Energy 185 (2019) 1225–1234

Contents lists available at ScienceDirect

Energy

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

Exploring energy-water-land nexus in national supply chains: China 2012

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ARTICLE INFO

Article history:
Received 3 January 2019
Received in revised form
9 June 2019
Accepted 21 July 2019
Available online 22 July 2019

Keywords:
Energy-water-land nexus
Input-output analysis
Structural path analysis
Supply chains
Chinese economy

ABSTRACT

Ensuring energy, water and food security is a core challenge as well as an opportunity to national sustainable development. This paper aims to perform an in-depth analysis on demand-driven energy, water and land resource requirements by Chinese economy 2012 and corresponding energy-water-land nexus relationships in its supply chains by using the input-output analysis and the structural path analysis. Results show that *Agriculture* and *Light industry*, mainly related to household consumption, are critical aggregated sectors for water and land requirements, in contrast to *Heavy industry* and *Construction*, which are related to investment for energy requirements. 15.41% of the total energy requirement, 44.18% of water and 58.64% of land can be attributed to the top 20 supply chain paths. The energy-water-land nexuses are explored by industrial sector, supply chain path and final demand category from the perspective of embodiment. On the final demand side, *Agriculture*, *Light industry*, *Construction* and *Service* are critical nexus sectors. Major sectoral nexus paths in terms of energy-land, energy-water, water-land, and energy-water-land nexuses are further identified. The energy-water-land nexus in China's supply chains reflect a strong dependence relationship of energy, water and land resource requirements, which then demonstrate essential intervention points of demand-side resource management.

1. Introduction

To promote socio-economic development, natural resources are directly and/or indirectly supplied to create housing and infrastructure as well as to produce goods and services to accommodate urban lifestyles with higher standards [1]. Energy, water and land resources are the most significant natural resources for sustaining the operation of social system [2]. By considering the consumption-based accounting principles, a full spectrum of both direct and indirect resource usages can be presented to reveal actual energy, water and land requirements by social development and economic growth. Thereafter, integrated approaches applying indicators such as embodied resource requirements or resource footprints can be developed for establishing sound resource and environmental policies [3].

Input-output models capture the complex economic linkages among industrial sectors [4]. Environmental extended input-output analysis (EEIOA) has been proved to be a powerful tool to identify embodied resource flows in a specific economic system from a macro perspective, ranging from industrial [5–9], city or provincial [10–13], national [14–19], to global scales [20–25]. China, as the second largest economy with the largest population in the world, has enormous energy, water and food demands, while its energy security, water security and food security have drawn increasing attention [26,27]. Researches on China's embodied resource uses often refer to energy, water and land separately. Some studies attempted to analyze the embodied energy-water uses or land-water uses at the regional and national scales [28,29]. Nevertheless, no study has been conducted to capture the panorama of embodied energy, water and land uses in an integrated national economic network simultaneously.

Nowadays, there is a growing recognition that the interdependence of energy, water and food demands calls for nexus thinking

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https://doi.org/10.1016/j.energy.2019.07.130
0360-5442/

[30–32]. Nexus relationship is a metaphor to depict resource or environmental elements interconnected and intertwined within a complex social economy [33–36]. The interrelation and interaction of energy, water and land (or food) resource uses are embedded in different economic processes [37–41]. Therefore, a comprehensive analysis on the energy-water-land nexus linkages at the national scale from the embodiment perspective is in great demand, with important implications for sustainable development.

For the extremely complex networks of the national economy, tracing resource uses via the supply chains can relocate the shift of resource demands from resource extraction and processing, intermediate production of industrial products, to final consumption of commodities or services [3,42]. A well-known method is the structural path analysis (SPA), which can excavate the intricate sectoral interrelationships along the supply chains [43,44]. It therefore provides a tool to map the supply chain linkages from resource extraction to final use, and to identify critical supply chain paths. The fluxes throughout the entire supply chains can clearly depict how final consumption drives the extraction of natural resources. So far, the SPA has been widely used to identify supply chain paths for causing resource uses and related environmental emissions at different scales [45–56]. For instance, Zhang et al. [3,42] traced the energy and resource uses via China's supply chains based on the EEIOA and the SPA methods. Recently, Wang et al. [57] reported critical industrial sectors and supply chain paths for the embodied resource uses in China.

In this study, a systematic and comprehensive analysis is performed on the demand-driven energy, water and land resource requirements by Chinese economy in 2012, a benchmark year in the economic 'new normal', a phrase coined by policy makers. Important industrial sectors and final demand categories of embodied energy, water, and land uses are investigated through the EEIOA method. An exhaustive map of supply chain linkages between original production and consumption attributions of embodied resource uses is explored using the SPA method. The nexus relationships of embodied energy-water-land in national supply chains are further illustrated and examined in terms of industrial sector, final demand category and supply chain path. A deeper understanding of energy, water and land demands and related nexus linkages through complex economic networks can provide important implications for resource use management in China.

2. Methods and data sources

2.1. EEIOA and SPA models

In this study, the input-output table for China in 2012 is directly adopted from National Bureau of Statistics of China [58]. This table covers 42 industrial sectors, with details presented in Table S1 in the Appendix. The basic row balance of the national input-output table can be expressed as

$$X = AX + F - X^m \tag{1}$$

where X is the total output; A is the technical coefficients matrix to describe the relationship between all sectors of the economy, of which the element is $a_{ij} = Z_{ij}/X_j$, with Z_{ij} and X_j standing for the input from Sector i to Sector j and the total output of Sector j, respectively; F represents the final uses or final demands (i.e., rural household consumption, urban household consumption, government consumption, capital formation, stock increase and exports); and X^m denotes the imports.

Since this study focuses on domestic resource extraction and use, the import items in the input-output table are removed. The imports-related supply chains are isolated, referring to the method used in previous studies [42,47]. We assume that each economic sector and domestic demand category utilize sectoral imports in the same proportions, though this assumption may result in some uncertainties for the embodiment analysis. Thus, new technical coefficient matrix in which only domestic goods are included can be derived as

$$A^d = (I - M)A \tag{2}$$

$$m_{ii} = \frac{X_i^m}{X_i + X_i^m - f_i^e} \tag{3}$$

where A^d is the direct technical coefficient matrix of domestic production; I is the identity matrix; and $M = diag(m_{ii})$, m_{ii} is the share of imports in the supply of products and services to each sector.

The new balance equation is shown as

$$X = Z^d + f^d + f^e = A^d X + f^d + f^e \tag{4}$$

where Z^d is the matrix of domestic intermediate demands; f^d is the vector of domestic final consumption; and f^e is the vector of the exports.

Eq. (4) can be re-expressed as

$$X = (I - A^d)^{-1}(f^d + f^e) = L^d(f^d + f^e) \tag{5}$$

where I is the identity matrix; $L^d = (I - A^d)^{-1}$ is the domestic Leontief inverse matrix, whose element l_{ij} tracks the overall direct and indirect economic input along the domestic supply chain from Sector i while generating unit output in Sector j.

