumers through global supply chains (Lenzen et al., 2013; Qu et al., 2018). The virtual scarce water flows have been quantified by input-output (IO) analysis to highlight the impacts of trade on local water scarcity. These studies reflect the interconnections among various regions (Feng et al., 2014; Lenzen et al., 2013; Wang et al., 2020; Zhao et al., 2018). Scholars have also analyzed the water scarcity footprints of nations and regions using IO analysis, which emphasize the impacts of consumption activities on regional water scarcity (Liao et al., 2020; Ridoutt et al., 2018). Moreover, Zhang et al. (2017) construct a node-flow model to quantify the scarce water embodied in trade. These studies help identify critical final consumers for demand-side measures (e.g., the optimization of consumption behaviors).

In addition to the production and final consumption stages, there are also other stages (e.g., primary inputs and intermediate transmission stages) playing important roles in global supply chains, which can inform different policy implications. For example, a supply chain starts from sector A, passes through sector B, and ends at sector C (Figure 1). The production-based method can identify sectors A, B, and C for production-side measures, and consumption-based method can identify final consumers (i.e., sector C driving scarce water uses of the whole supply chain) for demand-side measures. However, the indirect effects of sectors A and B on scarce water uses of the whole supply chain are overlooked. The primary inputs (e.g., labor and capital) of sector A enable downstream scarce water uses w_2 and w_3 (Lenzen

& Murray, 2010; Marques et al., 2012). If w_2 and w_3 were much larger than w_1, the importance of sector A would be underestimated by production-based and consumption-based methods. Sector A plays the role of primary supplier in the supply chain. Scarce water uses enabled by primary inputs of the primary supplier can be quantified by the income-based method. Supply-side measures (e.g., optimizing primary input and product allocation behaviors (Chen et al., 2019; Liang et al., 2016; Qi et al., 2019)) can be implemented in the stage of sector A to reduce scarce water uses of the whole supply chain. The importance of sector B would be underestimated by production-based and consumption-based methods if w_1 was large. Sector B plays an important transmission role for embodied scarce water in the supply chain. Improving the productivity of sector B (i.e., using less inputs from sector A to produce unitary output) can help reduce scarce water uses of the whole supply chain (Liang et al., 2016). Another example is shown in Figure S1 in the Supporting Information 1. Unfortunately, existing studies on global scarce water uses overlooked the primary suppliers (identified by income-based method (Lenzen & Murray, 2010; Liang et al., 2016; Marques et al., 2012)) and transmission centers (identified by betweenness-based method (Hanaka et al., 2017; Liang et al., 2016)).

Insert Figure 1 here.

This study fulfils the above knowledge gaps by identifying critical nation sectors for global scarce water uses from multiple perspectives (i.e., production-based, consumption-based, income-based, and betweenness-based methods). It integrates global environmentally extended multi-regional input-output (EE-MRIO) model and complex network analysis methods to identify critical nation sectors, critical inter-sectoral transactions, and major communities (i.e., the clusters of nation sectors closely interconnected through inter-sectoral transactions of embodied scarce water) for global scarce water uses.

2. METHODS

2.1. Direct scarce water uses of nation sectors

The water stress index (WSI) proposed by Pfister et al (2009) is used to calculate scarce water uses of nation sectors. For nation i, scarce water uses are quantified by Equation (1).

$$p_k^i = WSI^i q_k^i \tag{1}$$

The notation p_k^i (unit: billion m^3) indicates the scarce water use of sector k ($k = 1, 2, \cdots, n$) in nation i; WSI^i, a dimensionless parameter, represents the WSI of nation i; and q_k^i (unit: billion m^3) means the water use of sector k in nation i (Lenzen et al., 2013). The water uses of nation sectors are blue water consumption in this study.

2.2 The multiple-perspective framework

Critical nation sectors in this study include hotspots with direct scarce water uses (identified by the production-based method), final consumers driving upstream scarce water uses (identified by the consumption-based method), primary suppliers enabling downstream scarce water uses (identified by the income-based method), and transmission centers transferring embodied scarce water in global supply chains (identified by the betweenness-based method). The production-based method measures direct scarce water uses of nation sectors, which is the satellite account of the global EE-MRIO model (Miller & Blair, 2009). The consumption-based method evaluates direct and indirect upstream scarce water uses caused by the final demand of nation sectors (Leontief, 1936; Miller & Blair, 2009) (Equation (2)). The income-based method examines both direct and indirect downstream scarce water uses enabled by primary inputs of nation sectors (Chen et al., 2019; Dietzenbacher, 1997; Lenzen & Murray, 2010; Liang et al., 2016; Marques et al., 2012; Qi et al., 2019) (Equation (3)). Critical transmission centers identified by the betweenness-based method are those with high node betweenness. In network analysis, node betweenness measures the flow of information passing through a certain node (Freeman, 1977; Freeman, 1978). Thus, the betweenness-based method investigates the quantity of embodied scarce water passing through each nation sector (Liang et al., 2016; Tokito, 2018). Intermediate inputs to critical transmission centers contribute to large amounts of upstream scarce water uses (Equation (4)).

$$\mathbf{c} = \mathbf{f}\,(\mathbf{I} - \mathbf{A})^{-1}\,\hat{\mathbf{y}} \tag{2}$$

$$\mathbf{s} = \hat{\mathbf{v}}\,(\mathbf{I} - \mathbf{B})^{-1}\,\mathbf{f}' \tag{3}$$

$$b_i = \mathbf{f}\,\mathbf{T}\,\mathbf{J}_i\,\mathbf{T}\,\mathbf{y} = [\mathbf{f}\,\mathbf{A}\,(\mathbf{I} - \mathbf{A})^{-1}]_i\,[\mathbf{A}\,(\mathbf{I} - \mathbf{A})^{-1}\,\mathbf{y}]_i \tag{4}$$

$$\mathbf{f} = \mathbf{p}\,(\hat{\mathbf{x}})^{-1} \tag{5}$$

The notation **p** indicates the direct scarce water use of each nation sector (i.e., production-based scarce water uses); **f** is the national-sectoral intensity vector for scarce water uses, and **f**' is the transpose of vector **f**; **x** is a $n\times1$ column vector indicating the total output of each nation sector; **c** represents upstream scarce water uses caused by the final demand of products from nation sectors (i.e., consumption-based scarce water uses); **I** is an identity matrix; **A** stands for the direct input coefficient matrix; the $n\times1$ column vector **y** indicates the final demand of nation sectors; **s** represents downstream scarce water uses enabled by primary inputs of nation sectors (i.e., income-based scarce water uses); the $1\times n$ row vector **v** represents the primary inputs of each nation sector; **B** stands for the direct output coefficient matrix; $\hat{\mathbf{x}}$, $\hat{\mathbf{y}}$, and $\hat{\mathbf{v}}$ are diagonal matrixes for vectors **x**, **y**, and **v**, respectively; b_i means the betweenness of nation sector i; and $\mathbf{J}_i$ is a matrix with the $(i, i)^{\text{th}}$ element being 1 and other elements being 0.

