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Understanding the tele-coupling mechanism of urban food-energy-water nexus: Critical sources, nodes, and supply chains

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ABSTRACT

With the increasing urbanization but growing resource scarcities, the securing provision of fundamental resources as food, energy and water (FEW) has become a unique challenge for urban sustainability. This is not only because of continuous demand of resource imports from different regions for urban areas, but also due to the complex interrelationships among FEW systems. In such context, exploring the interactions between FEW resources and economic activities when investigating FEW provisions to meet urban demand through trade is very essential to find effective policy intervention points and priority areas for actions. This paper investigates external binding FEW resource flows with internal certain interlinkages driven by final demand of Beijing city at different nodes along their supply chains, by combing structural path analysis and multi-regional input-output model of China 2010. The results show that the key source regions present overall neighborhood pattern that Hebei, Inner Mongolia, Anhui, Jiangsu, and Shandong near Beijing are the five leading contributors of tran-regional FEW provisions. The top 20 nexus paths are identified and the most important nexus pathways start with the other services in Beijing. Besides this, the critical supply chains appear divergent directions for FEW flows, driven by food, construction and agriculture industries respectively. Moreover, the key nodes mainly concentrate on less developed regions and energy-related sectors. For example, non-metal products manufacturing in Hebei, petroleum refining and coking in Heilongjiang, and coal mining and washing in Inner Mongolia have larger impacts on all of FEW flows across the supply chains. These results are very informative to targeting our efforts to address the urban FEW nexus issue both from the perspective of supply side and demand side.

1. Introduction

Our world is increasingly urbanized with immense changes in physical and social infrastructures (Seto and Ramankutty, 2016), which correspondingly alter our relationships with fundamental resources as food, energy and water (FEW) (Bazilian et al., 2011). The sustainable provisions of FEW for urban system are becoming very challenging under the global context of growing demand but depleting supply due to resource scarcity (Chen, 2007). Such predicament is tangled and exacerbated by the complex interdependence of these three systems, which is framed by the food-energy-water nexus—FEW nexus. Changing components of one system may procure desired or undesired ripple effects on other systems. That is, solutions implemented in one sector can have unintended and dangerous consequences in other two sectors (Eftelioglu et al., 2017). For instance, production of food or energy at a location (e.g., the vast plain in northwest China) is limited by and has great impact on the availability of water. Traditional sector-based and region-bound governance paradigm often places food, energy and water in competition (Owen et al., 2018). This calls for innovative approaches to model the FEW nexus as an integrated whole, instead of examining them individually, to identify co-benefits and

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avoid unexpected consequences or problem-shifting.

Urban systems largely obtain FEW resources outside of their physical boundaries, and create environmental impacts that extend beyond city borders (Heard et al., 2017). In other words, most of FEW demands for urban systems are met through trade and direct imports (Walsh et al., 2006). The increasing share of trade has made the relationship between FEW provisions more complex at urban scale as materials and energy are transferred crossing regions along multifaceted supply chains. The impacts of cities outside of their immediate geographies and their relationships to FEW resources must be considered in the planning and policy, otherwise the true sustainability of cities will not have been properly considered (Heard et al., 2017). To produce fully informed analysis of urban sustainability, there is also great need for innovation in modeling methods and governance practices that recognize the tele-connections between cities and their interlinked regions.

There is increasing attempts to address urban FEW issues under nexus view (Artioli et al., 2017; Gondhalekar and Ramsauer, 2017; Sherwood et al., 2017). To date, several studies have been conducted to explore the local FEW nexus in a single city, or some comparative cities. The central focus of these studies are mainly associated with FEW footprints accounting (Zhang et al., 2014, 2018a; Fang and Chen, 2017; Wang et al., 2018), resilience/sustainability evaluation (Willis et al., 2016; Abbott et al., 2017; Schlör et al., 2018), and dynamic modeling of FEW demands (Feng et al., 2013; Li et al., 2016; Xu and Szmerekovsky, 2017). These research works definitely improve our understanding of FEW nexus at urban scale, but the tele-connections between cities and their interlinked regions with regard to combined FEW provisions and their relationships among the supply chain networks remain unknown and need further investigation.

The development of input-output analysis technology especially the multi-regional input-output (MRIO) model offers new option to use these environmental accounting tools to investigate the tele-coupling mechanism between FEW nexus across global supply chains (Owen et al., 2018; White et al., 2018). Such models are capable of tracing the trans-boundaries resource consumption and environmental pressures embodied in the goods and services brought by consumers, through inter-industry linkages, multi-regional/national supply chain and global trade (Peters et al., 2011; Xia et al., 2015; Hong et al., 2016). Using MRIO database to investigate the role of trade in carbon leakage, land use and resources/material flows have been proved to be useful (Giljum et al., 2009; Strømman et al., 2009; Lenzen et al., 2013; Wen and Wang, 2019). Meanwhile, only few of researches have involved city-induced resource-environmental impacts based on MRIO database (Wiedmann et al., 2015), for example carbon emission (Feng et al., 2014; Lin et al., 2017), water/energy consumption (Zhang et al., 2011, 2015) and water-energy nexus (Chen et al., 2018).

Structural path analysis (SPA) is a well-established technique in input-output analysis (Treloar, 1997; Lenzen, 2007; Meng et al., 2015). Combined with SPA, MRIO model has a significant advantage to identify the intricate chain of regional production process instigated by urban final demand, and thus can help to unveil the tele-coupling mechanism of resources/material flows between cities and their hinterlands. Matching the new development in detailed MRIO database and growing interests from multiple disciplines, some researches were conducted in the last several years, to investigate the resource-environmental impacts of FEW systems along supply chain by using SPA and MRIO models at national and global scales (Owen et al., 2016; Liang et al., 2016; Zhang et al., 2017; Shao et al., 2018). For instance, Font Vivanco et al. (2018) analyzed the critical supply chain and feedbacks of water-energy nexus between China and the United States, based on these two models. More importantly, Owen et al. (2018) adopted global MRIO model to investigate the interlinkages between FEW impacts of products consumed by UK and identify the top twenty nexus pathways contributing to UK's FEW footprints.