To connect the energy, water and land resource uses with the input-output model, the total embodied resource uses (ERUs) can be formulated as

$$ERU = \varepsilon^d L^d (f^d + f^e) = \varepsilon (f^d + f^e) \tag{6}$$

where ε^d represents the direct resource intensity (i.e., the direct resource input per unit of total output); ε is the embodied resource intensity, which is the sum of the direct and indirect resource intensities; εf^d is the resource uses embodied in domestic final consumption; and εf^e is the domestic resource uses embodied in exports.

To extract the supply chain paths of embodied resource use, the revised Leontief inverse matrix is expanded using the Taylor series approximation as

$$L^d = (I - A^d)^{-1} = I + A^d + (A^d)^2 + (A^d)^3 + \cdots + (A^d)^t \tag{7}$$

On the right-hand side of the equation, each element in the expansion denotes a different production layer or tier. We define a

$$\varepsilon^d (I - A^d)^{-1} y^d = \varepsilon^d I y^d + \varepsilon^d A^d y^d + \varepsilon^d (A^d)^2 y^d + \varepsilon^d (A^d)^3 y^d + \cdots + \varepsilon^d (A^d)^t y^d \tag{8}$$

production layer (PL) as each term in the power series expansion, $PL^t = (A^d)^t$. Each additional layer, $PL^{t+1} = PL^t A^d$, represents the production of intermediate products in $(t+1)^{th}$ production tier used as inputs into the t^{th} production tier. Thereafter, embodied resource uses in the final demand (y^d) can be expressed as,

where $\varepsilon^d (A^d)^t y^d$ represents the contribution of embodied resource uses from the t^{th} production tier. The first tier (PL^0) illustrates the sectors that directly deliver resource products for final demand, and the sectors in the second tier (PL^1) are required to provide support for the production in the sectors of the first tier. Similarly, the sectors in the third tier (PL^2) are required by those in the second tier, and the fourth tier is required by the corresponding upper tiers, respectively. The quantity of nodes in the production network increases exponentially with each tier. There are n^{t+1} nodes in tier t, and n is the number of industrial sectors in the economy. For example, the n^2 first tier nodes are evaluated as $\varepsilon_i^d A_{ij}^d y_j$, representing the path $i \rightarrow j$. The n^3 second tier nodes are evaluated as $\varepsilon_i^d A_{ij}^d A_{jk}^d y_k$, indicated by the path $i \rightarrow j \rightarrow k$. The same pattern repeats for all tiers. Detailed procedures to illustrate the process of SPA can be referred to Zhang et al. [3].

2.2. Data sources and processing

To avoid double accounting, the domestic energy, water and land resource supply from the ecosystem have been carefully defined. The extraction of primary energy resources refers to raw coal, crude oil, natural gas, hydropower, nuclear power, wind power and other renewable energy. All primary energy data for the year of 2012 are obtained or derived from China Energy Statistical Yearbook 2016 [59] and China Electric Power Yearbook 2013 [60]. The inputs of hydropower, nuclear power, wind power and other renewable power are estimated based on electricity generation data and corresponding electricity generation efficiencies [11,42].

Water resources include only those withdrawn from natural water bodies. Freshwater intakes (or blue water) for direct irrigation and livestock production, industrial use, municipal use or supply and ecological protection refer to the agriculture, industry and service sectors. The total water withdrawal data for such sectors in 2012 are available from China Statistical Yearbook 2013 [61]. Since the water withdrawal data for the subdivision of the industry sector in the same year cannot be directly obtained, we resort to an authoritative source. The water withdrawal in terms of surface water, ground water and tap water for 38 industrial sectors in 2008 (see Table S2) are provided in China Economic Census Yearbook 2008 as the only public source [62]. We assume that the water use structures of all the industrial sub-sectors were kept relatively stable over the period of 2008–2012. Thereafter, detailed industrial water withdrawal data at the sub-sectoral level in 2012 are estimated based on the total water use by the industry and estimated water use structures. According to the statistical explanation and sectoral classification, the tap water uses for industrial production and in the service sector can be classified into the sector of *Water Production*.

The main purpose of land use is for agricultural production to supply food and other biomass resources. In this study, the land resources for agricultural usages are covered and categorized into five categories including cultivated land, garden land, grassland, forests land, and other land types. All land resource data are directly obtained from China Statistical Yearbook 2015 [63], which provides the total land area at the national scale based on the national land change survey in 2013.

Detailed results of energy, water and land resource inputs at the sectoral level in 2012 are listed in Table S3. Improving national statistics in the future will be essential to provide a high-quality resource use inventories for the EEIOA-based studies, and then reduce uncertainties in dealing with the resource and environmental issues.

3. Embodied energy-water-land uses in final demand

Demand-driven domestic energy, water and land resource inputs into Chinese economy amount to 101.03 EJ, 603.17 billion m^3 and 646.47 Mha, respectively. Fig. 1 presents the embodied energy, water and land uses in final demand. The sectoral distributions of embodied energy, water and land resources used by Chinese economy demonstrate significant disparities.

The embodied energy uses (EEUs) in final demand in terms of the 42 industrial sectors are shown in Fig. 1(a). *Construction* (Sector 28) contributes the largest EEU, amounting to 30.14 EJ and accounting for 29.83% of the national total. Some manufacturing sectors such as *Transportation Equipment* (Sector 18, 5.96% of the national total), *Chemical Products* (Sector 12, 4.81%), and *Electrical Equipment* (Sector 19, 4.57%) have significant EEUs. In Fig. 1(a), the pie chart (the outer cycle) shows that *Heavy industry*, as an aggregated sector, accounts for 35.41% of the national total EEU, followed by *Construction* (29.83%) and *Service* (16.54%). The remaining four aggregated sectors are responsible for only 18.22% of the total. For final demand category, investment has the largest share of 47.09% to the total EEU, followed by consumption of 30.75% and exports of 22.15%. Capital formation is the leading final demand category in construction activities and most sectors belonging to the heavy industry (e.g., Sectors 16–19 and 28). In the sector of *Coal Mining* (Sector 2), 53.91% of its sectoral EEU can be attributed to stock increase. Meanwhile, the shares of exports are relatively high in the EEU compositions of Sectors 10–13 and 20 (*Other Electronic Equipment*).

