Science of the Total Environment 673 (2019) 128–135

Contents lists available at ScienceDirect

Science of the Total Environment

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

Interactive national virtual water-energy nexus networks

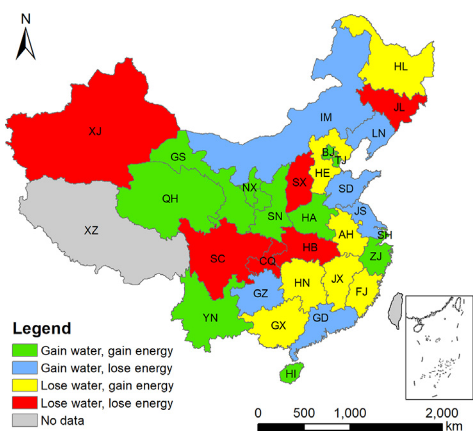
Zhenci Xu [a], Yingjie Li [a], Anna Herzberger [a], Xiuzhi Chen [b], Mimi Gong [a], Kelly Kapsar [a], Ciara Hovis [a], Julia Whyte [a], Ying Tang [b,a], Yunkai Li [c], Jianguo Liu [a,*]

[a] Center for Systems Integration and Sustainability, Michigan State University, East Lansing 48823, USA
[b] College of Water Resources and Civil Engineering, China Agricultural University, Beijing 100083, China
[c] Department of Geography, Environment, and Spatial Sciences, Michigan State University, East Lansing 48823, USA

HIGHLIGHTS

- Flow patterns of virtual energy and water trade within China were analyzed.
- Most of provinces depended more on distant trade than adjacent trade.
- Trade shaped the nexus relationship between provinces' water and energy consumption.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 1 January 2019
Received in revised form 19 March 2019
Accepted 19 March 2019
Available online 22 March 2019

Editor: Jay Gan

Keywords:
Virtual water
Virtual energy
Nexus
Trade
China
Network

ABSTRACT

Across the globe, many regions import virtual resources to support their development. Although many researchers have studied transfers of a single virtual resource, interactions across two types of virtual resource transfer networks – energy and water, for example – have rarely been explored simultaneously. To address these knowledge gaps, we constructed and analyzed interprovincial virtual water and energy transfer networks, using China (the largest energy consumer and is undergoing severe water scarcity) as a demonstration. The results unexpectedly showed that more than 40% of provinces gained one kind of resource (either water or energy) through trade at the expense of losing the other kind of internal resource (energy or water), and 20% of provinces suffered a double loss of both water and energy. The remaining provinces gained both water and energy. Surprisingly, approximately 40% of transferred water/energy was from relatively water/energy-scarce provinces to water/energy-abundant provinces, further deepening resource inequality. Moreover, 33.3% and 26.7% of the provinces relied more on cross-border trade than on internal resources to support their water and energy consumption, respectively. Furthermore, in terms of total trade volume, 83.3% and 73.3% of provinces depended more on distant provinces via trade than adjacent ones to support their water and energy consumption, respectively. Overall, virtual water-energy networks tended to enhance each other. Trade largely shaped the nexus relationship between water and energy consumption in provinces. Our study suggests that there is an urgent need

* Corresponding author.
E-mail address: liuji@msu.edu (J. Liu).

https://doi.org/10.1016/j.scitotenv.2019.03.298

to assess multiple virtual resource networks simultaneously in other countries to uncover unintended consequences and to develop cross-sectoral and holistic policies to achieve global sustainability and human well-being.

1. Introduction

Economic development and population growth substantially increase global resource demand (e.g., water and energy) (Liu et al., 2015a, 2015b, Steffen et al., 2015), resulting in resource scarcity that becomes a barrier for sustainability (Yergin, 2006; Mekonnen and Hoekstra, 2016). Virtual resources, such as water and energy, that are consumed in commodity production processes have gained global attention as a key mechanism for alleviating resource scarcity in a receiving system (e.g., a region, a city) through commodity trade (Novo et al., 2009; Wiedmann, 2009; Steinmann et al., 2017; Xu et al., 2018). Today, transfers of virtual resources such as water and energy have been intensified by globalization (Dalin et al., 2012; Chen et al., 2018). For example, the volume of global virtual water transfers embodied in international food trade has substantially increased over time (Dalin et al., 2012). The virtual energy flows embodied in international trade have also evolved into a highly interconnected network (Chen et al., 2018).

Many studies have evaluated trade within a single virtual resource trade network (e.g., water). These analyses focus on virtual resource trade's spatial pattern, structure, and impacts on sending and receiving systems (Hoekstra and Hung, 2002; Chapagain and Hoekstra, 2003; Chapagain et al., 2006; Dabrowski et al., 2009; Wiedmann, 2009; Konar et al., 2011; Zhang et al., 2011; Mubako et al., 2013; Zhang and Anadon, 2014; Zhao et al., 2015; Oita et al., 2016). However, based on the integrated framework of metacoupling (Liu, 2017), we found that little research has simultaneously explored the interactions between trading systems in two types of virtual resource transfer networks from a nexus perspective (von Braun and Mirzabaev, 2016), as different kinds of virtual resource transfer may influence each other and cross-sectoral impacts may happen. Cross-sectoral impacts occur when changes in one sector influence another sector. For example, while China constructed more hydropower stations to develop hydropower and satisfy energy demand, substantial water loss occurred when water evaporated from reservoirs, resulting in regional water scarcity (Liu et al., 2015a, 2015b). Current water-energy nexus studies mainly focus on one specific place instead of the relationship between multiple distant places (Liu et al., 2018a, 2018b). Also, there is little research comparing trade between distant systems with trade between geographically adjacent systems. Furthermore, little research has explored drivers of two types of virtual resource transfer simultaneously by using a gravity model (Duarte et al., 2018). Such information is urgently required as the world demand for various natural resources in different places may change at differing rates. A more holistic understanding of multiple types of virtual resource trade should be developed to improve resource management efficiency. Moreover, comparing the influences from adjacent and distant provinces can help reveal influential places in different geographical regions. This comparison can also help unveil socioeconomic and environmental impacts from trade with adjacent and distant provinces (e.g., distant trade often consumes more energy for transportation and therefore emits more CO_2) (Liu et al., 2018a, 2018b).