As illustrated above, the FEW nexus was primarily proposed and defined as linkages among food, energy and water. This concept has been expanded and interpreted from different perspective since Bonn conference in 2011, with regard to resource efficiency, resource security and system resilience (Chang et al., 2016; Zhang et al., 2019). Some studies have extended the nexus as a dual coupling between human beings and nature (FAO, 2014; Liu et al., 2015; Bleischwitz et al., 2018; Liu et al., 2018), which is particularly meaningful for urban scale analysis. In such case, FEW nexus is perceived as an external binding resource component with internal certain interlinkage that is an essential ingredient to drive economic development. White et al. (2018) regarded FEW nexus as the interactions between FEW resources and economic activities when investigating water, energy, and food provisions to meet demand at the sub-national (regional), national, and supra-national level through global trade. The FEW nexus was also defined as the interaction between the energy, water and food impacts of products at different points along their supply chains (Owen et al., 2018).

This paper aims to explore the tele-coupling mechanism of urban FEW nexus that could help to promote coordinating resource management for city and its hinterlands. Take Beijing as case city, we use MRIO database of China 2010 to investigate the interaction between food, energy, and water impacts of products at different points along their supply chain crossing city and supporting regions. For instance, those products with highest food, energy and water impacts can be regarded as nexus product. In such context, the key sources, nodes and critical supply chain associated with final consumption can be identified.

The rest of the paper is structured as follows. In Section 2, we introduce the methods and data used in this study. Section 3 presents the modeling results of FEW provisions along supply chain driven by final demand of urban Beijing. In Section 4 we discuss the policy relevance of our results. Conclusion is given in Section 5.

2. Material and methods

A framework has been proposed to denote the interrelationships between city and its supporting regions. As illustrated in Fig. 1, there are two ways for city to access to FEW resources from other regions. On one hand, FEW resources are directly imported to satisfy the urban demands of residential consumption and economic activities. On the other hand, FEW resources embodied in the products and services are transferred into urban system through

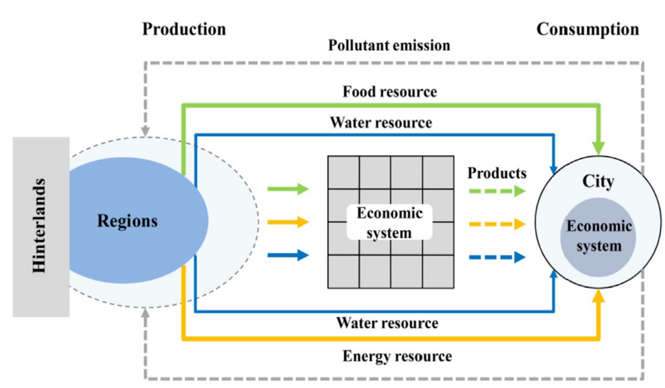

Fig. 1. The framework for modeling the FEW nexus between city and its hinterlands.

trade flows. Since the direct import of FEW is easily accounted, this paper mainly focuses on the embodied FEW along supply chain using MRIO model that driven by urban final consumption.

2.1. MRIO analysis

As mentioned above, to date MRIO models are one of the most widely used approaches to investigate the economic and resource interdependence between different regions (Wiedmann, 2009; Li et al., 2017). In general, the fundamental equation in the IO table can be expressed as:

$$x = Ax + y \tag{1}$$

$$x = (I - A)^{-1} y = Ly \tag{2}$$

where x represents total output of each sector; I is the identity matrix; A denotes the technology coefficient matrix, indicating the amount of intermediate input from one sector of the total input used by another sector; $L = (I - A)^{-1}$ is the Leontief inverse matrix; y is the vector of final demand.

The essential equation for accounting sectoral food, energy and water consumption can be expressed as

$$Q = \varepsilon L y \tag{3}$$

where Q is the embodied food, energy and water consumption; ε represents the food, energy and water resource intensity per output of one sector.

2.2. SPA

The basic idea underneath SPA method is the unraveling of the Leontief inverse by means of a series expansion of the direct requirements matrix (Waugh, 1950). To extract the main upstream impacts, the Leontief inverse matrix of Equation (2) can be rewritten using the Taylor expansion approximation as:

$$L = (I - A)^{-1} = I + A + A^2 + A^3 + \cdots + A^n \quad (n \to \infty) \tag{4}$$

The Equation (3) can then be expanded to

$$Q = \varepsilon (I - A)^{-1} y = \varepsilon I y + \varepsilon A y + \varepsilon A^2 y + \varepsilon A^3 y + \cdots \varepsilon A^n y \tag{5}$$

where $\varepsilon A^n y$ denotes the resource-environmental impacts from the *nth* production layer. For example, given y is the final demand for a car: $\varepsilon I y$ represents the direct resource consumption in the production of the car by its manufacturer, which is well known as the zeroth order path. To produce the car, it needs Ay from other sectors inputs; these sectors consumed $\varepsilon A y$ of resources, which is the first paths. In turn, these sectors also need $A(Ay)$ inputs and $\varepsilon A^2 y$ of resources are consumed (Peters and Hertwich, 2006). In such manner, this process could continue through the infinite expansion of Leontief inverse matrix continues.

For MRIO model, the element Q for accounting resources consumption can be similarly estimated by the following equation,

$$Q = \sum_{i,j=1}^{n} \varepsilon_i \left(I_{ij} + A_{ij} + A_{ij}^2 + A_{ij}^3 + \cdots \right) y_j \tag{6}$$

$$Q = \sum_{i,j}^{n} \varepsilon_i \left(I_{ij} + A_{ij} + \sum_{k=1}^{n} A_{ik} A_{kj} + \sum_{l=1}^{n} \sum_{k=1}^{n} A_{il} A_{lk} A_{kj} + \cdots \right) y_j \tag{7}$$

where i, j, k and l are the sectors. The first layer path is accounting by $\varepsilon_i A_{ij} y_j$; the second layer path is calculated by $\varepsilon_i A_{ik} A_{kj} y_j$, from sector i through sector k into sector j, and so on (Wood and Lenzen, 2003).