The indirect input coefficient matrix **T** is calculated by Equation (6).

$$\mathbf{T} = \mathbf{A}\,(\mathbf{I} - \mathbf{A})^{-1} \tag{6}$$

2.3. Centrality of inter-sectoral transactions

This study also identifies critical inter-sectoral transactions transmitting large amount of embodied scarce water in global supply chains. The centrality of the transaction from sector *s* to sector *t* (hereinafter called the transaction *s→t*) indicates the total scarce water uses in upstream sectors of sector *s* triggered by downstream sectors of sector *t*, passing through the transaction *s→t* (Hanaka et al., 2017). Thus, the centrality of the transaction *s→t* is measured by scarce water uses of all the global supply chain paths directly passing through this transaction.

The centrality of the transaction *s→t* can be quantified by Equation (7).

$$b_{st} = [\mathbf{f}\,(\mathbf{I} - \mathbf{A})^{-1}]_s\, a_{st}\, [(\mathbf{I} - \mathbf{A})^{-1}\, \mathbf{y}]_t = [\mathbf{f}\,(\mathbf{I} - \mathbf{A})^{-1}]_s\, a_{st}\, x_t \tag{7}$$

The notation b_{st} indicates the centrality of the transaction from sector *s* to sector *t*; and a_{st} represents the input from sector *s* directly required to produce unitary output of sector *t*. The notation $[\mathbf{f}\,(\mathbf{I} - \mathbf{A})^{-1}]_s$ indicates the scarce water uses in the upstream sectors of sector *s* driven by unitary output of sector *s*; $[(\mathbf{I} - \mathbf{A})^{-1}\, \mathbf{y}]_t$ represents the output of sector *t* driven by the final demand of downstream sectors; and x_t represents the total output of sector *t*.

2.4. Community Detection

This study uses the modularity maximization algorithm (Newman, 2004) to detect the community structure of the input-output based global virtual scarce water network. A community is a cluster of nodes among which interconnections are dense. Nodes in the same community have stronger relationships with one another than with nodes in other communities. The modularity maximization algorithm divides the network into communities that present high values of modularity over all possible divisions of the network. There are multiple ways to define the adjacency matrix for community detection (Kagawa et al., 2013; Kagawa et al., 2015). In this study, we employ the concept of environmental footprint to define the adjacency matrix. The embodied scarce water matrix is used as the adjacency matrix.

Based on the global MRIO model, the global virtual scarce water network **W** is constructed by Equation (8).

$$\mathbf{W} = \hat{\mathbf{f}}\,(\mathbf{I} - \mathbf{A})^{-1}\,\hat{\mathbf{y}} \quad (8)$$

The notation **W** indicates a matrix with element w_{ij} representing the transfer of embodied scarce water from sector *i* to sector *j*; and $\hat{\mathbf{f}}$ and $\hat{\mathbf{y}}$ are diagonal matrixes for vectors **f** and **y**, respectively.

The modularity is defined by Equation (9).

$$M = \sum_h (e_{hh} - r_h^2) \quad (9)$$

The notation e_{hh} means the fraction of transactions that are in community h; r_h indicates the fraction of all ends of transactions that are connected to nodes in community h; *e* and *r* are both weighted using transaction strengths; and r^2 indicates the weighted fraction of transactions connecting nodes in community h if the network is connected at random. The level of the modularity is denoted by the value of *M*. A higher value of *M* means a higher degree of the modularity. Details of the community detection method can be found in our previous study (Liang et al., 2015).

2.5. Data Sources

We obtained the MRIO data and data for water uses of nation sectors during 1995-2011 from the EXIOBASE database (https://www.exiobase.eu). The EXIOBASE version 3 monetary tables are used (EXIOBASE, 2018; Stadler et al., 2018). The global MRIO data in this study include 49 nations and 200 sectors for each nation. The WSIs are obtained from the study of Pfister et al. (2009). Since the WSI for Taiwan (China) is not directly provided, we derive the data from watershed-level results in the same study. Moreover, the WSI for Malta is not available. In consideration of climatic conditions and geographical positions, we use the WSI of Sicily (an island of Italy, located near Malta) as that of Malta.

3. RESULTS

3.1. Critical nation sectors from multiple perspectives

This study identifies critical nation sectors for global scarce water uses from multiple perspectives. The production-, consumption-, income-, and betweenness-based hotspots of global water scarcity are recognized. The hotspots of direct scarce water uses are mostly agricultural sectors in water-scarce regions such as the Middle East. The critical final consumers are mainly agricultural and food sectors. The detailed production-based and consumption-based results are shown in Supporting Information 1.

Income perspective. From 1995 to 2011, sectors whose primary inputs enable remarkable scarce water uses include the *wheat* sectors in India and China, the *paddy rice* sectors in India and China, as well as the *vegetables, fruit, nut* sectors in India and the rest of the Middle East, etc. Primary inputs of these nation sectors indirectly cause water scarcity of downstream nation sectors and may exacerbate water scarcity of remote water-scarce regions. The service sectors in India and the United States (the U.S.) are also important primary suppliers, such as the *services auxiliary to financial intermediation*, *financial intermediation services*, and *wholesale trade and commission trade services* sectors. These sectors are important manufacture-related services enabling downstream production activities and associated scarce water uses. India, China, and the U.S. are major nations where numerous sectors play as crucial primary suppliers (Figure 2a).

During 1995-2011, the primary-supplier roles of the *crude petroleum & related services* sector in the rest of the Middle East and the *financial intermediation* sector in the U.S. have remained within the top 80 among all the 9800 nation sectors. According to the EXIOBASE database (Stadler et al., 2018), the primary inputs of the *crude petroleum & related services* sector are among the highest in the rest of the Middle East; and the primary inputs of the *financial intermediation* sector are among the highest in the U.S. This indicates that lots of labor and capital are put into these two sectors. Crude petroleum is the basic material for production of fossil fuels and chemical products. Thus, the *crude petroleum & related services* sector is crucial for various downstream industries. The *financial intermediation* sector occupies an important position in financial activities. Most of financial activities are centered around financial intermediation and need support from financial intermediaries. These two sectors have substantial primary inputs and have significant influences on downstream sectors. Consequently, their primary inputs enable large amounts of scarce water uses in the downstream. These two sectors have become more important with fluctuations. The fluctuations may be influenced by financial crises during 2000-2002 and during 2007-2010. The financial crises may change the trade relationships in the downstream of the *crude petroleum & related services* sector in the rest of the Middle East and the *financial intermediation* sector in the U.S. Thus, the rankings of these sectors fluctuated. For most of the critical primary suppliers, their impacts on global scarce water uses remain relatively stable during 1995-2011 (Figure 2b).

The income-based viewpoint can recognize key sectors neglected by production-based and consumption-based viewpoints. These sectors are more important as primary suppliers than as producers or final consumers. For instance, in 2011, the *service auxiliary to financial intermediation* sector in the U.S. (ranking 10^{th}), the *financial intermediation services* sector in India (ranking 21^{st}), the *crude petroleum & related services* sector in the rest of the Middle East (ranking 26^{th}), and the *wholesale trade and commission trade services* sector in the U.S. (ranking 28^{th}) are critical primary suppliers, but their water scarcity is evidently low from the production- and consumption-based perspectives. The rankings by consumption-based scarce water uses of these sectors are outside of the top 900, and the rankings by their production-based results are outside of the top 6,000 (Data S3 in Supporting Information 2). This implies that these sectors contribute more to water scarcity from income-based perspective than from production- and consumption- based perspectives. However, primary inputs of these sectors greatly intensify water scarcity of downstream nation sectors.