To address these knowledge gaps, we studied China's interprovincial virtual water and energy transfer networks simultaneously. Water and energy are strongly interrelated in human activities and play significant roles in both environmental conservation and socioeconomic development (Liu et al., 2015a, 2015b). Therefore, analyzing virtual water and energy transfer networks together can help us better understand the interactions between provinces in different virtual resource transfer networks. China is facing a serious water crisis and energy shortage in the 21st century (Crompton and Wu, 2005; Zhao et al., 2015). Even though China ranks fourth in the world for freshwater resources, its high population makes its per capita renewable freshwater resources levels only one quarter of the world average (Liu and Yang, 2012). Furthermore, uneven water resource distribution within China is a barrier to development (Liu and Yang, 2012). China has also become the world's largest energy consumer after surpassing the United States (U.S.) in 2009 (Swartz and Oster, 2010; Chen et al., 2013). The distribution of coal, natural gas and electricity in China is largely uneven and has negative impacts on China's development (Ma and Oxley, 2012). Understanding the interactions between China's interprovincial virtual water and energy transfer networks and their impacts can provide useful information and lessons for enhancing water and energy security through virtual resource transfer in other developing countries.

Based on the most recently available multiregional input-output table for developing interprovincial energy and water trade networks simultaneously in China (Zhang et al., 2013; Zhao et al., 2015), we used network analysis to study interactions across virtual water and energy networks between provinces. We also constructed a "without trade" scenario to study the impact of trade on the nexus between water and energy consumption across provinces. Furthermore, we used the augmented gravity model to explore the drivers of China's virtual water/energy transfer.

2. Material and methods

2.1. Data sources

We used the most recently available multiregional input-output table for developing energy and water networks simultaneously in China (Zhang et al., 2013, Zhao et al., 2015). The Chinese 2007 interprovincial input-output table was constructed by the Chinese National Bureau of Statistics. Being consistent with the previous research (Zhao et al., 2015), water withdrawal data by sector at the provincial level were derived from Water Resource Bulletin and Chinese Economic Census Yearbook 2008 (Provincial Water Resources Bureau, 2007; Census, 2008; Zhao et al., 2015). The sources of water withdrawal were surface water, groundwater, and transferred water (Ministry of Water Resources of China, 2007; Zhao et al., 2015). The energy consumption data for sectors in provinces were obtained from the 2008 Energy Balance Table (National Bureau of Statistics, 2008).

2.2. Construction of virtual water/energy trade network

We quantified the interprovincial virtual water and energy transfer network by running multi-region input-output analysis and direct water/energy consumption coefficients. We treated each trading province as one node (or a coupled human and natural system) (Liu et al., 2007), thus all provinces construct the interprovincial virtual water/energy trade network. A direct link between any pair of nodes indicates a virtual water/energy flow between trading provinces and the weight of the link reflects the volume of the virtual water/energy flow.

First, we applied multi-region input-output analysis to study interdependencies between different provinces' economies by tracing capital flows. This method shows the contribution from production of sectors in a particular province to the final and intermediate consumption of all sectors in all provinces measured by monetary value. Intermediate consumption is the monetary value of goods and services consumed as inputs for a process of production, while final consumption is represented by the monetary value consumed for direct satisfaction of individual needs and collective needs of members of communities.

Assuming the number of trading provinces is m, and each province has n sectors. The output in sector i of province R is represented by Eq. (1) as follows:

$$x_i^R = \sum_{S=1}^{m}\sum_{j=1}^{n} x_{ij}^{RS} + \sum_{S=1}^{m} y_i^{RS} \quad (1)$$

where x_{ij}^{RS} represents the intermediate consumption in sector j of province S supported by sector i of province R. The y_i^{RS} is the final consumption in province S supported by sector i of province R.

The direct input coefficient a_{ij}^{RS} is calculated by Eq. (2):

$$a_{ij}^{RS} = x_{ij}^{RS}/x_j^S. \quad (2)$$

where x_j^S represents the total output in sector j of province S. a_{ij}^{RS} represents the amount of monetary input in sector i of province R needed to increase the output in sector j of province S by one monetary unit.

Based on Eq. (2), we converted Eq. (1) into matrix notation as follows:

$$X^* = A^* X^* + Y^* \quad (3)$$

$X^*=[x^1, x^2, \ldots, x^m]^T$ represents the vector of total output for all provinces. A is matrix for direct input coefficient. Y^* is the vector of all provinces' final consumption.