Fig. 1(b) presents the embodied water uses (EWU) in final demand. *Agriculture* (Sector 1) holds the largest EWU with a value of 149.02 billion m^3, amounting to 24.70% of the total. *Food Processing* (Sector 6) is the second largest, followed by *Construction* and *Water Production* (Sector 27). The above-mentioned four sectors, out of the total 42 sectors, contribute to 61.62% of the national total EWU. Overall, *Light industry* among all the seven aggregated sectors accounts for 27.40% of the national total, followed by *Agriculture* (24.71%) and *Heavy industry* (20.85%). The EWU of *Service*, as an aggregated sector, amounts to 84.52 billion m^3 with a share of 14.02%. For final demand category, consumption-driven EWU amounts to 361.55 billion m^3 and accounts for 59.94% of the total EWU, of which 66.65% from urban consumption, 24.43% from rural consumption and 8.92% from government consumption. Investment-driven EWU amounts to 151.28 billion m^3 while exports induce 90.38 billion m^3. At the sectoral level, consumption-driven EWUs take a large proportion in *Agriculture*, *Food Processing*, *Water Production* and *Accommodation, Food and Beverage Services* (Sector 31). Government consumption contributes the dominated share in several service sectors. Investment-driven EWU take a major share in *Construction* while exports-driven EWU is mainly related to *Garments* (Sector 8), *Chemical Products* and *Other Electronic Equipment*.

Fig. 1(c) presents the embodied land uses (ELU) in final demand. Compared to the sectoral distribution of the EWU, the ELU displays a similar pattern. *Agriculture* has the highest ELU with an amount of 242.72 Mha, followed by *Food Processing* of 165.17 Mha. These two sectors contribute to 63.11% of the national ELU. *Construction*, *Garments*, *Accommodation, Food and Beverage Services* and *Textile* (Sector 7) consume 40.77, 34.50, 25.77 and 16.81 Mha of the ELU, respectively. Totally, *Agriculture*, *Light industry* and *Service* contribute 37.55%, 36.27% and 12.55% to the national total, respectively. The ELUs of *Heavy industry* and *Construction* are

Fig. 1. Embodied resource uses in final demand: (a) energy; (b) water; (c) land. *Note*: The column graphs on the left side describe the distribution of embodied resource by sector and by final demand category. The pie charts on the right side display the structure of embodied resource in final demand, and the original 42 sectors are further merged into seven aggregated sectors in the outer circle (detail sectoral information is listed in Tables S1 and S4).

relatively small. As to the final demand category, consumption contributes the largest share of 66.28% to the total, followed by investment of 20.09% and exports of 13.63%. The consumption-driven ELUs in *Agriculture* and *Food Processing* amount to 179.44 and 147.15 Mha, respectively. In addition, export is the leading final demand category for the ELU compositions of Sectors 7–9.

4. Embodied energy-water-land uses in supply chains

To reveal the circulation and distribution process of embodied resource uses, Sankey diagrams are devised to visualize the demand and supply processes of energy, water and land resources. Fig. 2 displays the embodied energy, water and land resource flows via the supply chains at the national scale. After capturing resource movements along the supply chains, critical economic sectors and supply chain paths (from the resource extraction to intermediate production, and eventually to final demand) can be identified.

Fig. 2(a) shows *Heavy industry*, as an aggregated sector, consumes a large portion of energy in every production layer, especially in production layer 1, mainly due to its complex economic relationships with other sectors. *Power* is the critical intermediate sector. *Construction* and *Service* have a similar pattern of energy usage, with both sectors consume a large amount of embodied energy. Fig. 2(b) and (c) show that *Agriculture* and *Light industry* are the dominated sectors not only in the final consumption but also in the intermediate process. A large part of the water and land resources are directly used by *Agriculture*. This sector also provides intermediate products for other important embodied water- and land-intensive sectors such as *Light industry*.

In order to identify how the final demand drives resource uses in each tier, we further extract and analyze critical supply chain paths. Since it is not feasible to quote all the SPA results, major supply chain paths are ranked to provide a comprehensive understanding of the connections between production and consumption attributions. Tables S5–S7 list the top 20 ranking paths of embodied energy, water and land uses, respectively. The total EEU related to the top 20 paths amounts to 15.57 EJ, representing 15.41% of the national total. The largest path is '*Coal Mining* → *Nonmetal Mineral Products* →*Construction*→ Capital formation', which contributes 4.21 EJ, with a share of 4.25%, followed by the paths of '*Coal Mining* → *Smelting and Pressing of Metal* → *Construction* → Capital formation' and '*Coal Mining* → *Electric Power* → Urban consumption'. Given that coal is the major energy resource in China, eighteen of the top 20 paths can be traced back to the sector of *Coal Mining*. Eight of the top 20 ranking paths are driven by *Construction*, which are always associated with *Nonmetal Mineral Products*, *Smelting and Pressing of Metal* and *Electric Power*, indicating that construction activities consume large amounts of industrial raw materials. The sector of *Electric Power*, as a critical intermediate sector, which consumes raw coal and provides power and heat to other sectors or household consumption, is linked with six of the top 20 paths. *Petroleum Processing* and *Chemical Products* also consume a large amount of energy directly or indirectly. Eight ranking paths are driven by capital formation.

For the EWU, the top 20 paths are responsible for 266.56 billion m^3, representing 44.18% of the national total. The largest EWU path of '*Agriculture* → Urban consumption' contributes 51.85 billion m^3 with a share of 8.59%, followed by the path of '*Agriculture* → *Food Processing* → Urban consumption'. Sixteen of the top 20 EWU paths can be traced back to *Agriculture*, indicating that *Agriculture* is a critical sector for water use. Seven of the top 20 EWU paths are distributed in Tier 0, and these sectors consume a lot of water directly for final demand. Nine of the top ranking paths are driven by urban consumption and five paths by rural consumption.

For the ELU, the top 20 paths amount to 379.06 Mha with a share of 58.64%. The largest path of '*Agriculture* → Urban consumption' contributes 86.38 Mha of the ELU, followed by '*Agriculture* → *Food Processing* → Urban consumption'. The top 10 paths occupy 49.62% of the national total ELU. *Agriculture* and *Food Processing* are critical sectors for agricultural land use. Eight of the top 20 paths are related to *Food Processing*. Food industry consumes a lot of water and land resources indirectly through *Agriculture*. Some sectors of light industry are critical final users of agricultural land resources such as *Timber Processing*, *Paper Products*, *Garments* and *Textile*. Seven of the top 20 ranking paths are driven by urban consumption while four paths by rural consumption. Such information could be important for designing targeted resource policies at supply chains precisely.

Fig. 3 further displays the composition of the EEUs, EWUs and ELUs at each layer instigated by the final consumption of aggregated sectors. For example, *Agriculture* in total uses 2.01 EJ of embodied energy, 149.02 billion m^3 of embodied water and 242.71 Mha of embodied land. About 80% of the embodied water and land uses concentrate on Tier 0. About 70% of the embodied energy distributes in Tier 3 and higher tiers. *Agriculture* uses a large amount of water for irrigation and land for crop production directly. Instead, agricultural machinery, pesticides and chemical fertilizer consume the majority of the embodied energy which distributes in higher tiers, though energy directly used for agricultural activities only occupies 1.3% of the total embodied energy in Tier 1. Except for *Agriculture*, the sectoral EWUs occur at the second and higher tiers. Most of the ELUs in the aggregated sectors (except for *Agriculture* and *Light industry*) occur at the third or higher tiers. The compositions of resource consumption in production tiers reflect the sectoral resource utilization pattern for providing industrial products and services to a certain extent.