These findings indicate that ignoring the primary-supplier role of nation sectors would underestimate the impacts of certain nation sectors on global water scarcity (e.g., the *financial intermediation services* in India and *wholesale trade and commission trade services* sectors in the U.S.). Supply-side measures (e.g., the optimization of primary input and product allocation behaviors), instead of production-side and demand-side measures, are required in critical primary suppliers identified in this study.

Insert Figure 2 here.

Betweenness perspective. The rankings of sectors by betweenness-based scarce water uses reveal critical transmission centers for global scarce water uses. Figure 3a shows that China has the maximum number of critical transmission centers in the world. This finding is consistent with China's "world factory" role in the world. In particular, the most crucial transmission sectors during 1995-2011 include the *textiles*, *chemicals*, *paddy rice*, *basic iron and steel,* and *hotel & restaurant services* sectors in China. Other important transmission centers include the *paddy rice* sector in the rest of Asia-Pacific Region, the *chemicals* sectors in India, and the *food products* sector in the U.S. (Figure 3b). The rankings of transmission centers fluctuated. This might be caused by changes in the trade relationships among nations, which influenced the structure of supply chains. The transmission roles of the *processed rice* sector in China and the *wheat* sector in India have been becoming more and more crucial during 1995-2000. The *processed rice* sector in China has remained within the top 30 during 2005-2011, and the *wheat* sector in India has remained within the top 30 during 2000-2011 (Figure S4 in Supporting Information 1). This trend might be caused by larger trade volumes and closer inter-sectoral cooperation. According to the MRIO data from the EXIOBASE database (Stadler et al., 2018), the total outputs of the *processed rice* sector in China and the *wheat* sector in India have obviously increased during the studied years. Supply chain paths passing through these two sectors may involve larger trade volumes in recent years. This may prompt these two sectors to become more important as transmission centers. The nation sectors recognized as critical transmission centers contribute essential semi-manufactured products to the world. Their products are further processed by downstream producers, and their upstream sectors usually have high water scarcity. Therefore, they have great influences on scarce water flows within the global trade network. Most of the transmission centers are in China, India, the rest of Asia-Pacific Region and the U.S., which are strong manufacturing entities.

The betweenness-based viewpoint reveals different functions of nation sectors, compared with production-based and consumption-based viewpoints. In 2011, The *raw milk* sector in the U.S., the *precious metal ores* sector in the U.S., and the *sand & clay* sector in China rank within top 200 by betweenness-based scarce water uses. However, they are unidentifiable by production-based and consumption-based viewpoints. Sectors related to fossil fuels, metallic materials, and non-metallic materials usually work more as transmission centers than as producers or final consumers (Data S4 in Supporting Information 2). These sectors have low scarce water uses. Meanwhile, their products are usually delivered to downstream sectors for further processing and less used by final consumers. The final demand of products from these sectors slightly exacerbates the water scarcity of upstream nation sectors. However, these sectors are characterized by relatively strong transmission functions.

Further taking the income-based results into account, the *raw milk* sector in the U.S., the *transmission services of electricity* sector in China, and the *other hydrocarbon* sector in China are highlighted for their transmission roles, compared with their roles as primary suppliers, producers, and final consumers (Data S4 in Supporting Information 2). These nation sectors directly suffer relatively slight water scarcity; the primary inputs of these sectors have relatively low impacts on downstream water scarcity; and the final demand of their products does not drive large amounts of scarce water uses. However, large amounts of embodied scarce water pass through these sectors.

These findings indicate that ignoring the transmission role of nation sectors would underestimate the impacts of certain nation sectors on global scarce water uses (e.g., the *raw milk* sector in the U.S. and the *transmission services of electricity* sector in China). Productivity improvement measures (i.e., using less upstream inputs to produce unitary output), instead of production-side, demand-side, and supply-side measures, are required in critical transmission centers identified in this study. The governments could formulate technical standards to urge transmission centers to reduce wastes. Enterprises below the standards may receive fines. For instance, technical standards for the *raw milk* sector can limit the waste of animal feed and require material recovery. This could help reduce scarce water uses of the supply chains.

Insert Figure 3 here.

3.2. Critical inter-sectoral transactions

Figure 4 and Figure 5 show the critical domestic and international inter-sectoral transactions with high centrality in 2011, respectively. These inter-sectoral transactions are crucial in transmitting scarce water uses in global supply chains, thereby strongly influencing global scarce water uses. For the top 50 domestic inter-sectoral transactions (Figure 4), agricultural sectors (e.g., the *paddy ric*e, *wheat*, and *crops* sectors) and *chemicals* sectors act as the most crucial origin sectors, and the most important destination sectors include agricultural, *food products*, and *service* sectors. The agricultural sectors supply large amounts of intermediate products to the *food products* and *service* sectors. Thus, transactions starting from agricultural sectors have high levels of centrality. The related nations and regions include India, China, the U.S., the rest of Asia-Pacific Regions, and the rest of the Middle East.

In 2011, the most outstanding international inter-sectoral transactions mainly involve the agricultural, agricultural products, *food products*, *chemicals*, *tobacco products*, and *hotel & restaurant services* sectors (Figure 5). Typical examples include the transactions from the *crops* sector in the rest of Asia-Pacific Region to the *chemicals* sector in China and from the *crops* sector in the rest of Asia-Pacific Region to the *food products* sector in China. In particular, the agricultural sectors are the most critical origins, and the *food products* sectors act as the most important destinations. Since Asia and the U.S. have strong agricultural sectors, the transactions involving agricultural sectors in Asia and the U.S. have large impacts on global scarce water uses. International transaction from the *chemicals* sector to the *health* *and social work services* sector is also an important transaction, which requires special attention.

During 1995-2011, there are slight changes in the rankings of most of the critical domestic inter-sectoral transactions. In particular, the transaction from *paddy rice* in the rest of Asia-Pacific Region to itself remains within the top 5 (Figure S5 in Supporting Information 1). The transaction from the *crops* sector to the *raw milk* sector in India becomes more important in recent years (Figure 4). This might be related to the change in trade structure. More inputs from the *crops* sector are required by unitary output of the *raw milk* sector in India. Moreover, the total output of the *raw milk* sector in India increases (Stadler et al., 2018). These changes prompt more scarce water uses in the upstream production of the *crops* sector. Thus, more embodied scarce water uses pass through this transaction.

For international inter-sectoral transactions, the transactions from the *cereal grains* sector in the U.S. to the *food products* sector in the Japan and from the *crops* sector in Mexico to the *food products* sector in the U.S. remain as critical international transactions (Figure S6 in Supporting Information 1). Transactions from the *crops* sector in the rest of Asia-Pacific Region to the *chemicals* sector in China has become more important in recent years. It ranks outside 3,869,100th in 1995, while 1889th in 1998, 451st in 2000, and within the top 300 after 2002 (Figure 5). The fluctuations in 1997 and 2001 are influenced by the changes in international trade structure and the trade relationship between these two sectors. According to the MRIO data from the EXIOBASE database, the direct input from the *crops* sector in the rest of Asia-Pacific Region to produce unitary output of the *chemicals* sector in China dropped to 0 in 1997 and 2001 (Stadler et al., 2018). The data show no trade contacts between these two sectors. Thus, the transaction played weak transmission roles in 1997 and

2001. Detailed information on critical inter-sectoral transactions in 1995, 2000, 2005, and 2010 are shown in Figures S7-10 in Supporting Information 1, respectively.