Then we converted Eq. (3) into the following format:

$$X^* = BY^*, B = (I-A)^{-1} \quad (4)$$

The term $(I-A)^{-1}$ is the Leontief inverse matrix, which represents the amount of output from other provinces that is required to satisfy one monetary unit of final consumption. To link the monetary value transfer with virtual water/energy transfer, we defined the direct water/energy consumption coefficients. The direct water/energy consumption coefficients of sector j in province R can be expressed as Eq. (5):

$$e_j^R = \frac{w_j^R}{x_j^R} \quad (5)$$

where the w_j^R represents total water/energy consumption in sector j of province R, and x_j^R is the output of sector j of province R. e_j^R represents the amount of water/energy used to yield one monetary unit value of output in sector j of province R.

For a province R, the total water/energy footprint WF^R which is equal to the sum of net virtual water/energy import and internal water/energy consumption (Hoekstra and Hung, 2002) can be calculated by Eq. (6):

$$WF^R = E\, B\, Y^R \quad (6)$$

where $E=[e^1, e^2, \ldots, e^N]$ is a 1×n×m vector of all provincial sectors' direct water/energy consumption coefficients, Y^R represents the final consumption in province R.

2.3. Drivers of water/energy transfer

We determined the drivers of national virtual water/energy transfer by using the gravity model.

The general pattern of the gravity model is represented as follows (Bergstrand, 1985):

$$X_{ij} = \beta_0 Y_i^{\beta_1} Y_j^{\beta_2} N_i^{\beta_3} N_j^{\beta_4} D_{ij}^{\beta_5} A_{ij}^{\beta_6} u_{ij} \quad (7)$$

where X_{ij} represents the volume of virtual water/energy that flows from province i to province j. Y_i and Y_j represent the gross domestic product (GDP) in province i and j, respectively. N_i and N_j indicates population of province i and province j. D_{ij} represents the distance between province i and province j. And A_{ij} is a dummy variable indicating whether provinces are adjacent to each other. If they are adjacent to each other, $A_{ij} = 1$ and, conversely, $A_{ij} = 0$. u_{ij} indicates the error term.

Eq. (7) was log-transformed into a linear equation as follows:

$$\log(X_{ij}) = \beta_0 + \beta_1.\ \log(Y_i) + \beta_2.\ \log(Y_j) + \beta_3.\ \log(N_i) + \beta_4.\ \log(N_j) + \beta_5.\ \log(D_{ij}) + \beta_6.\ \log(A_{ij}) + u_{ij} \quad (8)$$

We added the cropland area per capita (CAP) in the gravity equation to investigate the impacts of land use on interprovincial virtual water/energy flow. This variable was added since and agricultural development can largely drive water and energy consumption (Foley et al., 2005). We also added precipitation (P) to explore its impact on virtual resource transfer.

After model specification, the augmented model can be represented by Eq. (9) as follows:

$$\log(X_{ij}) = \log(\beta_0) + \beta_1.\ \log(Y_i) + \beta_2.\ \log(Y_j) + \beta_3.\ \log(N_i) + \beta_4.\ \log(N_j) + \beta_5.\ \log(CAP_i) + \beta_6.\ \log(CAP_j) + \beta_7.\ \log(D_{ij}) + \beta_8.\ \log(A_{ij}) + \beta_9.\ \log(P_i) + \beta_{10}.\ \log(P_j) + u_{ij} \quad (9)$$

We ran the multivariate analysis to explore drivers associated with virtual water/energy transfer. We performed the homogeneity test of variance for the virtual water and energy transfer data to evaluate the degree of heteroskedasticity of the variables included in the analysis. The P-values for the homogeneity test of variance for virtual water and energy transfers are 0.080 and 0.162, respectively, indicating that the degree of heteroskedasticity in the data is not significant. Ordinary Least Square (OLS) regression was then applied in order to explore the drivers of virtual water or energy transfers. We used the ratio between internal water consumption (W_C) and energy consumption (E_C) (Eq. (10)) as the measurement for water-energy nexus relationship.

$$\text{nexus ratio} = Wc/Ec \quad (10)$$

We defined this index ourselves based on our understanding of the water-energy nexus. In Liu et al. (2015a, 2015b), nexus relationships refer to the interdependency between multiple issues and are addressed together. Water and energy are consumed in most of the human activities involved in the sectors of the multiregional input-output table. Additionally, the consumption of water and energy coincide with each other. For example, in agriculture, the water consumed in the food production process requires energy to pump the water. In industry, energy production requires the use of water to cool down machines and plants, or produce the materials used to generate the energy (e.g., biofuel). In order to represent the interdependency between water and energy consumption, we calculated the ratio between their consumption.