5. Energy-water-land nexus hidden in national supply chains

Growing scarcity and increasing demands of energy, water and food deserve innovative thinking from a nexus prospective. Traditionally, researches on the energy-water-food nexus theories focused on the discussion of interconnections between energy, water and food resources on the production side [2]. The direct dependencies of these three resources are indicated by the energy-water nexus, water-food nexus, energy-food nexus, and energy-water-food nexus at the macro-scale socio-economic system, which have been extensively explored in the literature [30–32,64]. In China, energy-related industrial sectors consume a large amount of water resources directly (mainly in *Electric Power*, 77.61 billion m^3 in 2012), which account for 64.67% of the total water usage by the industry sector and 12.86% of the total water supply. The sector of *Agriculture* directly and indirectly consumes large amounts of water and land resources, most of which are used for food production. Water for irrigation reaches 388.03 billion m^3 in 2012, accounting for 64.35% of the total water supply. Energy system also provides power support for water and food systems. In fact, it is not enough to investigate the energy-water-food nexus only on the production side [65–67].

Identifying the energy-water-land nexus hidden in national supply chains provides new insights to understand how energy, water and land interact in the economic system. In addition to the production-side energy-water-land nexuses in concrete industrial sectors covering traditional energy-water nexus, water-land nexus, energy-land nexus and energy-water-land nexus (Nexus 1), the consumption-based resource concept from the embodiment perspective adds a new dimension to understand the nexus relationships in terms of supply chain path nexus (Nexus 2), the sectoral nexus (Nexus 3), and the final demand category nexus (Nexus 4). A systems diagram is further devised to present the

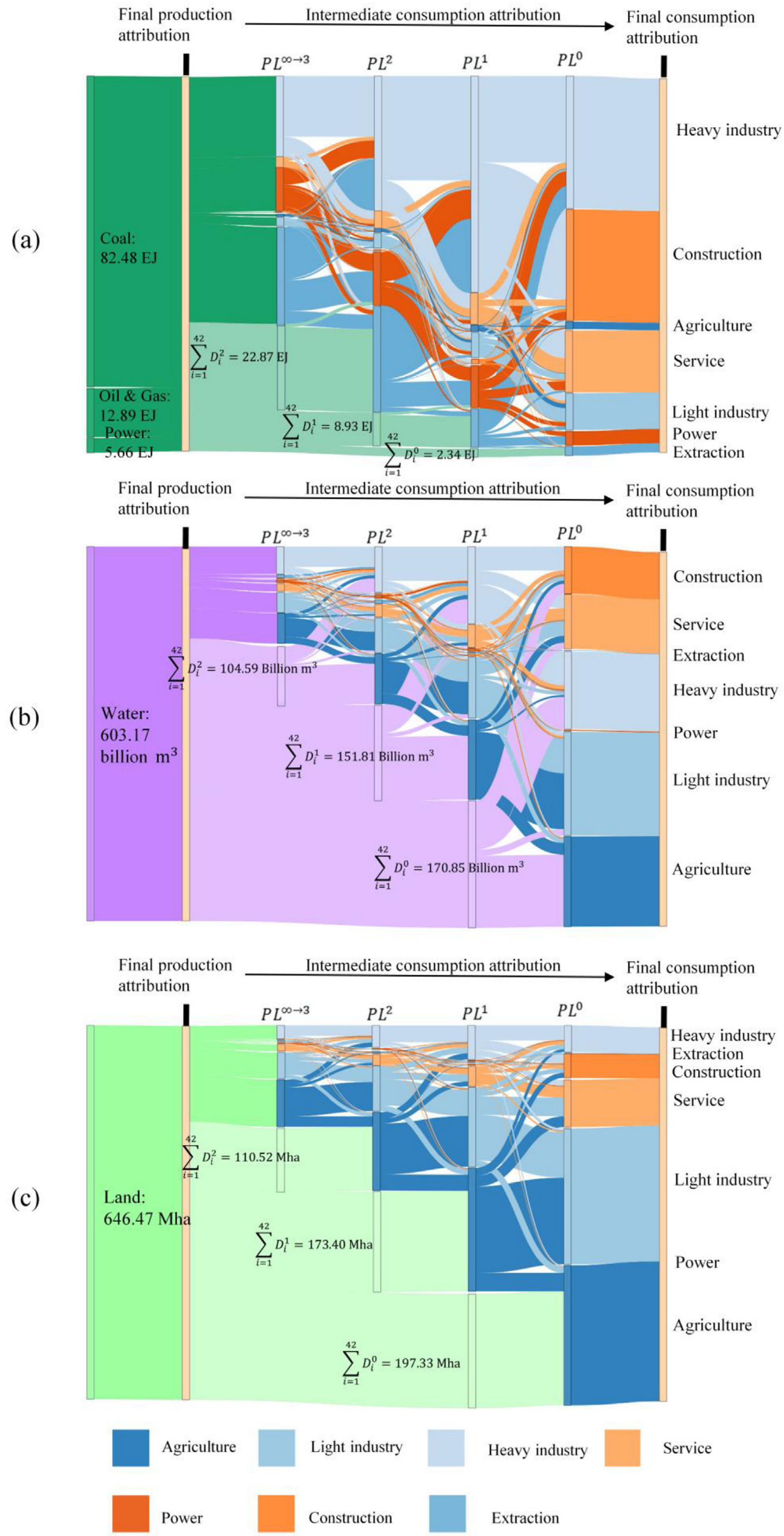

Fig. 2. Sankey diagram of embodied resource flows via domestic supply chains: (a) energy; (b) water; (c) land. *Note*: The left-hand side of the figure shows the original production of resources. The right-hand side of the figure presents the final consumption attributions of each resource. The central part of the diagram reveals the intermediate consumptions for each resource at each production layers (*PL*) by aggregated sector. The element PL^t represents a production layer, and element D_s^t represents direct resources input from sector *s* at PL^t (light colors). There are seven aggregated sectors in every production layer. Industrial sectors in production layer 0 deliver products directly for final demand and obtain products from production layer 1, and so on. Colors of the nodes and flows indicate the seven aggregated sectors and corresponding products, respectively. Direct resource inputs into each sector at PL^0, PL^1 and PL^2 are indicated in the bottom of each production layer by light color. Contributions from PL^3 and all higher layers have been combined. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