For certain inter-sectoral transactions, the rankings by transaction centrality show evident disparities from those by embodied scarce water flows (Table S1 in Supporting Information 1). For instance, in 2011, the centrality of the transaction from the *chemicals* sector in the rest of the Middle East to the *chemicals* sector in China ranks 158th, while its embodied scarce water flow ranks 1,858,355th. The centrality of the transaction from sector *s* to sector *t* is measured by scarce water uses of all the global supply chain paths directly passing through this transaction. It measures the importance degree of the transaction from sector *s* to sector *t* in controlling embodied scarce water flows in the global trade network. In contrast, the embodied scarce water flow means the scarce water use of sector *s* directly and indirectly caused by the final demand of sector *t* through global supply chains. It evaluates the direct and indirect effects of the final demand of sector *t* on the scarce water use of sector *s*. A transaction with high centrality but low embodied scarce water flow indicates that, the transaction from the starting point to the endpoint transmits large amounts of embodied scarce water uses, but the endpoint acts as a weak final consumer for scarce water use of the starting point. In other words, the final demand of the endpoint drives small amounts of scarce water uses of the starting point. The transaction centrality can bring distinguishing implications to policymaking, compared with embodied scarce water flow results. Policy decisions based on transaction centrality need to focus on production efficiency improvement, while policies based on embodied scarce water flows focus on consumption behavior optimization. The detailed policy implications are discussed later. The critical inter-sectoral transactions (mainly involving the agricultural and food products sectors in India, China, and the U.S.) further provide explicit directions for the production-side, demand-side, supply-side, and productivity improvement measures.

Figure 4 inserts here.

Figure 5 inserts here.

3.3. Community structure

In the global virtual scarce water network, nation sectors in the same community are strongly interconnected with one another. They affect one another's scarce water use more significantly than nation sectors outside this community. In 2011, the global virtual scarce water network is divided into 2,054 communities by the modularity maximization algorithm (Newman, 2004). Table 1 shows the top 5 communities with the largest scarce water uses. The largest community mainly includes industries of the rest of the Middle East, attached by several sectors in Bulgaria, Cyprus, Greece, UK, Turkey, and the rest of Europe. It leads to 107 billion m^3 of global scarce water uses (occupying 15% of the global total). The second largest community is dominated by mainland China, and involves nations in different geographical areas such as Canada, South Korea, Brazil, Australia, and Norway. This community has 93 billion m^3 of global scarce water uses (occupying 13% of the global total). The top 15 communities with the largest scarce water uses are shown in Table S2 in Supporting Information 1.

Some communities are in accordance with geographical boundaries of nations (e.g., communities 3 and 11, see Table S2 in Supporting Information 1). However, most of the large communities involve sectors from different nations. For instance, the *motor vehicle services* and *wholesale trade* sectors in mainland China are more closely connected with sectors in European countries (community 9, see Table S2 in Supporting Information 1) than to the other sectors in mainland China (community 2). Thus, sectors in the same community do not always fall into the same nation. Identifying major communities in this study can provide foundations for international cooperation strategies to reduce global scarce water uses.

Moreover, some critical transmission centers belong to the top communities. For instance, the *wheat* and *chemicals* sectors in the rest of the Middle East belong to the largest community; the *paddy rice*, *food products*, *textiles*, and *chemicals* sectors in China belong to the second largest community (Data S5 in Supporting Information 2). These critical transmission centers transmit large amounts of embodied scarce water in global supply chains, thereby closely linking sectors in the same community. They can play important roles in the reduction of scarce water uses in the top communities. Improving their productivity can help mitigate water scarcity in the top communities.

Table 1. Top 5 communities of the global virtual scarce water network [a].

Ranking	Scarce water uses (billion m^3)	Descriptions of communities
1	106.7	Industries of the rest of the Middle East; attached by *basic iron* in Bulgaria, *cereal grains* in Cyprus, *other non-metallic mineral products* in Greece, *sugar* in UK, *basic iron*, *foundry work services*, and *fabricated metal products* in Turkey, and *cereal grains* in the rest of Europe.
2	93.3	Most of the industries in mainland China; industries related to agricultural products, fossil fuels, metal and non-metals, chemicals, electronic equipment, transport equipment, energy, and services in Canada, South Korea, Brazil, Mexico, Russia, Australia, Switzerland, Taiwan (China), Norway, and Indonesia; fossil fuels, metal and non-metals in India and the rest of Asia-Pacific Region; fossil fuels and metals in South Africa; electronic and transport equipment in the rest of America; attached by *P- and other fertilizer* in Belgium, *basic plastics* in Czech Republic, *pulp* and *P- and other fertilizer* in Luxembourg,

		chemicals and *basic iron* in Sweden, *chemicals* in Latvia, *oil seeds* in the U.S., *products of vegetable oil* in Japan.
3	91.5	*Wheat* in India
4	90.0	Most of the industries in India; industries related to fossil fuels, transportation, and services in Mexico; metals, non-metals, energy and transportation in Russia; fossil fuels, metals, non-metals, and services in Australia; agriculture and agricultural products, fossil fuels, pulp and paper, chemicals, energy, and services in Switzerland; metals and services in Turkey; agriculture, fossil fuels, non-metals, chemicals, energy, and services in Taiwan (China); fossil fuels, metals, non-metals, electronic equipment, energy, transportation, and services in Norway; agricultural products, fossil fuels, non-metals and services in Indonesia; agricultural products, chemicals, and biofuels in the rest of Asia-Pacific Region; metals in the rest of America; non-metals in the rest of the Middle East; attached by *plant-based fibers* in Canada, *lead, zinc, and tin ores*, *retail trade*, and *auxiliary transport services* in South Africa.
5	76.3	Most of the industries in the rest of Asia-Pacific Region, the rest of Europe, and the rest of Africa; industries related to energy and waste treatment in the rest of the Middle East; attached by *basic iron* in Greece, Portugal, and Norway, *P- and other fertilizer* in Italy, Russia, and Norway, *wheat* in Brazil and Australia, and *N-fertilizer* in Russia, Norway, and Australia.

[a]The italic font in Table 1 is used to show the sector names. Detailed information for the top 5 communities is shown in Data S5 in Supporting Information 2.

4. DISCUSSION

Existing studies on global scarce water uses have not well characterized the critical nation sectors in primary input and intermediate transmission stages of global supply chains (namely the critical primary suppliers and transmission centers). This ignorance leads to the underestimation of the importance of certain nation sectors in the global virtual scarce water network (Table S3 in Supporting Information 1). This would reduce the efficiency of the policy decisions on mitigating global water scarcity. Production-side and demand-side measures play limited roles in the management of critical primary suppliers and transmission centers. The ignorance of critical primary suppliers and transmission centers can result in inadequate policy decisions, which limits the mitigation of global water scarcity. This study presents a profile of nation sectors from multiple (production-, consumption-, income-, and betweenness-based) perspectives to reveal global supply chain hotspots driving global scarce water uses. The most important inter-sectoral transactions and virtual scarce water communities are also identified. Our findings provide hotspots for policy decisions of related international organizations such as the World Water Council and Global Water Partnership (Global Water Partnership, 2019; World Water Council, 2014).