Following previous research (Zhao et al., 2015; Wood et al., 2018), we created a hypothetical without-trade scenario to estimate the influence of current interprovincial trade on the water-energy nexus relationship in provinces. The nexus ratio* under the "without-trade" scenario refers to the hypothetical water-energy nexus in a province in which no virtual water and energy were imported (Eq. (11)). Previous research assumes that under a "without-trade" scenario a given province would use more domestic resources to meet the total resource demand since no resources were imported, resulting in more domestic resource consumption (Zhao et al., 2015, Wood et al., 2018). Provinces' water-energy nexus ratio* under a without-trade scenario was therefore calculated by adding the trade balance (net import in our case) back to provinces in previous research (Zhao et al., 2015, Wood et al., 2018). To simulate the "without-trade" scenario, we followed Zhao et al. (2015) and Wood et al. (2018)'s methods by assuming that additional domestic production would supplement the original imported materials (Zhao et al., 2015, Wood et al., 2018). For example, the original nexus ratio under the "with-trade" scenario was evaluated using the ratio of domestic water consumption to domestic energy consumption for a province in reality. Under the "without-trade" scenario, there is no virtual water/energy trade to support domestic demand for water and energy. The province depends entirely on water and energy from local sources.

$$\text{nexus ratio}^* = (W_C + VW_{\text{net import}})/(E_C + VE_{\text{net import}}) \quad (11)$$

where $VW_{\text{net import}}$ and $VE_{\text{net import}}$ are the net imported virtual water/energy (Zhao et al., 2015, Wood et al., 2018). Admittedly, this approach must be seen as a simplified estimation given the complex environmental and socioeconomic dynamics that might unfold in the absence of trade. However, this without-trade scenario has been used in other fields to evaluate the impacts of trade on water scarcity and nutrient supply (Zhao et al., 2015, Wood et al., 2018), since it provides a useful approximation for measuring the impacts of trade on environmental systems.

3. Results

3.1. Interactions across water-energy nexus network

In interprovincial virtual water-energy flow network, more than 40% of the provinces gained in trading water at the expense of losing their own energy or gained in trading energy at the expense of losing their own water (Fig. 1). Almost a quarter (23%) of the provinces (Guangxi, Hunan, Jiangxi, Fujian, Anhui, Hebei, Heilongjiang) gained virtual energy but lost water, while 20% (Guizhou, Guangdong, Jiangsu, Shandong, Liaoning, Inner Mongolia) gained virtual water but lost energy. Twenty percent of the provinces (Xinjiang, Sichuan, Chongqing, Hubei, Shanxi, Jilin) lost both their water and energy. The remaining 36.7% of the provinces gained both water and energy at no cost.

Virtual water and energy networks tended to enhance each other (Fig. 2). The total exported water and exported energy for all provinces were significantly positively correlated, as were the total exported water and imported energy, the total imported water and imported energy, and the total imported water and exported energy (Fig. 2).

Surprisingly, 39.4% and 40.6% of interprovincial trade for energy and water trade, respectively, were from relatively resource-scarce provinces to resource-abundant provinces (Fig. 3). Furthermore, 33.3% and 26.7% of the provinces depended more on cross-border trade than their own internal resources to support their water and energy consumption, respectively (Table 1). Moreover, in terms of total trade volume, 83.3% and 73.3% of the provinces depended more on distant trade than adjacent trade to support their water and energy consumption, respectively.

Trade largely shaped the nexus ratio between internal water and energy consumption in provinces (Fig. 4). Trade increased the ratio between water and energy consumption in 47% of the provinces, while decreased the ratio in 53% of the provinces. The three provinces that increased most are Xinjiang (840%), Heilongjiang (140%) and Guangxi (122%). The provinces that decreased most are Shandong (−58%), Beijing (−50%) and Qinghai (−43%).

3.2. Drivers of virtual water and energy trade

GDP per capita, precipitation, cropland area per capita of both the sending and the receiving provinces, distance between provinces, whether or not provinces shared a border, population, and percent of industrial GDP in total GDP in the receiving province all significantly

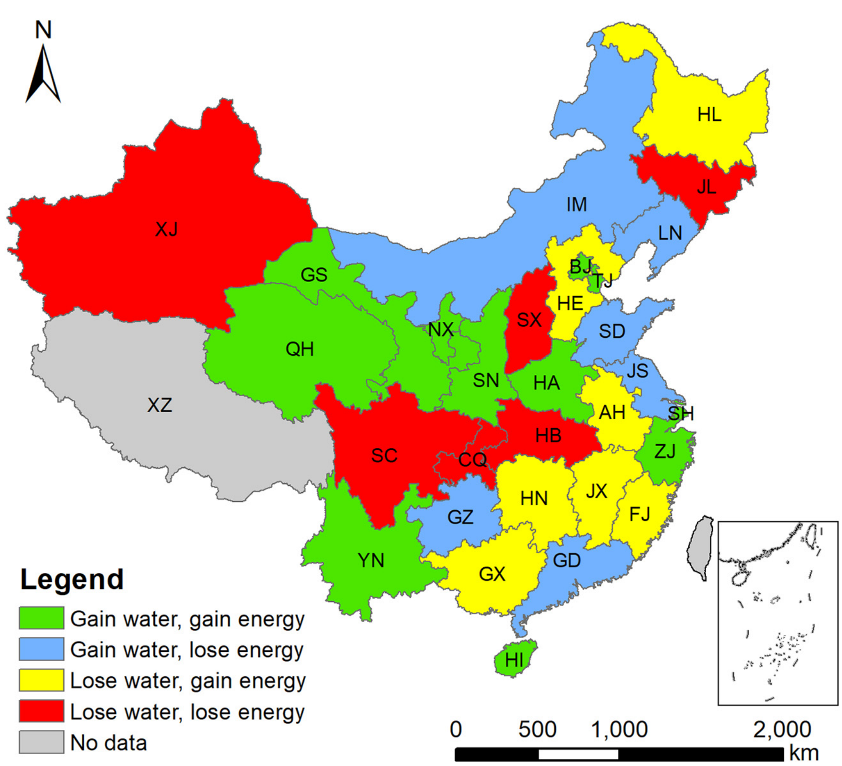


Fig. 1. Concurrent impact of interprovincial virtual water-energy transfer network on provinces (see full names of the provinces in Table 1).