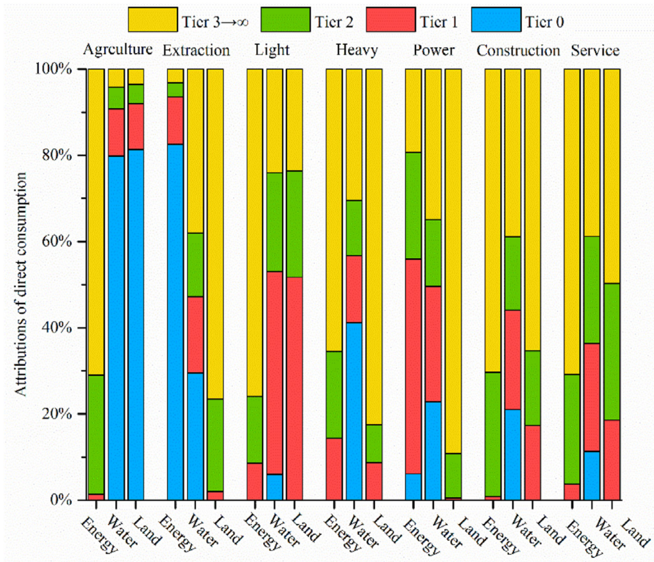

Fig. 3. Compositions of embodied energy, water and land uses in the production tier.

overall energy-water-land nexus relationship in the supply chains at the national scale, as shown in Fig. 4.

To find out the common paths where water, energy and land interact with each other indicated by Nexus 2, Fig. 5(a) visually synthesizes the embodied water, energy and food resource flows via China's supply chains in an integrated Sankey diagram. *Agriculture* consumes a significant amount of water and land directly. In the intermediate process, *Light industry*, as an aggregated sector, is the core nexus sector of the three resources, especially for water and land. On the final demand side, *Agriculture*, *Light industry*, *Construction* and *Service* are critical aggregated sectors of nexus. The highest impact on the EEUs occurs in Tier 3 of the supply chain, amounting to 22.87 EJ, implying that a large amount of energy is used by final demand via one or two sectors as transition notes for intermediate production. For example, *Construction* uses a lot of embodied energy via the three sectors of *Manufacture of Nonmetallic Mineral Products*, *Manufacture and Pressing of Metals*, and *Electric Power* through the top 20 paths of embodied energy. Embodied water and land uses are mainly appeared in the first two tiers (53.40% of the total for water and 57.39% of the total for land), implying that these two kinds of resources are mainly used by final demand or by one transition sector (e.g., *Food Processing*) directly. In the intermediate consumption attribution, *Agriculture* and *Light industry*, among all the seven aggregated sectors, consume a large portion of the embodied water and land, while *Heavy industry* consumes a large amount of embodied energy.

Fig. 5(b) further illustrates the top 50 sectoral supply chain paths of the EEUs, EWUs and ELUs simultaneously. The top 50 ranking paths (from the original resource extraction to the final demand sectors) together represent 26.84%, 58.11% and 71.45% of the national total EEU, EWU and ELU in final demand, respectively. The sectoral supply chain paths don't distinguish the end of supply

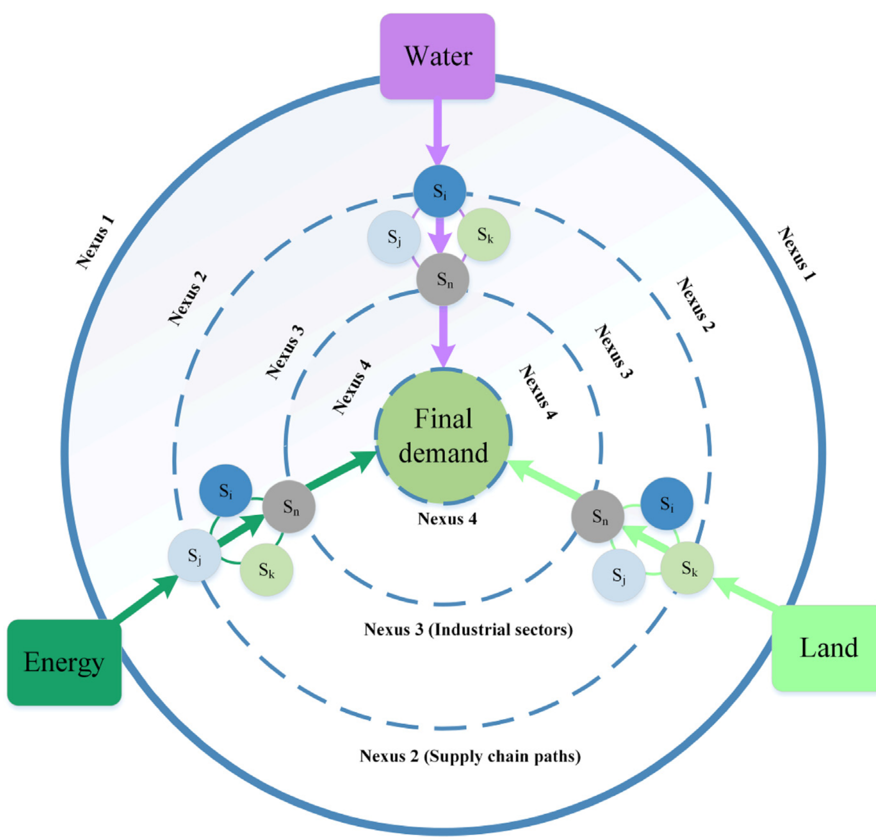

Fig. 4. Systems diagram of the energy-water-land nexus relationship in national supply chains. *Note*: Nexus 1 represents traditional energy-water-land nexus in the production side; Nexus 2 indicates common sectoral supply chain paths to link with the final demand; Nexus 3 represents common industrial sectors to provide commodities or service for the final demand; and Nexus 4 represents common final demand categories (e.g., urban consumption, rural consumption, government consumption, capital formation, stock increase, and exports). S_i, S_j, S_k and S_n represent different sectoral notes in the supply chains.

