Journal of Environmental Management 345 (2023) 118849

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

How robust are current narratives to deal with the urban energy-water-land nexus?

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ARTICLE INFO

Handling Editor: Jason Michael Evans

Keywords:
Energy-water-land nexus
Resource efficiency
Weighting
Urban sustainability
Consumption-based flow

ABSTRACT

Current energy, water, and land (EWL) nexus research treats all resources equally, causing bias in complicated nexus studies. To make the analysis robust, we consider resource endowment and significance. Here, we provide a methodological framework where the urban industrial resource nexus strength is constructed and assign weights to resources according to policies, describing resource efficiency and representing it in ternary diagrams to assess the urban industrial nexus innovatively. Results showed that energy drives urban development under all weights, with energy resource efficiency exceeding 60%. From consumption-based accounting, energy continues to dominate most industries under physical weightings but emphasizes the significance of water and land. While, under economic weightings, land supplants energy's dominance in specific sectors. Setting weights helps understand resource interaction, establish synergy based on urban development objectives, and minimize robustness. Our findings provide quantitative evidence for assessing urban resource efficiency to highlight priority sectors for intervention in urban decision-making.

1. Introduction

Energy, water, and land (EWL) resources are urban sustainable development's core materials and lifeblood (Facchini et al., 2017; Deng et al., 2020). Urban multi-resource nexus is the current frontier and hot spot (Ding et al., 2022; Pedersen Zari et al., 2022). Policymakers have applied the nexus approach to urban resource management (Artioli et al., 2017; Bleischwitz et al., 2018; Emamjomehzadeh et al., 2023). Scholars have investigated the multi-resource nexus from different perspectives (Zhang et al., 2019a), but most studies considered the multi-resource nexus to be one resource-centric (Villarroel Walker et al., 2014; Ramaswami et al., 2016). Most urban resource nexus studies were conducted assuming that all resources were equal, ignoring resource endowment characteristics and importance (Schlör et al., 2018; Li et al., 2020), which may lead to blind spots in urban resource management. Therefore, as policy implementers (Wang et al., 2020), it is urgent for cities to rethink the multi-resource nexus and adopt scientific approaches to achieve more local-based accurate sustainable urban resource management, which will be critical to their environment, economy, society, and the whole world (Bleischwitz et al., 2018).

As hotspots for resource consumption (Vanham et al., 2019; Lucertini and Musco, 2020), to fulfill the expanding demand for resources, cities inevitably have to rely on resources outside their geographical boundaries to sustain their socioeconomic processes and promote economic growth, while increasing resource consumption and environmental pressure within and outside their boundaries (Feng et al., 2014; Liu et al., 2015; Ramaswami et al., 2016, 2017; Seto et al., 2017; Liang et al., 2019; Zhang et al., 2019b; Zheng et al., 2019; Hu et al., 2020a, 2020b; Elmqvist et al., 2021; Wiedmann and Allen, 2021; Ding et al., 2022). Consequently, it is necessary to consider the cascade effects of resources in cities within the multiscale economy (Seto et al., 2012; Rocha et al., 2018; Shi et al., 2020; Cao et al., 2021; Bai et al., 2022). For a resilient and sustainable urban development, the resource footprints of cities need to remain within the planetary boundary thresholds

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https://doi.org/10.1016/j.jenvman.2023.118849
Received 2 June 2023; Received in revised form 7 August 2023; Accepted 19 August 2023
Available online 30 August 2023

(Rockström et al., 2009; Steffen et al., 2015; Wiedmann and Lenzen, 2018; Wiedmann and Allen, 2021). Most of the previous research on urban multiple resources were conducted from the perspective of resource flows to clarify the flow characteristics in the urban economic system (Liang et al., 2019; Zhang et al., 2019b; Newell and Ramaswami, 2020; Meng et al., 2022; Wang et al., 2022). However, flow analysis made it difficult to address the efficiency and management of multiple resources (Arthur et al., 2019). The study of urban resource efficiency is significant for sustainable urban development (Tan et al., 2021). Most studies combined resources and the economy to reflect resource efficiency from an economic perspective (Wood et al., 2018). Furthermore, some research on urban resource efficiency mainly adopted the nexus approach with an emphasis on the energy intensity of water use and the water intensity of energy use (Chen and Chen, 2016; Fang and Chen, 2017; Wang and Chen, 2021). These studies focused on nexus among resources, ignoring the fact that demand from other economic sectors also affects the multiple resources, and there is a lack of research on how to integrate multiple resources, considering the quality and scarcity of these resources, within the economic system along the supply chains.