For hotspots of direct scarce water uses, production-side measures, such as improving the irrigation efficiency, are effective in mitigating the water scarcity. For instance, China has launched the "Three Red Lines" policy for water resources, which controls national water consumption and requires the improvement of water use efficiency and irrigation efficiency (China State Council, 2012). The final demand of products from critical final consumers contributes to not only the water scarcity of themselves, but also the water scarcity of other nation sectors. It is essential for these sectors to improve the production efficiency in the utilization of upstream inputs and to choose alternative upstream inputs with lower scarce water use intensity. Moreover, optimizing consumption behaviors helps reduce upstream water scarcity. Policies can guide consumers to purchase products with lower consumption-based scarce water uses through subsidizes on commodities and introduce tax on products with high consumption-based scarce water uses (Liang et al., 2015).

Critical nation sectors recognized from the income-based viewpoint require environmental strategies related to primary inputs and product allocation (Liang et al., 2016). For these nation sectors, policy decisions should focus on adjusting production taxes and optimizing product allocation behaviors to downstream users. Governments can construct databases to track the income-based scarce water uses of enterprises and establish the labelling scheme for embodied scarce water of their products. Both the direct scarce water use intensity and income-based scarce water uses of enterprises are necessary for the databases. For instance, the *wheat* and *paddy rice* sectors in India are critical sectors with high income-based scarce water uses. India may support *wheat* and *paddy rice* enterprises with relatively lower income-based scarce water uses through reducing production taxes and increasing subsidies. These financial incentives can prompt enterprises to voluntarily reduce their income-based scarce water uses. The enterprises might firstly clarify the scarce water use intensity of downstream users through the databases and product labels. Downstream users with high scarce water use intensity can aggravate water scarcity in the whole supply chains, compared with their peer enterprises with lower scarce water use intensity. Thus, the *wheat* and *paddy rice* enterprises in India can decide to sell their products to downstream users with lower scarce water use intensity. In this way, the products of the *wheat* and *paddy rice* sectors would be more possibly allocated to downstream users with lower water scarcity. India could also limit technology-backward enterprises by tightening loan supplies and subsidies to enterprises with high income-based scarce water uses. Moreover, developing related databases requires the efforts of not only one single nation, but all related nations along global supply chains. Therefore, international cooperation is necessary for reducing income-based scarce water uses.

Similar policies may apply to critical nation sectors that are overlooked by production-based and consumption-based accountings, such as the *service auxiliary to financial intermediation* sector in the U.S., the *financial intermediation services* sector in India, and the *crude petroleum & related services* sector in the rest of the Middle East. These nation sectors are important primary suppliers and enterprises of these nation sectors may focus on optimizing product allocation and database construction.

For critical transmission centers of global scarce water uses, improving their productivity (i.e., minimizing inputs from upstream sectors while sustaining the supply to downstream sectors) is a fundamental pathway to reduce global scarce water uses. For instance, the *raw milk* sector in the U.S. has relatively low scarce water uses from the production-, consumption, and income- based viewpoints, but relatively high betweenness-based scarce water uses. This indicates limited space for reducing scarce water uses through production-, demand-, and supply-side measures. However, enterprises in this sector can reduce global scarce water uses by improving their productivity. Moreover, reusing materials and wasting less can help reduce the requirements of upstream inputs and the embodied scarce water transmitted by this sector. For critical transmission centers related to foods (e.g., the *hotel & restaurant services* sector in China and the *food products* sector in the U.S.), avoiding food loss can help reduce global scarce water uses. Local governments could formulate standards for enterprises to improve their technologies, reduce wastes, control purchases, and optimize production processes. Enterprises meeting the standards can be subsidized. Similar strategies can also apply to other transmission centers such as the *textiles*, *chemicals*, and *metals* sectors in China.

The policy implications from multiple perspectives can supplement one another. Production-side measures are important for reducing direct scarce water uses; consumption-based measures can help lower scarce water uses of upstream sectors. Moreover, income-based measures promote the reduction of downstream scarce water uses and betweenness-based measures can help control the transmission of embodied scarce water. Therefore, multi-perspective measures can overcome the limitations of one another and reduce water scarcity in the whole supply chains.

The production-, consumption-, income-, and betweenness-based scarce water uses can lay the foundations for quantifying the shared responsibilities for water scarcity of nation sectors. Existing studies have developed frameworks to combine the environmental responsibilities of producers and consumers (Cadarso et al., 2012; Chang, 2013; Zhu et al., 2018). The concept of the shared responsibilities has been applied to describe the impacts of trade on CO_2 emissions and ecosystems (Cordier et al., 2018; Guo et al., 2020). Zhao et al. (2016) have also discussed the shared responsibility among trade partners to reduce water stress in the context of burden shifting. The shared responsibilities for water scarcity can be further analyzed in future studies, taking into account all of the responsibilities of producers, final consumers, primary suppliers, and transmission centers.

The critical inter-sectoral transactions can offer more elaborate policy implications to specific nation sectors. Strategies aiming at the starting points and ending points of key transactions will help reduce global scarce water uses. For instance, the transaction from the *crops* sector in the rest of Asia-Pacific Region to the *chemicals* sector in China transmits large amounts of embodied scarce water. Encouraging the *chemicals* sector in China to efficiently use products from the *crops* sector can help reduce global scarce water uses. It is also important for the *crops* sector in the rest of Asia-Pacific Region to improve its water use efficiency. Our results emphasize the significance of the cooperation between the starting and ending points of the critical inter-sectoral transactions.

The major communities identified in this study can promote further understandings of policy interventions aiming at specific nation sectors. Nation sectors in the same community are strongly interconnected. Water use interventions in one nation sector would significantly influence scarce water uses of the other nation sectors in this community. On one hand, strategies on mitigating global water scarcity can be implemented more effectively within one community. That is, policy decisions on one nation sector would probably mitigate water scarcity of the other nation sectors in the same community. On the other hand, interventions in one nation sector may also increase scarce water uses of certain nation sectors in the same community, thereby reducing the community's water-saving efficiency. Either positive or negative impacts of a nation sector's policy interventions on scarce water uses of the other nation sectors are stronger within the same community than across different communities. Nations falling within the same community can make decisions together to maximize the policy effects on mitigating global water scarcity. Future research can focus on the synergy or trade-offs among policy decisions on water scarcity of various nations within the same community. Such investigation may provide more concrete basis for international cooperation.

Sectors in the same community are usually not limited by geographical boundaries. This provides new insights for international cooperation strategies. For instance, the *motor vehicle services* and *wholesale trade* sectors in mainland China belongs to the community dominated by the sectors of European countries. Improving the material use efficiency of sectors in European countries may help reduce the scarce water uses of the *motor vehicle services* and *wholesale trade* sectors in mainland China. Meanwhile, improving the material use efficiency can reduce the economic cost of sectors in Europe, thereby achieving the co-benefits of these nation sectors.

The United Nations has set the target of increasing water use efficiency across all sectors to address water scarcity in the Sustainable Development Goals (Goal 6) (UN, 2015). This target is set from the production perspective. This study recognized critical sectors acting as final consumers, primary suppliers, and transmission centers, which can provide additional support for strategies at the sectoral scale. Moreover, the critical sectors and inter-sectoral transactions can provide scientific basis for the Integrated Water Resources Management (IWRM) project of the United Nations Environment Programme (UNEP). IWRM is an approach focusing on cross-sectoral water management (UNEP, 2002). The findings of this study highlight specific nation sectors to support more elaborate cross-sectoral strategies.