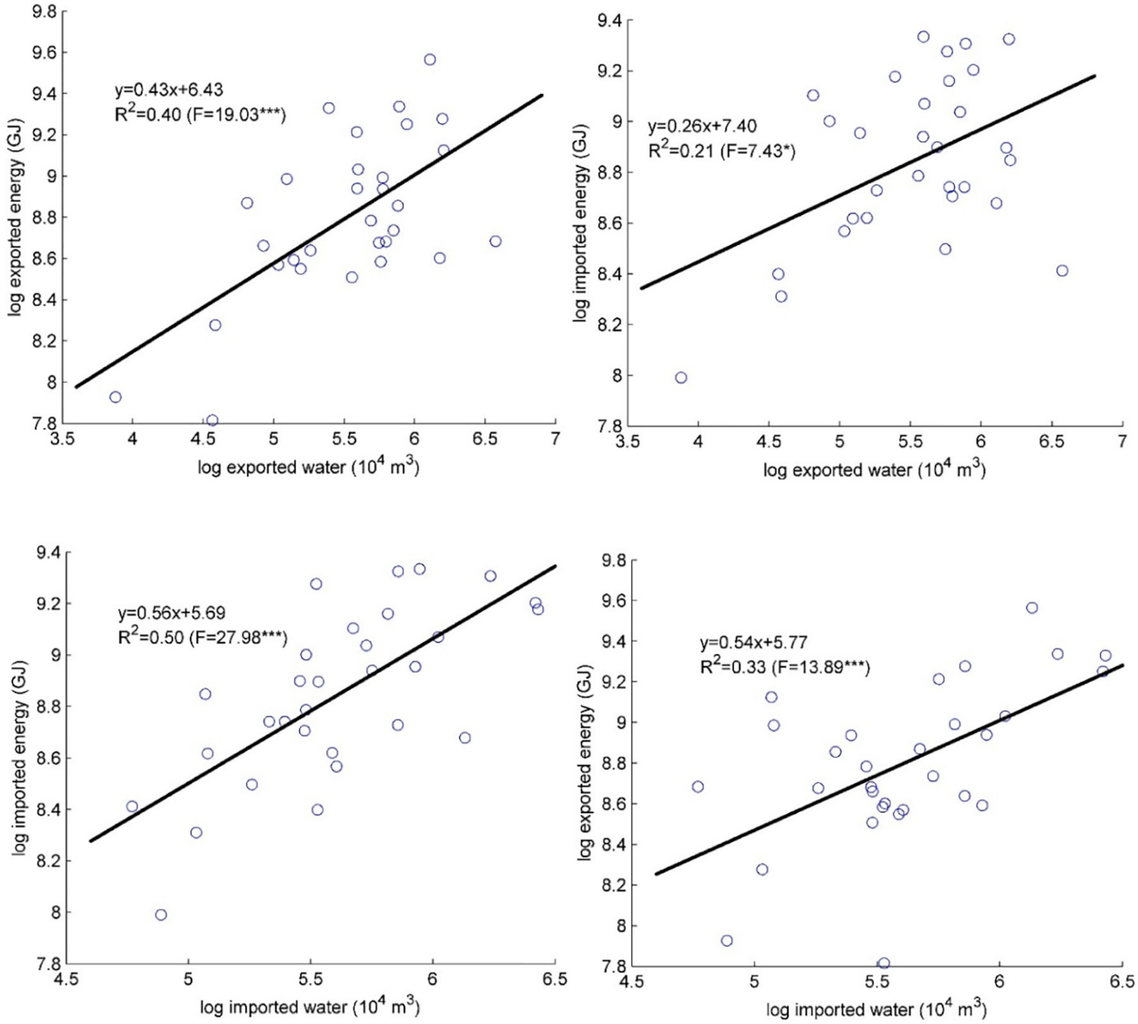


Fig. 2. Relationship between exported/imported water and exported/imported energy. The F-value represents the significance testing result from the fitting process. ***, and * reflects significance under significant level $a = 0.01$ and $a = 0.05$, respectively.

affected both the virtual water and energy flows. Population in sending provinces significantly affected the virtual energy flows, but not virtual water. Only the percent of industrial GDP in total GDP in sending provinces affected virtual water flows rather than energy (Table 2). There are more variables in receiving than sending areas that significantly affect the virtual water/energy transfer, indicating that receiving areas may be more determinant than sending areas in a virtual water/energy trade network, which is consistent with the previous research (Tamea et al., 2014).

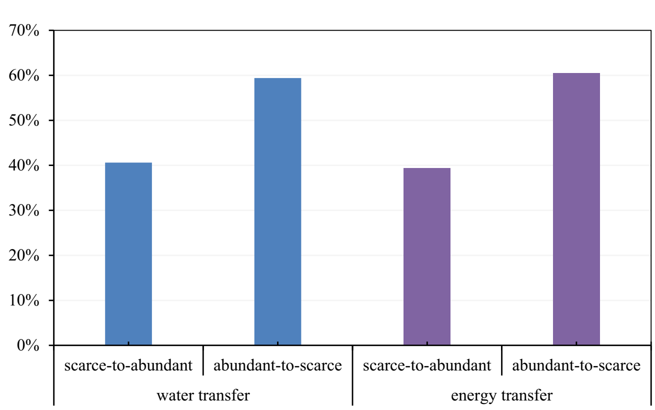


Fig. 3. Percentage of virtual water/energy transfer between relatively water/energy-scarce provinces and water/energy-abundant provinces.