Integrated planning can be developed to address the provisioning systems for EWL resources. Several indicators can be combined into a single index, enabling a comparative analysis of resources using various units (Arthur et al., 2019; Zhang et al., 2019a). This integrated indicator may prove suitable for understanding the economy-wide implications of resource nexus and resource efficiency. The notion of nexus strength was first proposed by Font Vivanco et al. to calculate the strength of resource linkage (Font Vivanco et al., 2018). The study quantified the nexus strength of five resources from global and national sectors to identify the relative importance node among multiple resources. The country-level analysis provides useful insights but aggregates data and loses the variation between cities. Understanding the potential variation is critical because heterogeneity among cities is highly similar to heterogeneity between countries (Mahtta et al., 2022). Sectors are the basis for reflecting economic linkages between cities and other regions.

We aim to fill the existing gap left by the prior studies by constructing a methodological framework (Fig. SI-1) for assessing urban resource efficiency based on the previously published urban ternary multidimensional nexus (UTMDN) framework covering multi-scale economies (Wang et al., 2022). This framework has been developed using the concepts of urban metabolism (Zhang et al., 2015; Emamjomehzadeh et al., 2023) and tele-coupling (Liu et al., 2013; Liu, 2017). This framework helps to open the black box of the urban system and provides a comprehensive understanding of it by examining the interconnections between various resources within the ternary subsystems along the supply chains. This analysis encompasses both local coupling within urban boundaries (in-boundary) (Zhang et al., 2019b; Chen et al., 2020) as well as peri- and tele-coupling across boundaries (trans-boundary) (Meng et al., 2018; Nawab et al., 2019b) We have applied this framework in four Chinese megacities to reveal hotpots of the EWL resource management (Meng et al., 2022; Wang et al., 2022).

The main results of this study are outlined and include the following: (1) flow and structure analysis based on the production- and consumption-based accounting, (2) urban industrial physical resource efficiency represented in ternary diagrams, and (3) Beijing's industrial physical resource efficiency under different weighting schemes.

2. Methods

2.1. Methodology framework

Our prior research has developed a UTMDN framework capable of modeling complex urban EWL resource provision by mapping the in- and trans-boundary resource interactions and further unfolding the cross-sectoral characteristics from a multi-sectoral perspective (Wang et al., 2022). We construct a matched methodological framework based on the UTMDN framework for urban resource management to evaluate the flow, structure, and efficiency of urban EWL resources (Fig. SI-1).

Firstly, data on energy consumption, water consumption, and land use in urban, domestic, and international sectors are collected as environmental satellite accounts using material flow analysis (MFA). Secondly, the flow and structure analysis of resources at different spatial scales (i.e., local-domestic-international) can be performed from both production- and consumption-based perspectives to reflect local, peri- and tele-coupling using the environmental extended multiscale input–output (EE-MSIO) model. The above analysis of flow and structure has been conducted previously and is the basis for urban physical resource efficiency (Meng et al., 2022; Wang et al., 2022). Afterward, various weighting schemes are applied to the selected resources according to meso and macro policies (Pauliuk et al., 2017). The urban industrial nexus strength (UINS) of resources under different policy interventions can be simulated and analyzed to identify critical hotspots for urban industrial development. Then, the urban industry physical resource efficiency (UIPRE) can be calculated.

2.2. Final demand driving urban resource flows

We use the EE-MSIO model to calculate the direct and indirect urban EWL flows driven by the final demand. This model has been considered to trace water flows (Liu et al., 2019), carbon flows (Meng et al., 2018), energy–water flows (Nawab et al., 2019a; Tian et al., 2020), and EWL flows across the local, interregional, and international regions for urban sectors (Wang et al., 2022). We used the global multiple regional input−output (MRIO) table in 2010 from the World Input−Output Database (WIOD) (Dietzenbacher et al., 2013). We combined China's multiple regional input−output (MRIO) table with the WIOD data to investigate the economic transactions between the four megacities and other domestic as well as international regions at the sector level (Liu et al., 2014). China's MRIO table was nested into the WIOD based on the methods by Peters et al. (Peters, 2008). We introduced the nesting approach relevant to our study in Supplementary Section 2-1. Details on the nesting methods were described in the study of Peters et al. (Peters, 2008). As shown in Table SI-1, the world was divided into 17 regions: 11 domestic (including the 4 megacities) and 6 international regions. Additionally, as listed in Table SI-2, 7 aggregated economic sectors for each region were considered.

Based on the Leontief input-output model (Leontief, 1936; Miller and Blair, 2009), the Chinese four megacities' EWL flows driven by the final demand of each domestic and international region can be calculated by equation (1).

$$c = \widehat{e}(\boldsymbol{I} - \boldsymbol{A})^{-1}\widehat{f} \tag{1}$$

Where c represents the total environmental impacts. $\widehat{e}$ is a row vector representing the environmental impact intensity connected with various sectors, including the intensity of the consumption of energy and water as well as land use. $\boldsymbol{I}$ is the identity matrix, and $\boldsymbol{A}$ is the direct technical coefficient matrix. The notation $\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1}$ represents the Leontief Inverse matrix; $\widehat{f}$ stands for the diagonal vector of the final demand vector f.