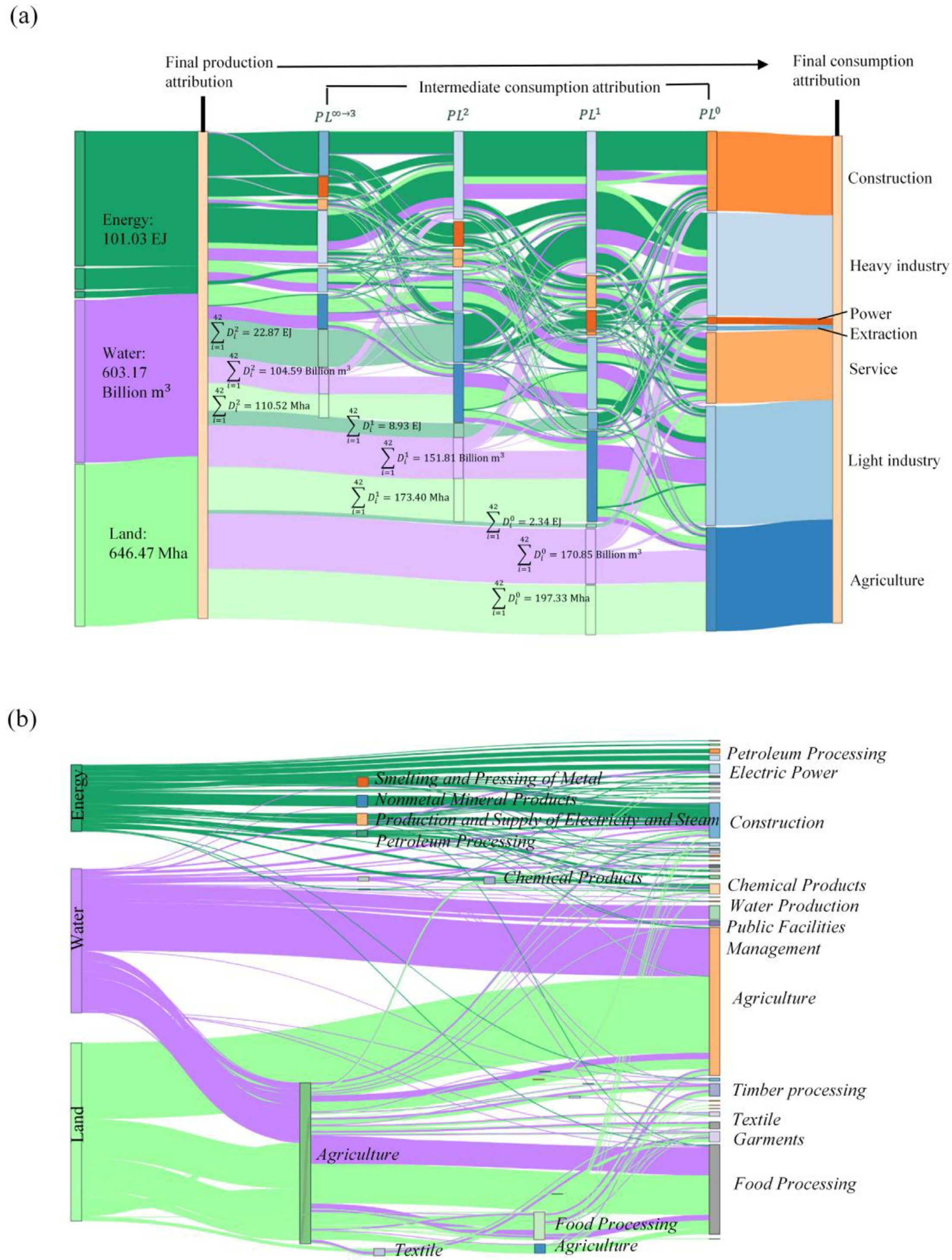

Fig. 5. Embodied energy-water-land uses in the supply chains: (a) supply chain paths from production to consumption; (b) major sectoral supply chain paths. *Note*: In Fig. 5(a), colors of the sectoral node indicate the seven aggregated sectors, and colors of the flows indicate different resource types. From left to right, the diagram reveals how the resource transfer from extraction via intermediate consumption to final consumption. Contributions from PL^3 and all higher tiers are combined to provide a comprehensive view of the system. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

chains (i.e., different final demand categories). Among the significant transition and syncretic sectors of the three resources, *Agriculture*, *Food Processing*, *Textile* and *Chemical Products* are critical transmission sectors. On the final demand side, products of *Agriculture*, *Food Processing*, *Chemical Products*, *Electric Power* and *Construction* are mainly used by final consumers.

The top 20 largest sectoral nexus paths for energy-land, energy-water and water-land are listed in Tables S8–S10, respectively. *Food Processing*, *Textile* and *Chemical Products* are critical transition sectors for the energy-land nexus as well as *Agriculture* and *Food Processing* for the energy-water nexus. The largest path of energy-water nexus is the ‘Energy & Water → *Food Processing*’, followed by

'Energy & Water → *Food Processing* → *Accommodation, Food and Beverage Services*'. For the water-land nexus, the largest path is the 'Water & Land → *Agriculture*', implying that water and land are mainly used by *Agriculture* and directly for final demand. This path contributes 19.64% and 30.52% to the national total EWU and ELU, respectively. The top 20 energy-water-land nexus paths contribute 3.70 EJ (3.70% of the total EEU), 133.18 billion m^3 (22.08% of the total EWU) and 206.85 Mha (32.00% of the total ELU) to the national total, respectively (see Table S11). The largest nexus path is the 'Water & Energy & Land →*Food Processing*', being responsible for 0.32 EJ of embodied energy (0.32% of the total EEU), 61.4 billion m^3 of embodied water (10.18% of the total EWU) and 102.29 Mha of embodied land (15.82% of the total ELU). *Food Processing* provides food for other sectors, which links with the top 4 high-ranking paths. The path 'Water & Energy & Land → *Construction*' covers 4.23 billion m^3 of embodied water (0.70% of the total EWU), 0.25 EJ of embodied energy (0.25% of the total EEU) and 7.05 Mha of embodied land (1.09% of the total ELU). Other critical sectors in domestic supply chains are also identified, including *Textile*, *Timber Processing* and *Chemical Products*. These sectors reflect their roles as transmission channel in the supply chain paths.

As to the common industrial sectors for providing final goods to meet final consumption indicated by Nexus 3, *Agriculture* contributes 24.71% and 37.55% to China's total EWU and ELU in final demand, respectively, though the proportion of *Agriculture* by EEU in final demand is far less than the former ones. Furthermore, *Light industry*, as an aggregated sector, consumes a large amount of water and food due to the processing and manufacturing of agriculture products. *Light industry* has direct linkages with *Agriculture*, therefore the shares of its EWU and ELU in final demand are much larger than that of its EEU. By contrast, *Heavy industry* and *Construction* among all the seven aggregated sectors have large amounts of the EEU in final demand. The demand of *Service* also leads to substantial consumption of embodied water, energy and food resources.

As to the common final demand category indicated by Nexus 4, investment takes the largest proportion of EEU in final demand (47.09%), compared to 25.08% of the EWU and 20.09% of the ELU. Consumption plays an important role in driving the EWUs and ELUs, among which the embodied resource uses of urban consumption are more than twice those of rural consumption in terms of the three resources. Thereafter, the energy-water-land nexus in China's supply chains are systematically displayed in terms of common industrial sectors, final demand categories and supply chain paths, indicating a strong dependence relationship of energy, water and land resource requirements.

6. Concluding remarks

Responsible consumption and production is an important indicator among United Nation's 2030 Sustainable Development Goals. Effective measures to reduce resource footprint are of great concern to gauge sustainability [68]. The growth of Chinese economy has a measurable impact on energy, water and land resource demands. By using the EEIOA and the SPA models, this study reveals how final demand drives domestic extraction and utilization of energy, water and land resources in 2012, highlighting the interconnections among embodied energy-water-land resource uses.