These results indicate that the volume of bilateral virtual water and energy flows tends to be large between two provinces with strong economic bases and scales. The scale of the economy reflects the resource demand capacity and trade demand potential of the region, as well as the combined production capacity and export potential of the region. The larger the economic scale is, the greater the outside trade flow is, the greater the flows of virtual water and energy are. Therefore, the relationship between the economic scale and virtual water and energy trade of the two regions is positive. Population size has a significant positive correlation with virtual water and energy export and import. Population is the basis for economic development, and resource demand. So provinces with greater population sizes tend to have more trade interactions with other provinces.

For each trade link between one pair of trading provinces, as distance between provinces increases, the amount of virtual water and energy trade declines (Table 2). When one pair of trading provinces share borders, they tend to transfer more virtual water and energy to each other. The reason is that greater distance increases transportation cost, which significantly decreases the amount of trade. Also, trading provinces that share borders tend to be geographically closer, thus

Table 1
Volume of provinces' resource consumption supported by internal, adjacent and distant systems.

Provinces	Water (10^4 m^3)			Energy (GJ)		
	From internal system	From adjacent system	From distant system	From internal system	From adjacent system	From distant system
Beijing (BJ)	1.82×10^5	7.59×10^4	3.96×10^5	9.23×10^8	2.59×10^8	1.01×10^9
Tianjin (TJ)	1.24×10^5	4.35×10^4	2.59×10^5	5.85×10^8	2.25×10^8	7.79×10^8
Hebei (HE)	5.01×10^5	2.04×10^5	5.19×10^5	2.75×10^9	1.47×10^9	6.46×10^8
Shaanxi (SN)	3.69×10^5	4.07×10^4	7.92×10^4	1.76×10^9	2.09×10^8	2.06×10^8
Inner Mongolia (IM)	6.88×10^5	1.22×10^5	1.23×10^6	5.21×10^9	2.54×10^8	2.24×10^8
Liaoning (LN)	8.21×10^5	3.28×10^5	2.37×10^5	2.49×10^9	4.35×10^8	4.37×10^8
Jilin (JL)	8.81×10^5	4.98×10^4	6.75×10^4	8.82×10^8	4.7×10^8	2.35×10^8
Heilongjiang (HL)	6.29×10^5	1.26×10^5	2.07×10^5	1.25×10^9	9.77×10^8	9.14×10^8
Shanghai (SH)	7.56×10^5	2.46×10^5	6.36×10^5	1.48×10^9	5.67×10^8	1.59×10^9
Jiangsu (JS)	3.59×10^6	3.54×10^5	2.28×10^6	2.83×10^9	4.35×10^8	1.16×10^9
Zhejiang (ZJ)	6.86×10^5	2.75×10^5	3.80×10^5	1.22×10^9	4.55×10^8	9.92×10^8
Anhui (AH)	8.63×10^5	1.82×10^5	3.52×10^5	1.03×10^9	5.39×10^8	5.52×10^8
Fujian (FJ)	7.29×10^5	8.77×10^4	2.11×10^5	1.16×10^9	1.65×10^8	3.43×10^8
Shanxi (SX)	1.15×10^6	1.31×10^5	1.71×10^5	8.6×10^8	2.77×10^8	3.34×10^8
Shandong (SD)	1.92×10^6	6.94×10^5	2.00×10^6	4.08×10^9	3.31×10^8	1.17×10^9
Henan (HA)	1.11×10^6	1.71×10^5	8.81×10^5	2.71×10^9	3.58×10^8	8.17×10^8
Hubei (HB)	1.22×10^6	5.56×10^4	1.92×10^5	1.94×10^9	1.79×10^8	3.73×10^8
Hunan (HN)	1.59×10^6	1.29×10^5	1.57×10^5	1.81×10^9	3.75×10^8	4.19×10^8
Guangdong (GD)	2.50×10^6	1.00×10^6	7.21×10^5	2.75×10^9	3.75×10^8	1.65×10^9
Guangxi (GX)	1.31×10^6	1.50×10^5	1.90×10^5	8.77×10^8	3.76×10^8	4.12×10^8
Hainan (HI)	2.84×10^5	0	3.38×10^5	2.11×10^8	0	2.51×10^8
Chongqing (CQ)	4.05×10^5	6.69×10^4	1.15×10^5	7.16×10^8	98,564,763	2.16×10^8
Sichuan (SC)	1.52×10^6	4.19×10^4	1.72×10^5	1.79×10^9	1.73×10^8	3.79×10^8
Guizhou (GZ)	5.93×10^5	2.97×10^5	1.06×10^5	9.68×10^8	1.91×10^8	1.79×10^8
Yunnan (YN)	8.34×10^5	2.06×10^5	1.81×10^5	1.37×10^9	1.7×10^8	2.47×10^8
Shaanxi (SN)	4.40×10^5	1.51×10^5	6.97×10^5	8.77×10^8	5.25×10^8	3.77×10^8
Gansu (GS)	5.85×10^5	6.53×10^5	6.58×10^4	6.06×10^8	2.61×10^8	2.74×10^8
Qinghai (QH)	7.61×10^4	2.47×10^4	5.26×10^4	2.47×10^8	4.97×10^7	4.83×10^7
Ningxia (NX)	2.67×10^5	9.32×10^3	9.83×10^4	3.19×10^8	9.96×10^7	1.05×10^8
Xinjiang (XJ)	2.96×10^5	6.26×10^3	5.26×10^4	8.11×10^8	4.91×10^7	2.1×10^8