2.3. Identification of critical paths and nodes

Considering that the MRIO table of China 2010 contains 900 sectors (see section 2.4), there would be inexhaustible supply chain paths to feed resource to Beijing region. As formulated by Equation (6), the amount of supply chain paths in the first layer would be $30 \times 30 = 900$, the amount of paths in the second layer is $900^2 = 810000$, and the amount of the path in the nth layer is 900^n. In practice, although SPA could generate innumerable paths, only a very small share of the total paths is analyzed (Sinos et al., 1997), since the contribution usually decreases sharply along with the increase of orders of upstream layers. In such case, we only search the supply chain paths up to the 5th layer and identify the top 2000 unique paths that rank highly in FEW consumption by MATLAB programming. For each type of the FEW resource consumption, the highest sector or path is scored 1, the second highest is 2, and so on. Then, we re-sort the sum of these three scores in descending order to identify the comprehensive highest ranking sectors and paths.

Among the large network of multi-regional interactions, there are certain sectors of certain regions simultaneously play important role for all the FEW resource paths, which can be regarded key node for supply chains. That is, they have large flow rates and multiple connections to other sectors. To identify these sectors or nodes, Pajeck and VOSviewer tools are used to denote and visualize FEW resource flows under the driver of target city of Beijing.

2.4. Data source

In this study, two types of data are involved for the development of MRIO model, i.e., multi-regional input-output table, and environmental satellite matrices of Beijing city and other provinces. The most recent MRIO table available for China was published in 2010, with 30 provinces and 30 sectors (not including Xizang, Hong Kong, Macao, and Taiwan), complied by Liu et al. (2014). Environmental satellite matrices are developed based on FEW resources consumption data. Specifically, food consumption was taken from the China Agriculture Yearbooks (MARA, 2011). Similarly, the energy and water consumption data was collected and compiled from the Chinese Energy Statistics Yearbooks, Provincial or City Statistics Yearbooks (NBS, 2011a; NBS, 2011b), Water Resources Bulletin for each province and the China Environmental Statistics Database. The detailed information about provinces and sectors can be found in the appendix (see Table A.1, A.2, A.3 in appendices).

3. Results

3.1. FEW footprints of final demand

Fig. 2 illustrates the total FEW footprints triggered by Beijing's final demand in 2010. Evidently, Beijing city has been highly dependent on other regions for FEW inputs to satisfy its final consumption. In terms of footprint, about 65.5% of food, and 55.4% of energy, and 80.6% of water are from outside the geological boundary of Beijing. In other words, over half of FEW resources embodied in the products consumed by Beijing are transferred from other regions through domestic trade flows. In addition to the embodied flows, more than 90% of grain and energy are directly imported from other regions for end user, since Beijing has been lack of natural resources (BMBS, 2017). For water, the middle route of the South-to-North Water Diversion Project has started to work since 2008, with the accumulated amount of 3.2 billion m^3

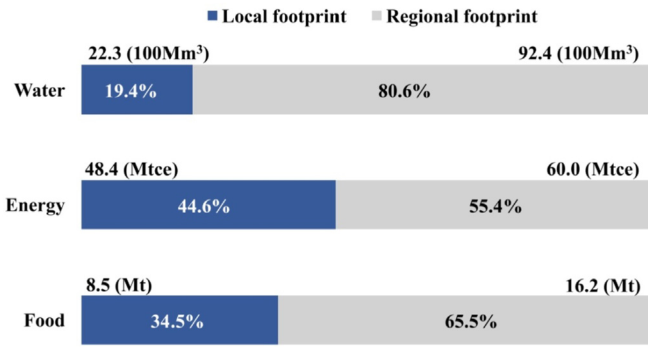

Fig. 2. FEW footprint of final demand in 2010.

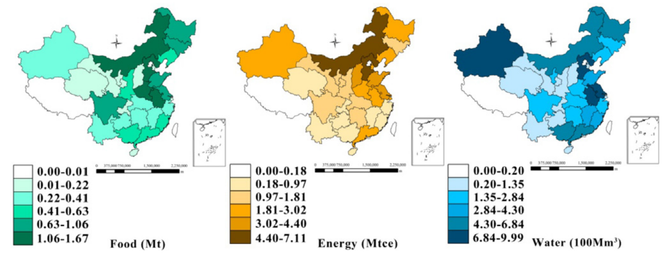

Fig. 3. Regional FEW provisions to Beijing.

transferred to Beijing.

Table 1 shows the top 20 nexus sectors that have highest FEW impacts, which contribute to 35.7%, 27.7% and 55.0% of the total FEW footprints induced by urban final consumption in Beijing, respectively. Overall, the other services sector in Beijing is the largest food-energy-water consumer. However, the majority of sectors identified are agriculture, the consumption of which leads to large FEW footprints, especially for indicators of food and water. With regard to individual indictor, the sector of other services in Beijing has the largest energy footprint and agriculture in Beijing highest water footprint. The largest consumer of food resource is food manufacturing sector in Beijing, which is not ranked in this table.

3.2. Key regions for FEW provisions

The spatial distribution of key regions for FEW provisions presents some characteristic of neighboring pattern, see Fig. 3. Provinces of Hebei, Inner Mongolia, Jiangsu, Anhui and Shandong which are close to Beijing serve as leading supporters for food and energy. Unlike food and energy, the key regions associated with water embodiment are not so concentrated geographically, with the largest four contributors of Xinjiang, Hebei, Jiangsu and Guangdong provinces. It is worthwhile to note that Xinjiang has transferred about 0.9 billion m^3 (8.1%) of virtual water with water-intensive goods (e.g. agricultural products as cotton and wheat) to Beijing in 2010. As the most controversial arid and semi-arid area for water use in China, Xinjiang has the highest agricultural water use, accounting for 96%–98% of the region's water consumption (Zhang et al., 2018b).