According to the final demand categories driving water, energy and land resource requirements, capital formation contributes the most to the energy requirements, while urban consumption is the leading driver for water and land resource requirements. *Agriculture* and *Light industry* are critical aggregated sectors for the EWUs and ELUs and *Heavy industry* and *Construction* for the EEUs in final demand. In order to excavate the complex resource linkages in the economic system network, the supply chain paths of embodied resource flows from the original extraction to the final demand are identified. The top 20 ranking paths together account for 15.41%, 44.18% and 58.64% of the national total EEU, EWU and ELU, respectively. The energy-water-land nexus in national supply chains are systematically elucidated from the embodiment perspective, covering common industrial sectors, final demand categories and supply chain paths. Major sectoral nexus paths in terms of energy-land, energy-water, water-land, and energy-water-land nexuses are further explored, reflecting the tight inter-sectoral energy-water-land connection. Among the sectoral energy-water-land nexus paths, for instance, the largest path is "Water & Energy & Land →*Food Processing*", responsible for 61.4 billion m^3 of embodied water, 0.32 EJ of embodied energy and 102.29 Mha of embodied land. Identifying these main dependence pathways is essential to address the trade-offs and synergies among embodied energy, water and land uses along the entire supply chains. Controlling critical nexus sectors and paths can yield multi-benefits for possible energy, water and land conservation. The supply chains of energy, water and land resource requirements in association with their connections and interactions can provide important information for policy makers to reduce resource and environmental footprints along with complex economic activities.

Acknowledgements

This study has been supported by the National Natural Science Foundation of China (Grant nos. 71774161, 41701135, 71701087 and 71804194) and the Yue Qi Young Scholar Project, China University of Mining &Technology (Beijing).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2019.07.130.

References

[1] Wiedmann TO, Schandl H, Lenzen M, Moran D, Suh S, West J, Kanemoto K. The material footprint of nations. Proc Natl Acad Sci U.S.A. 2015;112(20):6271–6.
[2] Chang Y, Li G, Yao Y, Zhang L, Yu C. Quantifying the water-energy-food nexus: current status and trends. Energies 2016;9(2):65.
[3] Zhang B, Guan SH, Wu XF, Zhao X. Tracing natural resource uses via China's supply chains. J Clean Prod 2018;196:880–8.
[4] Miller RE, Blair PD. Input-output analysis: foundations and extensions. 2nd revised edition. Cambridge University Press; 2009.
[5] Liu Z, Geng Y, Lindner S, Zhao HY, Fujita T, Guan DB. Embodied energy use in China's industrial sectors. Energy Policy 2012;49:751–8.
[6] Zhang B, Chen ZM, Zeng L, Qiao H, Chen B. Demand-driven water withdrawals by Chinese industry: a multi-regional input-output analysis. Front Earth Sci 2016;10(1):13–28.
[7] An Q, An HZ, Wang L, Gao XY, Lv N. Analysis of embodied exergy flow between Chinese industries based on network theory. Ecol Model 2015;318:26–35.
[8] Sun X, An H, Gao X, Jia X, Liu X. Indirect energy flow between industrial sectors in China: a complex network approach. Energy 2016;94:195–205.
[9] Wang X, Huang K, Yu Y, Hu T, Xu Y. An input–output structural decomposition analysis of changes in sectoral water footprint in China. Ecol Indicat 2016;69:26–34.
[10] Zhang LX, Hao Y, Chang Y, Pang MY, Tang SJ. Emergy based resource intensities of industry sectors in China. J Clean Prod 2017;142(Part 2):829–36.
[11] Zhang B, Chen ZM, Xia XH, Xu XY, Chen YB. The impact of domestic trade on China's regional energy uses: a multi-regional input-output modeling. Energy Policy 2013;63:1169–81.
[12] Zhang B, Qiao H, Chen B. Embodied energy uses by China's four municipalities: a study based on multi-regional input–output model. Ecol Model 2015;318:138–49.
[13] Liu S, Wu X, Han M, Zhang J, Chen B, Wu X, Wei W, Li Z. A three-scale input-output analysis of water use in a regional economy: Hebei province in China. J Clean Prod 2017;156:962–74.
[14] Chen GQ, Chen ZM. Carbon emissions and resources use by Chinese economy 2007: a 135-sector inventory and input-output embodiment. Commun Nonlinear Sci Numer Simul 2010;15(11):3647–732.
[15] Hawkins J, Ma C, Schilizzi ST, Zhang F. Promises and pitfalls in