Notes: Abbreviations of province names are labeled in the parentheses.

decreasing transportation costs and facilitating greater trade between adjacent provinces. In addition, the effects of the proportion of industrial GDP on sending and receiving systems are different. The greater the proportion of industrial GDP in the exporting province, the more restricted the flows of virtual water and energy were. However, virtual water and energy flows increased with increases in the proportion of industrial GDP in the importing province. The reason may be that the virtual water and energy trade is driven more by demand than supply (Tamea et al., 2014). Provinces with greater local industry would have greater internal resource consumption and import more resources but provide less resources to other provinces.

We also found that land use (cropland area per capita) significantly affects virtual water and energy trade. More cropland area per capita in the sending province tends to be associated with increased virtual water and energy trade. But in receiving provinces, more cropland per capita leads to less virtual water and energy trade. This may be because the surplus of cropland area can be used to produce food for export, which is one type of economic benefit that accelerates virtual water/energy export. Also, surplus cropland area may be indicative of less demand for trade since the province can feed itself to an extent. Precipitation has positive effects on trade in exporting provinces but negative effects on trade in receiving provinces. The reason may be that precipitation increases local water

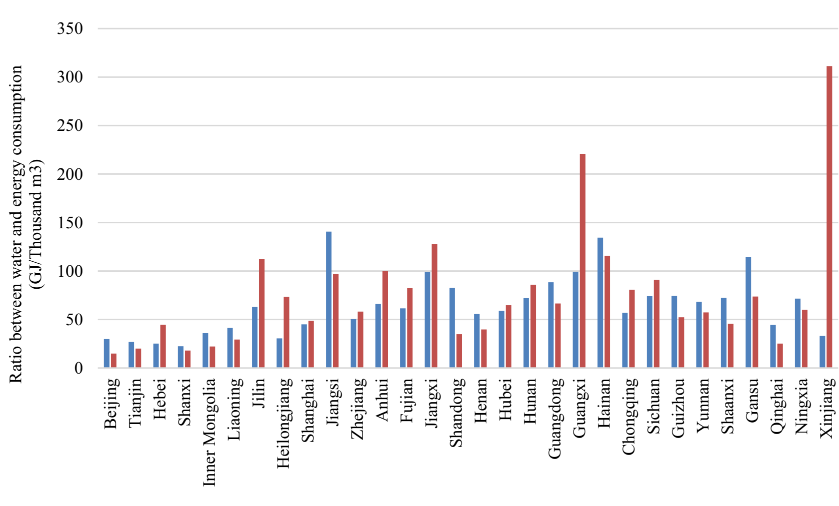


Fig. 4. Water-energy nexus ratio (the ratio between internal water and energy consumption) in each province under with trade and without trade scenarios.

Table 2
OLS results for augmented gravity model about drivers of water and energy transfer.

Variables	Water	Energy
Population_sending	0.158	0.749**
	(0.126)	(0.086)
Population_receiving	1.433**	1.354**
	(0.100)	(0.068)
GDP per capita_sending	1.497**	1.211**
	(0.126)	(0.086)
GDP per capita_receiving	0.471**	0.436**
	(0.077)	(0.052)
Cropland area per capita_sending	1.037**	0.304**
	(0.107)	(0.073)
Cropland area per capita_receiving	−0.425**	−0.404**
	(0.072)	(0.049)
Percent of industrial GDP in total GDP_sending	−1.327**	−0.024
	(0.107)	(0.191)
Percent of industrial GDP in total GDP _receiving	0.769**	0.480*
	(0.280)	(0.191)
Precipitation_sending	0.320**	0.475**
	(0.118)	(0.080)
Precipitation_receiving	−0.352**	−0.560**
	(0.113)	(0.077)
Distance between sending system and receiving systems	−0.696**	−0.833**
	(0.094)	(0.064)
Border dummy (whether provinces share border or not)	0.262**	0.248**
	(0.067)	(0.064)
Constant	−1.581	4.729**
	(0.853)	(0.583)
R^2	0.577	0.712
F	97.368	176.743
P-value for homogeneity test of variance	0.08	0.16

Dependent variable: virtual water and energy transfer. Standard deviations were put in parentheses.
Notes: the number in table represents the coefficients of variables. *, ** denotes significance at 0.05, and 0.01 level.

levels, therefore decreasing the demand for virtual trade of water and increasing the possibility of exporting virtual water for profit.

4. Discussion

Our study finds that in this virtual water and energy network, more than 40% of provinces gained in trading water at the expense of losing their own energy or gained in trading energy at the expense of losing their own water. Twenty percent of provinces suffered a double loss of both their own internal water and energy, while the rest of provinces gained both water and energy through trade at no cost to their own internal water and energy. GDP is one important driver of virtual water and energy transfer. After China's “reform and opening up”, China's GDP grew about 10% annually from 1979 to 2013 (Morrison, 2014), with associated growth in the demand for water and energy. This growing economic development likewise drives virtual water and energy transfer and increases their impacts on trading systems.