As described above, the rank of each province was obtained by summing the ranking of three individual indicators of FEW. The provinces of Hebei, Inner Mongolia, Jiangsu, Anhui and Shandong take the top five places as the largest FEW suppliers to Beijing, accounting for 39.1%, 37.4%, and 36.3% of total provisions, respectively. These five provinces are significant food and energy production bases, which also face severe water shortage problems in China. For instance, the per capita water resource of Hebei and Shandong were only 236.18 m^3 and 322.70 m^3 in 2010. To be specific, for food provision, the sectors of agriculture (S1), food industry (S6), and textile industry (S7) are identified as the greater contributing sectors with regard to Beijing's final demand in 2010. Water provision of these five top-ranking provinces mainly concentrates in agriculture (S1). In contrast, energy provision is much related to the heavy industries, such as coal mining and washing (S2), chemical industry (S12), non-metal products manufacturing (S13), metallurgy (S14), and so on. By province, the key sectors for energy provision are different. For instance, non-metal products manufacturing (S13), and electricity and heat water (S22) in Hebei are the larger contributors to provide embodied energy. Chemical industry (S12) and metallurgy (S14) in Inner Mongolia also have more important impacts on energy provision to Beijing.

3.3. Critical supply chain paths

Tables 2–4 show the top 20 supply paths with large FEW flows resulting from the products consumption of Beijing in 2010, respectively. These top 20 pathways contribute to 25.7%, 21.3%, and 20.6% of the total FEW consumption, respectively. The most

Table 1
Top 20 nexus sectors for FEW footprints.

	Regions	Sectors	Food rank, % of total	Energy rank, % of total	Water rank, % of total
1	Beijing	Other services	3 (5.1%)	1 (8.9%)	8 (4.0%)
2	Beijing	Agriculture	2 (5.3%)	21 (0.8%)	1 (8.5%)
3	Beijing	Hotel and restaurant	5 (4.2%)	10 (1.8%)	23 (1.1%)
4	Beijing	Chemical industry	7 (2.9%)	9 (2.0%)	49 (0.1%)
5	Beijing	Leasing and commercial services	4 (4.7%)	15 (1.4%)	51 (0.1%)
6	Beijing	Construction	21 (1.2%)	11 (1.5%)	42 (0.2%)
7	Beijing	Scientific research	26 (1.1%)	18 (1.0%)	30 (0.5%)
8	Hebei	Agriculture	24 (1.2%)	77 (0.2%)	5 (4.6%)
9	Shanxi	Coal mining and washing	57 (0.3%)	17 (1.0%)	43 (0.2%)
10	Inner Mongolia	Agriculture	31 (0.8%)	132 (0.1%)	10 (3.2%)
11	Beijing	Transport and storage	181 (0.04%)	2 (7.8%)	22 (1.2%)
12	Anhui	Agriculture	17 (1.4%)	189 (0.08%)	3 (6.2%)
13	Guangdong	Food industry	13 (1.7%)	109 (0.2%)	91 (0.07%)
14	Jiangsu	Agriculture	35 (0.7%)	185 (0.08%)	4 (5.8%)
15	Shandong	Agriculture	27 (1.0%)	190 (0.08%)	12 (3.0%)
16	Henan	Agriculture	19 (1.3%)	197 (0.07%)	20 (1.5%)
17	Xinjiang	Agriculture	39 (0.6%)	196 (0.07%)	2 (7.9%)
18	Hebei	Transport and storage	34 (0.7%)	43 (0.5%)	162 (0.04%)
19	Heilongjiang	Agriculture	22 (1.2%)	215 (0.06%)	6 (4.5%)
20	Fujian	Agriculture	53 (0.4%)	201 (0.07%)	13 (2.3%)

Table 2
Top 20-ranking paths for food consumption.

Rank	Contribution (Mt), % of total	Key paths
1	0.96 (3.88%)	Beijing-Other services
2	0.61 (2.47%)	Beijing-Other services → Beijing-Food industry
3	0.55 (2.22%)	Anhui-Food industry
4	0.52 (2.10%)	Beijing-Food industry
5	0.49 (1.98%)	Beijing-Hotel and restaurant
6	0.35 (1.42%)	Beijing-Leasing and commercial services
7	0.28 (1.13%)	Beijing-Agriculture
8	0.27 (1.09%)	Beijing-Other services → Beijing-Leasing and commercial services
9	0.27 (1.09%)	Beijing-Other services → Beijing-Food industry → Beijing-Hotel and restaurant
10	0.25 (1.01%)	Beijing-Construction
11	0.22 (0.89%)	Inner Mongolia-Food industry
12	0.22 (0.89%)	Beijing-Other services → Beijing-Hotel and restaurant
13	0.19 (0.77%)	Beijing-Chemical industry
14	0.18 (0.73%)	Beijing-Other services → Beijing-Chemical industry
15	0.18 (0.73%)	Jiangsu-Food industry
16	0.17 (0.69%)	Beijing-Scientific research
17	0.16 (0.65%)	Sichuan-Food industry
18	0.16 (0.65%)	Shandong-Food industry
19	0.16 (0.65%)	Guangdong-Food industry
20	0.15 (0.61%)	Henan-Food industry

Note: the paths starting from the final demand of a sector and ending with a resource supply sector.

Table 3
Top 20-ranking paths for energy consumption.