The results of this study can be influenced by the global MRIO data. The nation-sector resolution of MRIO tables plays an important role in the identification of critical primary suppliers and transmission centers. Some of the critical nation sectors might be unidentifiable and new critical nation sectors might be found if we used different MRIO databases. This could be a limitation of this study. The future improvement of nation-sector resolution in global MRIO databases can help address this issue.

In this study, the Ghosh MRIO model is applied to quantify sectoral scarce water uses enabled by primary suppliers (i.e., income-based accounting). There have been many debates on the understanding of the Ghosh MRIO model (Dietzenbacher, 1997; Oosterhaven, 1988). The Ghosh MRIO model regards price changes of primary inputs (e.g., labor and capital) as the exogenous driver of outputs (Dietzenbacher, 1997). However, this study does not focus on dynamic changes in prices and production. We instead focus on the environmental responsibilities assigned to sectors from the supply side in a particular year.

We also analyze the sensitivity of the results to all the parameters in 2011, using the method of Heijungs and Lenzen (Heijungs, 2010; Heijungs & Lenzen, 2014). The parameter elasticities are estimated to show the sensitivity. Most of the elasticities are small, indicating low sensitivity for the results (Figures S11 and S12 in Supporting Information 1). For scarce water use intensity, the parameter elasticity of the *wheat* sector in India is the highest (0.129).

This indicates that, if the scarce water use intensity of the *wheat* sector in India changed by 10%, the global scarce water uses driven by final demand or enabled by primary inputs would change by 1.29%. The *wheat* sector in India has the highest elasticity for the final demand (0.122) and for primary inputs (0.086). For the intermediate transaction matrix, the direct input of the *paddy rice* sector in India for unitary output of the *paddy rice* sector in India has the highest elasticity (< 0.07). Detailed information on sensitivity calculation is shown in Supporting Information 1.

5. CONCLUSIONS

Existing studies have not well characterized the hotspots in the primary input and intermediate transmission stages of global supply chains, which contribute to global water scarcity. These hotspots indicate nation sectors with high improvement potentials to reduce global water scarcity. This study integrates global EE-MRIO model and complex network analysis to identify critical nation sectors for global scarce water uses from multiple perspectives (i.e., production-based, consumption-based, income-based, and betweenness-based methods). The hotspots revealed in this study can provide additional understandings for multiple-perspective policy decisions on the mitigation of global water scarcity. Moreover, the critical inter-sectoral transactions and communities can provide a scientific basis for international cooperation strategies.

Results show that the *service auxiliary to financial intermediation* sector in the U.S., the *financial intermediation services* sector in India, the *crude petroleum & related services* sector in the rest of the Middle East, and the *wholesale trade and commission trade services* sector in the U.S. are critical primary suppliers, but they are not remarkable by production- and consumption-based accountings. Moreover, the *raw milk* sector in the U.S., the *transmission services of electricity* sector in China, and the *other hydrocarbon* sector in China are highlighted for their transmission roles, compared with their roles as primary suppliers, producers, and final consumers. In 2011, the most outstanding international inter-sectoral transactions mainly involve the agricultural, agricultural products, *food products*, *chemicals*, *tobacco products*, and *hotel & restaurant services* sectors, such as the transactions from the *crops* sector in the rest of Asia-Pacific Region to the *food products* sector in China. The agricultural sectors are the most critical origins, and the *food products* sectors act as the most important destinations. In 2011, the global virtual scarce water network is divided into 2,054 communities. Nation sectors in the same community are strongly interconnected with one another. They affect one another's scarce water uses more significantly than nation sectors outside this community. Most of the large communities involve sectors from different nations.

Critical primary suppliers require environmental strategies related to primary inputs and product allocation. Policy decisions should focus on adjusting production taxes and optimizing product allocation behaviors to downstream users. For critical transmission centers of global scarce water uses, it is important to improve their productivity (i.e., minimizing inputs from upstream sectors while sustaining the supply to downstream sectors) to reduce global scarce water uses. The critical inter-sectoral transactions can offer more elaborate policy implications to specific nation sectors. The major communities identified in this study involve sectors from different nations, providing foundations for international cooperation strategies. The findings can promote further understandings of policy interventions aiming at specific nation sectors.

The sensitivity of the results to the global MRIO data and scarce water uses is low. The nation-sector resolution of global MRIO data can influence the results, which is a limitation of this study. Future studies can improve the analyses on shared responsibilities for water scarcity, incorporating the responsibilities of primary suppliers and transmission centers. Moreover, the synergy or trade-offs among policy interventions on water scarcity of various nations within the same community can be further investigated.

FUNDING INFORMATION

This work was financially supported by the Program for Guangdong Introducing Innovative and Entrepreneurial Teams (2019ZT08L213) and the National Natural Science Foundation of China (71874014).

DATA AVAILABILITY STATEMENT

The data generated during this study are available from the corresponding author upon reasonable request.

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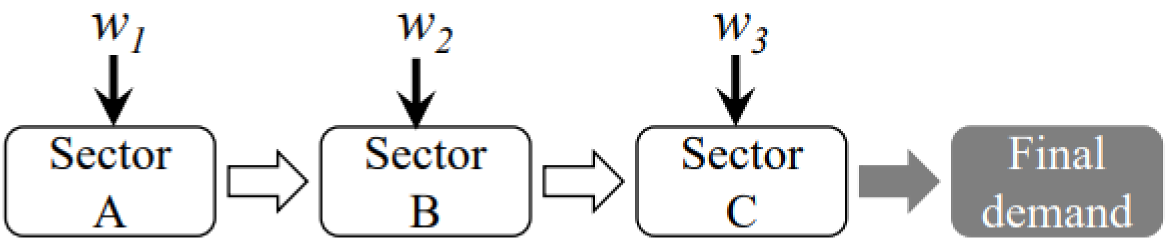
Figure Legends

Figure 1. A three-sector example showing the scarce water uses of each sector under different methods. The direct scarce water uses of sectors A, B, and C are w_1, w_2, and w_3, respectively.



Accounting frameworks	Sector A	Sector B	Sector C
Production-based	w_1	w_2	w_3
Consumption-based	0	0	$w_1+w_2+w_3$
Income-based	$w_1+w_2+w_3$	0	0
Betweenness-based	0	w_1	0

Figure 2. Rankings of nation sectors by income-based results. Panel (a) shows the rankings of nation sectors by income-based results in 2011. It includes nation sectors ranked within the top 20% from the income viewpoint. The indexes and corresponding sector names are listed in Data S1 in Supporting Information 2. Panel (b) shows changes in the rankings of critical primary suppliers during 1995-2011. The "W.T. & C.T. services" represents the *wholesale trade and commission trade services* sector. WA represents the rest of Asia-Pacific Region; WL represents the rest of America; WE represents the rest of Europe; WF represents the rest of Africa; and WM represents the rest of the Middle East. (Note: Underlying data for this figure can be found in Data S6 and S7 in Supporting Information 2)