2.3. Nexus approach to urban physical resource efficiency assessment

We constructed the UIPRE indicator based on the UINS indicator to analyze urban physical resource efficiency using the nexus approach (Font Vivanco et al., 2018). The UNIS indicator was calculated using the EE-MSIO model. This indicator synthesizes the interconnections among all sectors, which relies on certain resources and socioeconomic subsystems through supply chains. It can assess the direct and indirect nexus strength of multiple resources simultaneously induced by technological progress and economic relevance, both from the production and consumption perspectives. We only considered the absolute physical use of resources. Because resources have different units, a dimensionless

method is applied to cope with the issue of multidimensionality by computing unit-less deviations from pre-defined objectives to compare various resources. Many ways can be used to carry out dimensionless, and there is no standard for which one should be used strictly (Xu et al., 2020). The most appropriate dimensionless method should be selected in the context of the data or the research algorithm. In this study, the dimensionless method employs the maximum value for the reason of allowing the maximum use of the resources (Font Vivanco et al., 2018). There is an assumption that the more the usage of resources, the greater their utilization.

The UINS is the sum of the nexus strength for a certain industry in a megacity, and it ranges between 1 (maximum use of all resources) and 0 (no use of resources). By calculating, we can comprehensively analyze which sectors have the strongest nexus strength and readily identify critical nodes with a strong linkage of EWL resources. The sum of nexus strength for each industry can be expressed mathematically as follows:

$$UINS_i = \sum_{a\in(e,w,l)} q_a d_{a,i} \tag{2}$$

$$with\ i \in I;\ I = \{1, \ldots, n\};\ \sum_{M}^{n} (q_n) = 1;\ \mathrm{a} = \{e, w, l\} \tag{3}$$

$$\mathrm{d}_{a,i} = \frac{h_{a,i}}{h_a}, h_a = \max\left(\{h_{a,i}\}\right)_{i\in I} \tag{4}$$

Where e, w, and l stand for energy, water, and land, respectively; i stands for the i th sector; I represents all industries in each megacity that are linked to the supply chains. q_n is a weight that determines the significance of a given resource. $d_{n,i}$ is the deviation between the maximum industrial particular resource consumption and that consumption of sector i. $h_{n,i}$ reflects the consumption of a particular resource in sector i. h_n represents the maximum consumption of that particular resource among all the sectors for each megacity.

Before the nexus strength of sector i can be calculated by equation (1), the use of resources in any sector needs to be validated by the following prerequisites. We set h (i.e., $h = 1\%$) as the threshold for each given combination to contain at least two resources, excluding sectors that only used a single resource. This threshold ensures that no resource with little consumption is included in the UINS. That is, for sector i, if any two of the three resources are compared, the smaller one must be higher than the bigger one multiplied by h; otherwise, it is eliminated from the combination.

Further, UIPRE is the share of the total consumption of multiple resources by using one of Earth's limited resources. This index represents that every single resource can be interpreted as a contribution to the UINS, which reflects the physical resource efficiency in the urban sector, as calculated by equation (5).

$$UIPRE_i = \frac{q_a d_{a,i}}{UINS_i} \tag{5}$$

2.4. The ternary diagram

A ternary diagram is a helpful graphic tool for visualizing three different substances with a constant sum, usually represented by an equilateral triangle (Howarth, 1996). It is mostly used to investigate inequalities among the proportions of three substances. Ternary diagrams can conveniently display and clearly express the nexus strength of three resources and their resource efficiency (Giannetti et al., 2012). There will be an interpretation of compositions from ternary diagrams (Fig. 1). In this triangle, the values of the three resources (i.e., energy, water, and land) at the industrial scale add up to 1. Each triangle's apex corresponds to a unique composition of three resource components of the different industrial sectors. Each resource is 100% in the corner of the triangle and 0% of the remaining two resources, decreasing linearly with increasing distance (perpendicular to the opposite edge) from this corner. Lines that cross the cut point position represent aggregated use of a given resource. The size of each point within the triangle shows the combined usage of the given three resources (from 0 to 1). This diagram