Rank	Contribution (Mt), % of total	Key paths
1	7.43 (6.86%)	Beijing-Other services
2	2.30 (2.12%)	Beijing-Transport and storage
3	1.52 (1.40%)	Beijing-Construction → Hebei-Non-metal products manufacturing
4	1.32 (1.22%)	Beijing-Construction
5	1.17 (1.08%)	Beijing-Other services → Beijing-Transport and storage
6	1.10 (1.02%)	Beijing-Construction → Beijing-Non-metal products manufacturing
7	0.94 (0.87%)	Beijing-Hotel and restaurant
8	0.85 (0.79%)	Beijing-Other services → Beijing-Other services
9	0.73 (0.68%)	Beijing-Petroleum refining and coking
10	0.73 (0.68%)	Beijing-Scientific research
11	0.67 (0.62%)	Beijing-Construction → Inner Mongolia-Metallurgy
12	0.59 (0.54%)	Beijing-Chemical industry
13	0.56 (0.52%)	Beijing-Other services → Beijing-Chemical industry
14	0.56 (0.51%)	Beijing-Electric power and heat power supply
15	0.47 (0.43%)	Beijing-Transport and storage → Beijing-Transport and storage
16	0.45 (0.41%)	Beijing-Leasing and commercial services
17	0.43 (0.40%)	Beijing-Electrical equipment and machinery → Beijing-Metal ore mining
18	0.42 (0.39%)	Beijing-Other services → Beijing- Electric power and heat power supply
19	0.42 (0.39%)	Beijing-Other services → Beijing-Hotel and restaurant
20	0.40 (0.37%)	Beijing-Other services → Beijing-Petroleum refining and coking

important nexus pathways all start with the other services in Beijing (S30), responsible for 8.5%, 10.4%, and 4.3% of the total FEW consumption, respectively. There are 6, 7 and 3 of the top 20 paths for FEW flows, associated with other services in Beijing, and the closest path shared by FEW flows is its direct consumption.

The critical supply chains exhibit divergent directions for FEW flows, dominated by food industry (S6), heavy industries (such as petroleum refining, chemical industry, and non metal products) and agriculture (S1). The path patterns for food and water flows are similar, mainly caused by direct consumption of food industry and agriculture, respectively. This indicates that the connections between these two sectors and other sectors are relatively weak. However, energy paths are relatively complex, with a large fraction of its top pathways associated with heavy industry inputs driven by services and construction. For instance, indirect consumption of petroleum refining and coking (S11), chemical industry (S12), non-mental products manufacturing (S14), and metallurgy (S13) occur in these top energy paths. In addition, half of the top 20 paths for food and water flows have their destination outside Beijing, while there are only two supply chains for energy flow ending at other provinces in China: ‘construction (Beijing) → non-metal products manufacturing (Hebei)’ and ‘construction (Beijing) → metallurgy (Inner Mongolia)’. This is consistent with the fact that Beijing bought large products from non-metal products in Hebei and metallurgy in Inner Mongolia, such as cement, lime, and steels.

3.4. Key nodes

Since the FEW flows network driven by the final consumption (30×30 sectors) crossing regions and industries is very complex, we narrow the final demand to the local share of Beijing (30 sectors) to visualize tele-connections and then identify the key nodes with hub role in controlling FEW flows (see Figs. 4–6). Among these 900 sectors of 30 provinces in China, 26 sectors were identified as the key nodes for FEW nexus (see Table B.1 in appendices for more details). There are many paths for FEW flows through these key nodes, which mean that they play important roles in controlling FEW consumption. The changes in these key nodes might observably alter the resource-environmental performance of the key paths and have effect on the performance of the whole

Table 4
Top 20-ranking paths for water consumption.

Rank	Contribution (Mt), % of total	Key paths
1	3.54 (3.08%)	Beijing-Other services
2	2.66 (2.32%)	Xinjiang-Agriculture
3	2.09 (1.82%)	Beijing-Agriculture
4	1.97 (1.72%)	Shandong-Agriculture
5	1.91 (1.66%)	Hebei-Agriculture
6	1.37 (1.19%)	Heilongjiang-Agriculture
7	1.30 (1.13%)	Anhui-Agriculture
8	1.23 (1.07%)	Anhui-Food industry → Anhui-Agriculture
9	0.89 (0.77%)	Beijing-Other services → Beijing-Agriculture
10	0.87 (0.76%)	Ningxia-Agriculture
11	0.77 (0.67%)	Jiangsu-Food industry → Jiangsu-Agriculture
12	0.73 (0.63%)	Guangxi-Agriculture
13	0.68 (0.59%)	Guangdong-Food industry → Guangdong-Agriculture
14	0.65 (0.57%)	Beijing- Electric power and heat power supply
15	0.61 (0.53%)	Beijing-Hotel and restaurant
16	0.53 (0.46%)	Beijing-Hotel and restaurant → Beijing-Food industry
17	0.50 (0.43%)	Beijing-Other services → Beijing- Electric power and heat power supply
18	0.48 (0.42%)	Jiangsu-Agriculture
19	0.45 (0.40%)	Beijing-Food industry → Beijing-Agriculture
20	0.44 (0.39%)	Beijing-Hotel and restaurant → Beijing-Agriculture