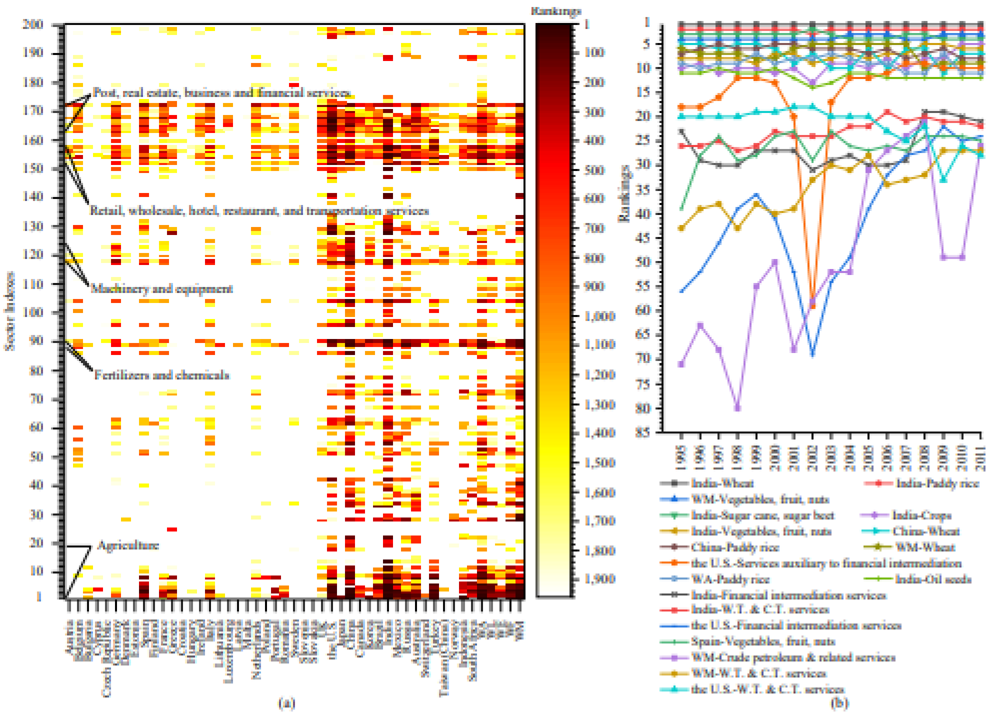


Figure 3. Rankings of nation sectors by betweenness-based results. Panel (a) shows the rankings of nation sectors by betweenness-based results in 2011. It includes nation sectors ranked within the top 20% from the betweenness viewpoint. The indexes and corresponding sector names are listed in Data S1 in Supporting Information 2. Panel (b) shows changes in the rankings of critical transmission centers during 1995-2011. WA represents the rest of Asia-Pacific Region; WL represents the rest of America; WE represents the rest of Europe; WF represents the rest of Africa; and WM represents the rest of the Middle East. (Note: Underlying data for this figure can be found in Data S8 and S9 in Supporting Information 2)

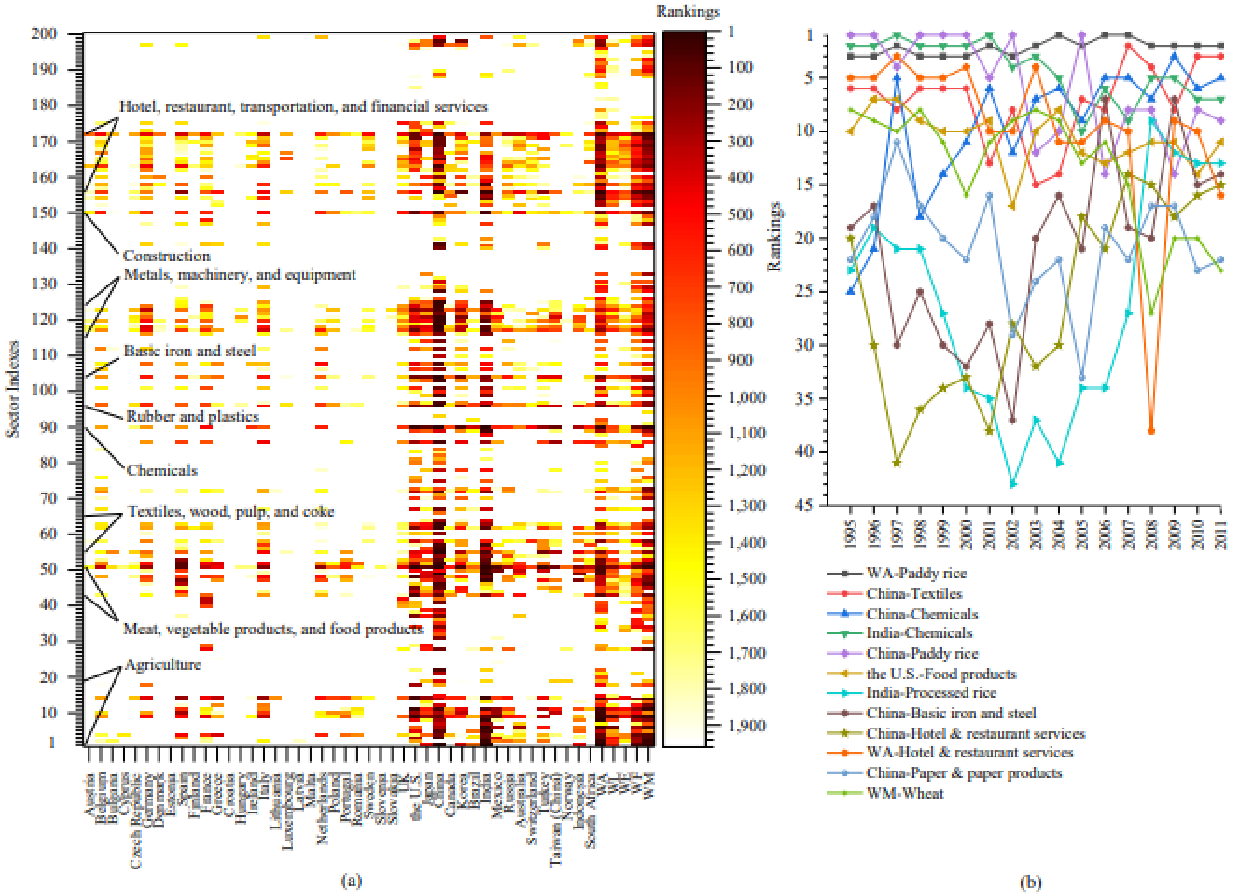


Figure 4. The top 50 domestic transactions leading to global scarce water uses in 2011. The line chart shows the changes in the rankings of a certain inter-sectoral transaction during 1995-2011. The arrows start from the origins of critical inter-sectoral transactions and end at their destinations. The width of the arrows indicates the importance of the inter-sectoral transactions. The numbers marked on the arrows indicate the values of transaction centrality (unit: billion m^3). WA represents the rest of Asia-Pacific Region and WM represents the rest of the Middle East. The "V. O. &F." represents the *products of vegetable oils and fats* sector. (Note: Underlying data for this figure can be found in Data S10 and S17 in Supporting Information 2)