environmentally extended input-output analysis for China: a survey of the literature. Energy Econ 2015;48:81–8.
[16] Wu XF, Chen GQ. Energy use by Chinese economy: a systems cross-scale input-output analysis. Energy Policy 2017;108:81–90.
[17] Chen W, Wu S, Lei Y, Li S. Virtual water export and import in China's foreign trade: a quantification using input-output tables of China from 2000 to 2012. Resour Conserv Recycl 2018;132:278–90.
[18] Guo S, Jiang L, Shen GQP. Embodied pasture land use change in China 2000-2015: from the perspective of globalization. Land Use Policy 2019;82:476–85.
[19] Rehkamp S, Canning P. Measuring embodied blue water in American diets: an EIO supply chain approach. Ecol Econ 2018;147:179–88.
[20] Bruckner M, Stefan G, Christian L, Kirsten SW. Materials embodied in international trade – global material extraction and consumption between 1995 and 2005. Glob Environ Chang 2012;22:568–76.
[21] Steen-Olsen K, Weinzettel J, Cranston G, Ercin AE, Hertwich EG. Carbon, land, and water footprint accounts for the European Union: consumption, production, and displacements through international trade. Environ Sci Technol 2012;46:10883–91.
[22] Chen ZM, Chen GQ. Demand-driven energy requirement of world economy 2007: a multi-region input-output network simulation. Commun Nonlinear Sci Numer Simul 2013;18(7):1757–74.
[23] Chen ZM, Chen GQ. Virtual water accounting for the globalized world economy: national water footprint and international virtual water trade. Ecol Indicat 2013;28:142–9.
[24] Chen GQ, Han MY. Global supply chain of arable land use: production-based and consumption-based trade imbalance. Land Use Policy 2015;49:118–30.
[25] Chen GQ, Wu XF. Energy overview for globalized world economy: source, supply chain and sink. Renew Sustain Energy Rev 2017;69:735–49.
[26] Jiang Y. China's water security: current status, emerging challenges and future prospects. Environ Sci Policy 2015;54:106–25.
[27] Han MY, Chen GQ. Global arable land transfers embodied in Mainland China's foreign trade. Land Use Policy 2018;70:521–34.
[28] Guo S, Shen GQ. Multiregional input–output model for China's farm land and water use. Environ Sci Technol 2015;49(1):403.
[29] Tang X, Jin Y, Feng C, McLellan BC. Optimizing the energy and water conservation synergy in China: 2007–2012. J Clean Prod 2018;175:8–17.
[30] Smajgl A, Ward J, Pluschke L. The water–food–energy Nexus – realising a new paradigm. J Hydrol 2016;533:533–40.
[31] Liu J, Mao G, Hoekstra AY, Wang H, Wang J, Zheng C, van Vliet MTH, Wu M, Ruddell B, Yan J. Managing the energy-water-food nexus for sustainable development. Appl Energy 2018;210:377–81.
[32] Dai J, Wu S, Han G, Weinberg J, Xie X, Wu X, Song X, Jia B, Xue W, Yang Q. Water-energy nexus: a review of methods and tools for macro-assessment. Appl Energy 2018;210:393–408.
[33] Peng K, Zou Z, Wang S, Chen B, Li J. Interdependence between energy and metals in China: evidence from a nexus perspective. J Clean Prod 2019;214:345–55.
[34] Ozturk I. Sustainability in the food-energy-water nexus: evidence from BRICS (Brazil, the Russian Federation, India, China, and South Africa) countries. Energy 2015;93:999–1010.
[35] Chen S, Chen B. Urban energy–water nexus: a network perspective. Appl Energy 2016;184:905–14.
[36] Fang D, Chen B. Linkage analysis for the water–energy nexus of city. Appl Energy 2017;189:770–9.
[37] Wang S, Chen B. Energy–water nexus of urban agglomeration based on multiregional input–output tables and ecological network analysis: a case study of the Beijing–Tianjin–Hebei region. Appl Energy 2016;178:773–83.
[38] Sherwood J, Clabeaux R, Carbajalesdale M. An extended environmental input-output lifecycle assessment model to study the urban food-energy-water nexus. Environ Res Lett 2017;12(10):105003.
[39] Wang S, Cao T, Chen B. Urban energy–water nexus based on modified input–output analysis. Appl Energy 2017;196:208–17.
[40] Chen B, Han MY, Peng K, Zhou SL, Shao L, Wu XF, Wei WD, Liu SY, Li Z, Li JS, Chen GQ. Global land-water nexus: agricultural land and freshwater use embodied in worldwide supply chains. Sci Total Environ 2018;613–614:931–43.
[41] Wang S, Liu Y, Chen B. Multiregional input–output and ecological network analyses for regional energy–water nexus within China. Appl Energy 2018;227:353–64.
[42] Zhang B, Qu X, Meng J, Sun XD. Identifying primary energy requirements in structural path analysis: a case study of China 2012. Appl Energy 2017;191:425–35.
[43] Skelton A, Guan D, Peters GP, Crawford-Brown D. Mapping flows of embodied emissions in the global production system. Environ Sci Technol 2011;45(24):10516–23.
[44] Yuko O. Identifying critical supply chain paths that drive changes in CO_2 emissions. Energy Econ 2012;34(4):1041–50.
[45] Llop M, Ponce-Alifonso X. Identifying the role of final consumption in structural path analysis: an application to water uses. Ecol Econ 2015;109:203–10.
[46] Yang ZY, Dong WJ, Xiu JF, Dai RF, Chou JM. Structural path analysis of fossil fuel based CO_2 emissions: a case study for China. PLoS One 2015;10(9):e0135727.
[47] Meng J, Liu JF, Xu Y, Tao S. Tracing primary $PM_{2.5}$ emissions via Chinese supply chains. Environ Res Lett 2015;10:054005.
[48] Hong JK, Shen QP, Xue F. A multi-regional structural path analysis of the energy supply chain in China's construction industry. Energy Policy 2016;92:56–68.
[49] Liang S, Wang YF, Zhang TZ, Yang ZF. Structural analysis of material flows in China based on physical and monetary input-output models. J Clean Prod 2017;158:209–17.
[50] Wang Z, Wei LY, Niu BB, Liu Y, Bin GS. Controlling embedded carbon emissions of sectors along the supply chains: a perspective of the power-of-pull approach. Appl Energy 2017;206:1544–51.
[51] Zhang B, Zhang Y, Zhao X, Meng J. Non-CO_2 greenhouse gas emissions in China 2012: inventory and supply chain analysis. Earth's Future 2018;6:103–16.
[52] Yang X, Zhang WZ, Fan J, Li JM, Meng J. The temporal variation of SO_2 emissions embodied in Chinese supply chains, 2002-2012. Environ Pollut 2018;241:172–81.
[53] Zhang J, Chang Y, Wang C, Zhang L. The green efficiency of industrial sectors in China: a comparative analysis based on sectoral and supply-chain quantifications. Resour Conserv Recycl 2018;132:269–77.
[54] Nagashima F. Critical structural paths of residential $PM_{2.5}$ emissions within the Chinese provinces. Energy Econ 2018;70:465–71.
[55] Shao L, Li Y, Feng KS, Meng J, Shan YL, Guan DB. Carbon emission imbalances and the structural paths of Chinese regions. Appl Energy 2018;215:396–404.
[56] Zhao GM, Gao C, Xie R, Lai MY, Yang LG. Provincial water footprint in China and its critical path. Ecol Indicat 2018. https://doi.org/10.1016/j.ecolind.2018.06.058.
[57] Wang J, Du T, Wang HM, Liang S, Xu M. Identifying critical sectors and supply chain paths for the consumption of domestic resource extraction in China. J Clean Prod 2019;208:1577–86.
[58] NBSC, National Bureau of Statistics of China. 2012 input-output table of China. Beijing: China Statistics Press; 2015.
[59] CESY. China energy statistical Yearbook 2016. Beijing: China Statistics Press; 2016.
[60] CEPY. China electricity power Yearbook 2013. Beijing: China Statistics Press; 2013.
[61] CSY. China statistical Yearbook 2013. Beijing: China Statistics Press; 2013.
[62] National Bureau of Statistics of China. China economic Census Yearbook 2008. Beijing: China Statistics Press; 2010.
[63] CSY. China statistical Yearbook 2015. Beijing: China Statistics Press; 2015.
[64] Gu A, Teng F, Wang Y. China energy-water nexus: assessing the water-saving synergy effects of energy-saving policies during the eleventh Five-year Plan. Energy Convers Manag 2014;85:630–7.
[65] Owen A, Scott K, Barrett J. Identifying critical supply chains and final products: an input-output approach to exploring the energy-water-food nexus. Appl Energy 2018;210:632–42.
[66] White DJ, Hubacek K, Feng K, Sun L, Meng B. The Water-Energy-Food Nexus in East Asia: a tele-connected value chain analysis using inter-regional input-output analysis. Appl Energy 2018;210:550–67.
[67] Feng C, Tang X, Jin Y, Guo Y, Zhang X. Regional energy-water nexus based on structural path betweenness: a case study of Shanxi Province, China. Energy Policy 2019;127:102–12.
[68] UNEP. Decoupling natural resource use and environmental impacts from economic growth, a report of the working group on decoupling to the international resource panel. Nairobi: United Nations Environment Programme; 2011. Also available at: http://wedocs.unep.org/handle/20.500.11822/9816.