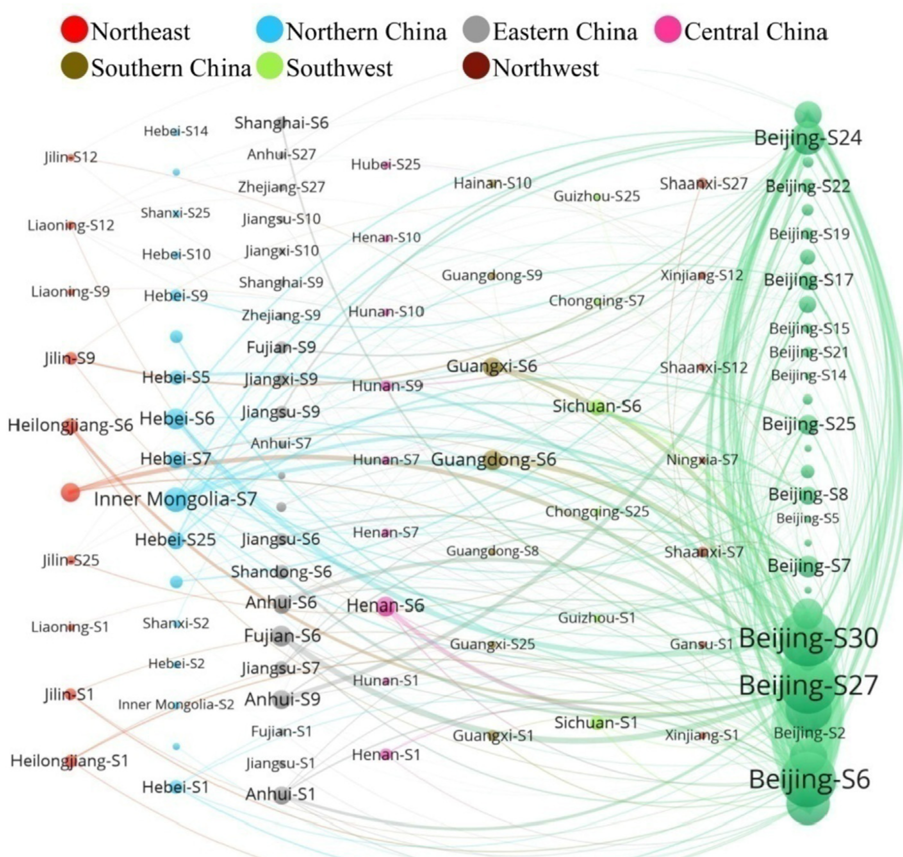

Fig. 4. Key nodes for food consumption.

economic systems. As shown in Figs. 4–6, such key nodes mainly belong to the provinces of northern and eastern China. Moreover, non-metal products manufacturing (S13) in Hebei, petroleum refining and coking (S11) in Heilongjiang, agriculture (S1) in Hebei and Anhui provinces, and coal mining and washing (S2) in Inner Mongolia are the top five important nodes for FEW flows. For example, 8 sectors in Beijing including food industry (S6), non-mental products manufacturing (S13), electrical equipment and machinery (S18), construction (S24), and scientific research (S29) are affected by non-mental products manufacturing (S13) in Hebei province.

For food case, the S6 and S7 in Hebei province and S7 in Inner Mongolia (S6 and S7 are food industry and textile industry) play hub role in food flow network. The key nodes pertinent to water are

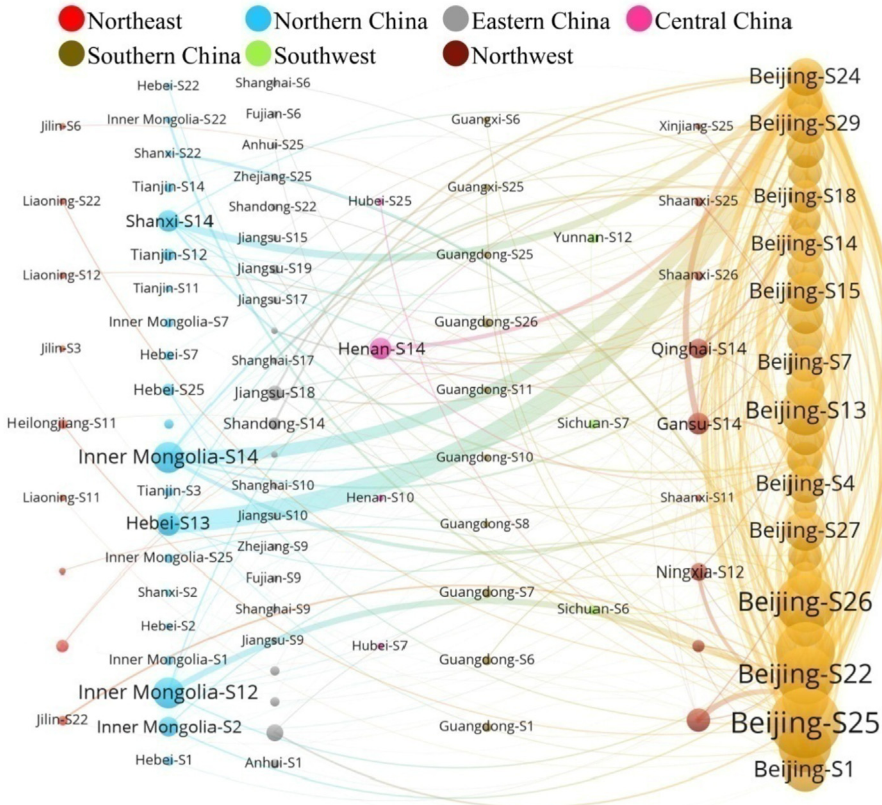

Fig. 5. Key nodes for energy consumption.

much related to agriculture sectors (S1) in Xinjiang, Heilongjiang and Anhui provinces. The network patter for energy flows presents a little different pattern with two largest flows from Hebei-S13 (Non-metal products manufacturing) and Inner Mongolia-S14 (Metallurgy) to construction (S24) of Beijing. It should be notice that the ball of S12 (Chemical industry) in Inner Mongolia is also very lager with thin flow line. This reflects that it plays the pivot role in controlling FEW flows.

4. Discussion and policy implications

The process of global urbanization has continues to alter and reshape the relationship between cities and their hinterlands. They are becoming more inter-coupled through people migration, information and natural resource (i.e. food, energy and water) flow, especially indirect inputs embodied in the products and services via trade flow. Nexus is such a metaphor that could describe the economic and resources flows interconnected and intertwined within cities and their hinterlands (Guo and Shen, 2015). The systematic modeling in this paper provides the general nexus profile of urban FEW supplies, and identifies critical sources, nodes, and supply chains, that are especially important for designing policies to reduce consumption of these resources and achieve urban and global sustainability.