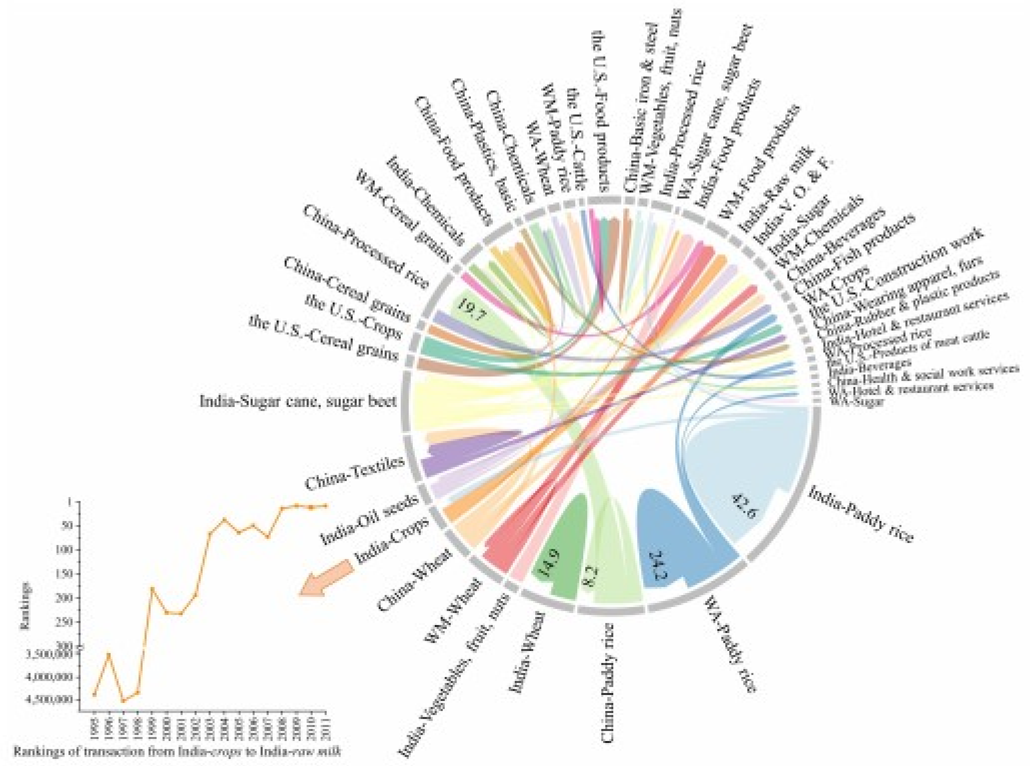
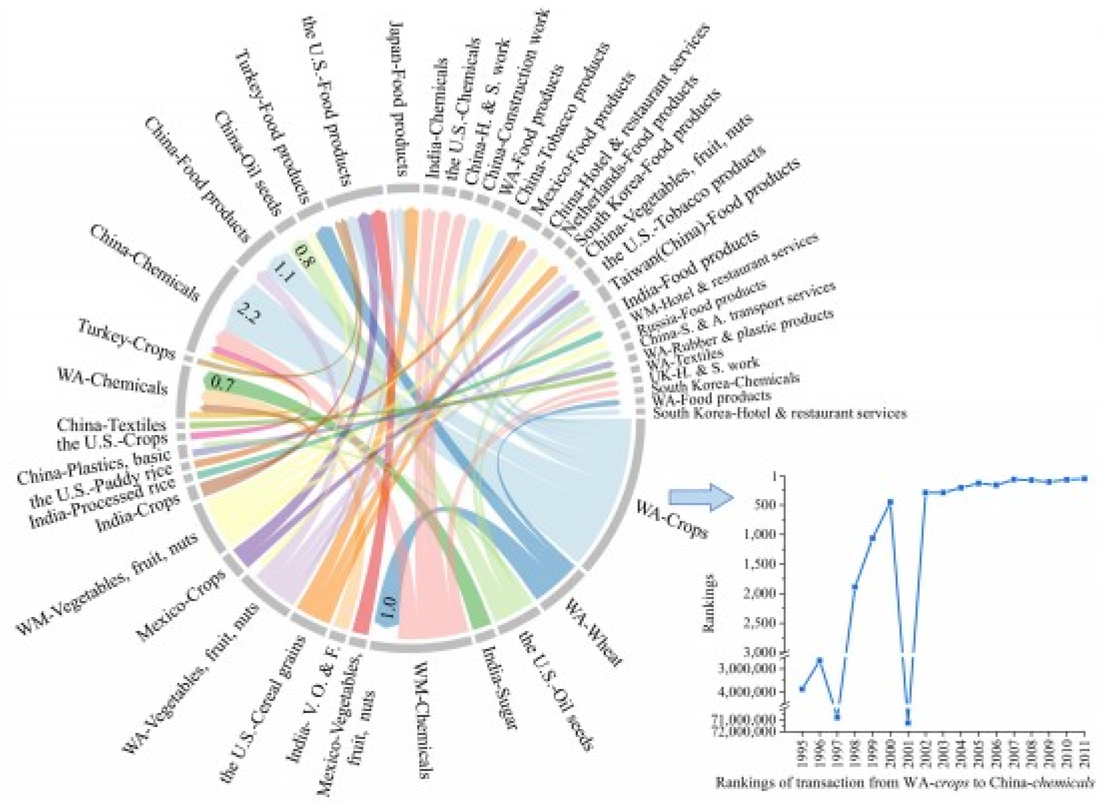


Figure 5. The top 50 international inter-sectoral transactions leading to global scarce water uses in 2011. The line chart shows changes in the rankings of a certain inter-sectoral transaction during 1995-2011. The arrows start from the origins of critical inter-sectoral transactions and end at their destinations. The width of the arrows indicates the importance of the inter-sectoral transactions. The numbers marked on the arrows indicate the values of transaction centrality (unit: billion m^3). WA represents the rest of Asia-Pacific Region and WM represents the rest of the Middle East. The "V. O. &F." represents the *products of vegetable oils and fats* sector; the "H. and S. work" represents the *health & social work services* sector; and the "S. & A. transport services" represents the *supporting & auxiliary transport services* sector. (Note: Underlying data for this figure can be found in Data S11 and S18 in Supporting Information 2)


the U.S.-Food products
Japan-Food products
India-Chemicals
the U.S.-Chemicals
China-H. & S. work
China-Construction work
WA-Food products
China-Tobacco products
Mexico-Food products
China-Hotel & restaurant services
Netherlands-Food products
South Korea-Food products
China-Vegetables, fruit, nuts
the U.S.-Tobacco products
Taiwan(China)-Food products
India-Food products
WM-Hotel & restaurant services
Russia-Food products
China-S. & A. transport services
WA-Rubber & plastic products
WA-Textiles
UK-H. & S. work
South Korea-Chemicals
WA-Food products
South Korea-Hotel & restaurant services
WA-Crops
WA-Wheat
the U.S.-Oil seeds
India-Sugar
WM-Chemicals
Mexico-Vegetables, fruit, nuts
India- V. O. & F.
the U.S.-Cereal grains
WA-Vegetables, fruit, nuts
Mexico-Crops
WM-Vegetables, fruit, nuts
India-Crops
India-Processed rice
the U.S.-Paddy rice
China-Plastics, basic
the U.S.-Crops
China-Textiles
WA-Chemicals
Turkey-Crops
China-Chemicals
China-Food products
China-Oil seeds
Turkey-Food products
2.2
1.1
0.8
0.7
1.0
Rankings
1
500
1,000
1,500
2,000
2,500
3,000
3,000,000
4,000,000
71,000,000
72,000,000
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
Rankings of transaction from WA-*crops* to China-*chemicals*