Virtual water and energy flows are driven by economic development rather than motivated by alleviating water or energy scarcity, as virtual water and energy transfers are embodied in commodity trade. Distance between trading systems has a significant negative impact on the transfer of virtual water and energy, most likely due to the increasing transportation cost. Cropland area per capita in a sending province is another important driver of virtual water/energy trade. This may be because the surplus of cropland area can be used to produce food for export, which is one type of economic benefit that accelerates virtual water/energy export.

Cross-sectoral impacts should be considered in future analyses (Liu et al., 2015a, 2015b). The virtual water and energy networks are highly positively interrelated. Provinces with large amounts of imported and exported virtual water tend to also have substantial amounts of imported and exported amounts of virtual energy and vice versa. Benefits in water or energy trade in one place may be associated with impacts on energy or water in a distant place, which may lead to unexpected costs and inefficiency of management. Therefore, more holistic policies considering cross-sectoral impacts over distances should be developed to maximize the efficiency of integrated management.

Considering distant interactions in trading networks helps local governments find hidden factors affecting local water and energy systems. In the case of virtual water-energy networks, distant areas have even more impacts on a focal area than adjacent areas. The reason may be that there are more distant provinces than adjacent provinces, thus the trade interactions between distant provinces were greater than those between adjacent provinces. Furthermore, in many provinces, cross-border virtual resource trade is greater than domestic resource consumption. Thus more cooperative resource management with distant systems should be developed (Liu et al., 2013).

Our driver analysis revealed that virtual water/energy trade may be motivated more by the demand side than by the supply side. Therefore, more demand-side policies should be developed to reduce resource consumption and environmental burden. For example, in virtual water trade, the false perception of limitless water availability due to low water usage cost in a virtual water-receiving province (demand side) would encourage the receiving province to promote water-intensive activities (Zhao et al., 2015), thus leading to water pressure on virtual water-exporting provinces (supply side). Ignoring such an issue may trigger a series of unexpected changes (e.g., water scarcity, biodiversity loss, and vulnerable economy) in both the water-receiving and water-exporting systems. Developing demand-side policies can avoid such negative consequences. For example, if the government considers charging a virtual water tax on imported commodities in virtual water receiving provinces, this could motivate more efficient water use and virtual water importing provinces could take more responsibility for water consumption in virtual water exporting provinces (Zhong and Mol, 2010; Lenzen et al., 2012). Thus, water waste and water scarcity due to virtual water trade can be controlled. Our driver analysis also provides useful information for predicting the virtual resource trade and choosing potential partners to develop collaborative relationships for managing virtual resource trade. Based on our analysis, if provinces were to develop collaborations and policies to control the virtual resource trade, it would be advantageous to choose receiving provinces with a strong economic base, particularly with a high industrial GDP and large population. Additionally, the results of the driver analysis can also supply information for dividing responsibility for virtual resource consumption and management when trading partners debate about who should take more responsibility and how to control the virtual resource trade based on the significant drivers.

In our study, the interactions between provinces across the virtual water and energy nexus network at the national scale are further revealed, contributing to a more holistic understanding of virtual resource studies. Future research should extend this study by assessing the interactions across multiple types of virtual resource/material flows beyond virtual water and energy, for example, to include virtual land and carbon across spatial and temporal scales (Lu et al., 2015). This could further reveal the relationships (e.g., trade-offs, synergies) between more complex virtual resource/material transfer networks and their impacts on national sustainability and result in a more in-depth understanding of the mechanism of interactions within and between adjacent and distant systems (Liu, 2018). Our study on two types of distant resource transfer networks could improve our understanding of cross-border interactions, uncover hidden problems that could give rise to national crises, and facilitate an increased understanding of the importance of adjacent and distant interactions and their associated implications for policy.

5. Conclusions

Our paper investigated the interactions across two types of virtual resource transfer networks – energy and water at the national scale, using China as a case study. The results showed that more than 40% of provinces gained one type of resource (either water or energy) by trade at the expense of losing the other type of internal resource (energy or water), and 20% of the provinces suffered a double loss of both water and energy. The rest of provinces gained both water and energy. Moreover, 33.3% and 26.7% of the provinces depended more on cross-border trade than on internal resources to support their water and energy consumption, respectively. Furthermore, most of provinces relied more on distant provinces via trade than adjacent ones to support their water and energy consumption. Unexpectedly, approximately 40% of virtual water/energy flow was from relatively water/energy-scarce provinces to water/energy-abundant provinces, leading to resource inequality. Virtual water-energy networks tended to enhance each other. Our study suggests the urgent need to study multiple virtual resource networks simultaneously and to build cross-sectoral and holistic policies to achieve sustainable resource use.

Acknowledgements

We acknowledge the insightful editorial comments from Sue Nichols.

Funding

We are grateful for financial support from the National Science Foundation, Michigan State University, MSU AgBioResearch, and China Scholarship Council.

Author contributions

Z. X., J.L., and Y.L. designed the research. Z. X., and J.L. performed the research. Z.X., A.H., X.C., K.K., C.H., M.M. and Y.T. analyzed the data and wrote the manuscript.

Competing interests

The authors declare that they have no competing interests.

Data and materials availability

All data related to paper which are publicly available online are at http://www.stats.gov.cn/. Additional data related to this paper may be requested from the authors.

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