Our study finds that key regions for FEW provisions largely concentrate in the neighboring provinces of Beijing, which conform to the principle of proximity. Hebei, Inner Mongolia, Jiangsu, Anhui, and Shandong are the five leading supporter to Beijing's resource demands. In particular, food and water demand in Beijing mainly rely on the direct supply of agriculture and food industry in these five top provinces, due to the scarcity condition of its own agriculture land and water resource. For energy flows, Beijing has a massive amount import of energy-intensive products, such as chemical, petroleum refining, non-metal, and metal products from these top five provinces to support its rapid development of construction, transport and storage, and tertiary industry. Furthermore, as the key nodes play critical role in shaping the FEW flows, they are control points to ensure the secure FEW provision for, and conversely affected by the changes of final FEW demand of target city as Beijing. Thus, although megacities like Beijing benefits from such outsourcing pattern, it may not be sustainable for other related regions. Current pattern may shift tremendous resource-environmental pressures to their surrounding areas, and even threaten the long term sustainable development of these provinces. For example, these supporting regions are facing with sustainability challenges as land degradation in Inner Mongolia and groundwater recession in Hebei. It is clear that these issues deserve great attentions paid to them. If these top paths and key nodes change, they may constitute a bottleneck which obstructs the sustainable provisions of FEW resources to the downstream cities.

In consideration of rapid ongoing urbanization in China, it can be sure that cities would further induce resources inputs and then put great resource-environmental pressures to neighboring regions. With regard to the tele-coupling mechanism from the FEW nexus perspective, policy-makers should make great efforts to hunt for the systematic solutions to the unsustainable issues of current pattern between city and its hinterlands. Co-governance covering cities and their hinterlands must be one of a policy option to mitigate resource-environmental pressure caused by urban socio-economic development. For instance, neighborhood regions as Beijing, Hebei, Shandong, and Inner Mongolia should strengthen regional cooperation and strive to regional coordinated

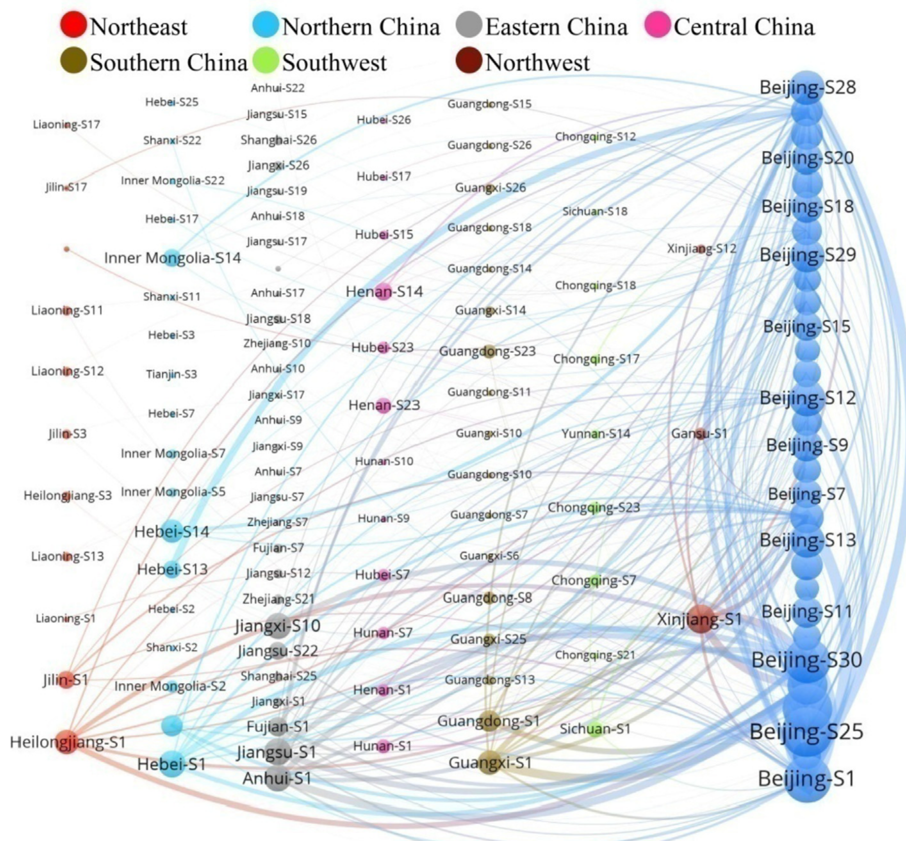

Fig. 6. Key nodes for water consumption.

development to search for cross-region efficiencies. The integrated resource management platform should be established to realize information and technology sharing. More holistic policies considering supply chain and key nodes impacts ought to be developed to maximize the efficiency of integrated management. In such case, the central government should play an essential role in working out blue print and reconciles the conflicts for regional coordinated development. Fortunately, China government has embarked such experiment in Collaborative Development of Beijing, Tianjin and Hebei Provinces.

In addition, cities and their supporting regions should also take the corresponding shared responsibility to reduce FEW consumption. Cities not only need to promote responsible consumption among their residents, and circular economy especially for sectors of construction, hotel and restaurant, and other services, but also provide technical, funding and talent supports to their hinterlands, to mutually improve FEW resources provision and demand security. For their hinterlands, improving the resource efficiency, upgrading equipment, and continue to advance the adjustment of economic structure in other provinces can contribute to reduce the total FEW consumption. However, we must keep in mind that the FEW nexus will be more complex and varied in the future, due to the increasingly intimate connection between cities and their hinterland regions. There is still a long way to go for China to realize its resource coordinate management and sustainable development of cities and regions.

5. Conclusions

Using models of MRIO and SPA, the tele-coupling mechanism of urban FEW nexus is explored in this paper by identifying key regions, key nodes and critical supply chains. The results reveal that Beijing has intensive tele-connections with other hinterland regions for FEW acquisitions. Evidently, it has been heavily rely on FEW provisions of other domestic regions to meet its final demand. Roughly, about 65.5% of food, and 55.4% of energy, and 80.6% of water embodied in the products are supplied by other domestic regions in China through trade flows.

The spatial distribution of key regions for FEW provisions presents neighboring characteristics. Provinces like Hebei, Inner Mongolia, Jiangsu, Anhui and Shandong serve as leading supporters for FEW resource provisions. Accordingly, the critical paths for food and water provision to Beijing extend to other regions of China. However, the top paths for energy begin with services and construction and are more inclined to the sectors within Beijing. The key nodes along the supply chain such as non-metal products manufacturing (S13) in Hebei, petroleum refining and coking (S11) in Heilongjiang, coal mining and washing (S2) in Inner Mongolia highlight the fact that any solutions to urban FEW nexus problem should have broader view on city and its hinterland regions.

The results are very informative to targeting our efforts to address the urban FEW nexus issue. From the demand-side, urban areas should reduce their end-of-pipe consumption. In particular, agriculture related sectors have larger impacts on the total FEW footprints and it should be the priority areas for saving strategies. From the supply-side, efforts should be direct to the efficiency improvement of production in upstream and optimizing the supply chain paths. Then, key nodes along the supply chain highlight the intervention points that can achieve great potential cost-effect benefits for the whole system. As a whole, co-governance covering cities and their hinterlands should be encouraged vigorously to promote resources integrative management.

At the same time, this study also demonstrates the robustness of MRIO models and related methods as SPA in integrating the connected properties of the FEW nexus into studies crossing regions. Such models capture the global supply chains connecting urban systems with external regions, and can trace the transboundary environmental impacts of urban systems. Future research should focus on developing high resolution urban IO data, which could benefit the comprehensive assessment of regional environmental impacts of urban FEW systems.

Table A.1
The administrative regions analyzed in this study

Number	Administrative regions	Number	Administrative regions
1	Beijing	16	Henan
2	Tianjin	17	Hubei
3	Hebei	18	Hunan
4	Shanxi	19	Guangdong
5	Inner Mongolia	20	Guangxi
6	Liangning	21	Hainan
7	Jilin	22	Chongqing
8	Heilongjiang	23	Sichuan
9	Shanghai	24	Guizhou
10	Jiangsu	25	Yunnan
11	Zhejiang	26	Shaanxi
12	Anhui	27	Gansu
13	Fujian	28	Qinghai
14	Jiangxi	29	Ningxia
15	Shandong	30	Xinjiang

Table A.2
The division of province in China

Regional level	Provincial level	Regional level	Provincial level
Northeastern	Liaoning	Eastern	Anhui
	Jilin		Shanghai
	Heilongjiang		Jiangsu
Northern	Hebei		Zhejiang
	Inner Mongolia		Fujian
	Tianjin		Shandong
	Shanxi		Jiangxi
Central	Henan	Southern	Guangdong
	Hunan		Guangdong
	Hubei		Hainan
Northwestern	Shaanxi	Southwestern	Chongqing
	Gansu		Sichuan
	Qinghai		Yunnan
	Ningxia		Guizhou
	Xinjiang		

Source: http://xzqh.org.cn/(accessed in 04.15.2018).

Table A.3
Sector classification in the MRIO model

ID	Sector classification	ID	Sector classification
S01	Agriculture	S16	General and specialist machinery
S02	Coal mining and washing	S17	Transport equipment manufacturing industry
S03	Extraction of petroleum and natural gas	S18	Electrical equipment and machinery
S04	Metal ore mining	S19	Communications equipment, computer, etc.
S05	Nonmetal and other mineral mining	S20	Instrument and meter
S06	Food industry	S21	Other manufacturing
S07	Textile industry	S22	Electric power and heat power supply
S08	Textile, Clothing, Shoes, Leather and related products	S23	Gas and water production
S09	Wood processing and Furniture manufacturing	S24	Construction
S10	Paper making, printing, Stationery, etc.	S25	Transport and storage
S11	Petroleum refining and coking	S26	Wholesale and retailing
S12	Chemical industry	S27	Hotel and restaurant
S13	Non-metal products manufacturing	S28	Leasing and commercial services
S14	Metallurgy	S29	Scientific research
S15	Metal products	S30	Other services

Table B.1
Key nodes for FEW flows

	Region	Sector	ID
1	Hebei	Non-metal products manufacturing	S13
2	Heilongjiang	Petroleum refining and coking	S11
3	Hebei	Agriculture	S1
4	Anhui	Agriculture	S1
5	Inner Mongolia	Coal mining and washing	S2
6	Heilongjiang	Transport equipment manufacturing industry	S17
7	Shanghai	Transport and storage	S25
8	Shanxi	Electric power and heat water supply	S22
9	Henan	Metallurgy	S14
10	Inner Mongolia	Electric power and heat water supply	S22
11	Guangdong	Agriculture	S1
12	Jiangsu	Electrical equipment and machinery	S18
13	Jiangsu	Textile industry	S7
14	Guangdong	Wholesale and retailing	S26
15	Heilongjiang	Extraction of petroleum and natural gas	S3
16	Jiangsu	Communications equipment, computer, etc.	S19
17	Hebei	Textile industry	S7
18	Guangdong	Textile, Clothing, Shoes, Leather and related products	S8
19	Inner Mongolia	Textile industry	S7
20	Inner Mongolia	Nonmetal and other mineral mining	S5
21	Tianjin	Extraction of petroleum and natural gas	S3
22	Jilin	Extraction of petroleum and natural gas	S3
23	Jiangsu	Paper making, printing, Stationery, etc	S10
24	Liaoning	Petroleum refining and coking	S11
25	Guangdong	Textile industry	S7
26	Shanxi	Coal mining and washing	S2

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