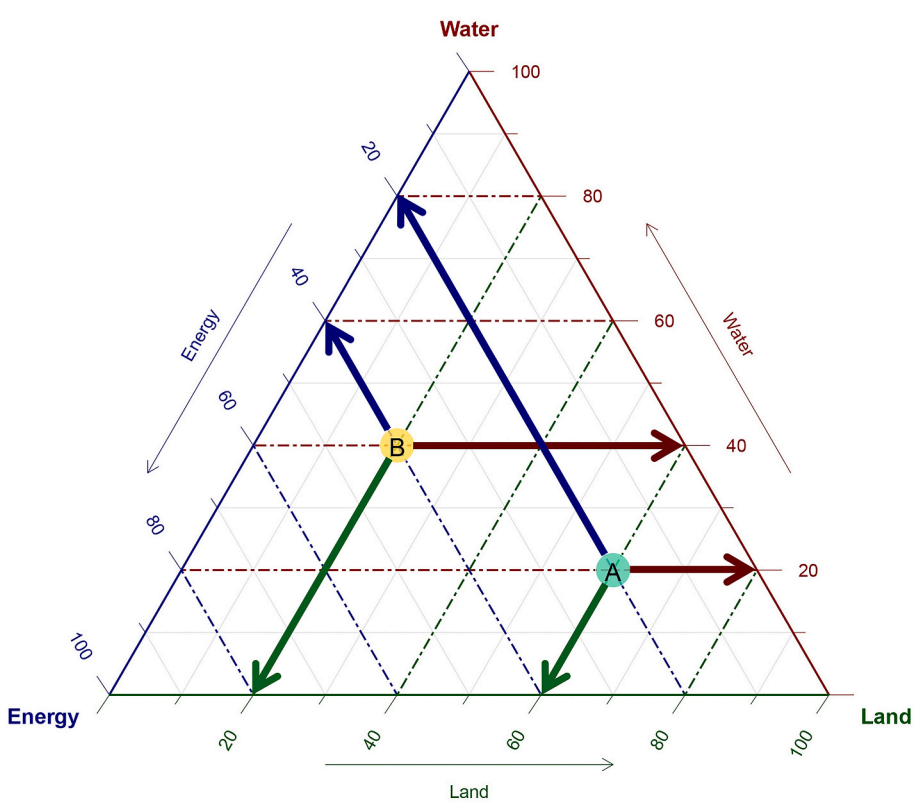

Fig. 1. The depiction of the urban industrial nexus strength and urban industrial resource efficiency of EWL in a ternary diagram. To better illustrate the meaning of the points in the ternary diagram, we labeled points A and B, both valued at 1 in the ternary diagram, as an example. Point A, the green dot, is within the triangle near the top land resource apex of the diagram. The percentage of EWL resources in a certain industry can be read off the axis parallel to and with the same color as the resource. Line Ac, drawn parallel to the Water-Energy side, shows the increase in Energy from 0 to 100%. Line Aa, drawn parallel to the Water-Land side, depicts growing Water from 0 to 100%. Line Ab, drawn parallel to the Energy-Land side, shows increasing Land from 0 to 100%. consequently, the line that cuts 'A' equals 20% of Energy, 20% of Water, and 60% of Land. Following the same principle, we can easily derive the percentage of EWL at point B in yellow, with 40% of Energy, 40% of Water, and 20% of Land.

can be ruled with lines parallel to the sides, and the composition can then be read directly at different points. Additionally, the colored arrows help understand how the percentage of each resource is determined.

2.5. Different weighting schemes

The weighting of alternative schemes for the chosen three essential resources impacts the UINS. To represent the significance degree, several weighting schemes considering scarcity, quality, absolute consumption, price, sustainable objectives, and other parameters are established for different resources. Therefore, it is vital to investigate its influence on the findings further. For that purpose, we devised five weighting schemes based on various criteria, classified them into physical weightings (i.e., equal weights, distance-to-target, and panel data) and economic weightings (i.e., shadow prices and exergy), and recalculated the nexus strength accordingly.

The equal weights approach prioritizes EWL as equally important. The distance-to-target method considers how far current resource utilization deviates from a target value. The target values for water with energy were set according to the resource environment binding aim for Beijing's 13th Five-Year Plan, and the target for land was set according to the global ecological footprint target for 2050 (Oers and Tukker, 2016). The panel data approach relies on expert assessment from panels of people with varied backgrounds (Oers and Tukker, 2016). The shadow prices approach derives weights by attributing monetary values to currently unknown costs (e.g., external costs), reflecting resource scarcity. Weighting numbers for shadow pieces come from Oers and Tukker (De Bruyn et al., 2010; Oers and Tukker, 2016). The exergy transformation coefficient is used to convert the absolute consumption of energy, water, and land to joules. For land, the exergy transformation coefficient is derived from the net primary productivity (NPP) of different land types. The specific weight values are shown in Supplementary Section 2-3 (Table SI-4). Generally, the average, panel data, and distance-to-target weightings were based on brainstorming or prior research and reports, so they emphasized the importance of primary energy. Instead, the weightings of shadow prices and exergy give notable importance to land use.

2.6. Data availability

Data on energy consumption, water consumption, and land use are employed as environmental satellite accounts in this study. Detailed sources and calculations of energy and water consumption, as well as land use are provided in the supplemental methods. This dataset consists of two distinct components. The data pertaining to sectors of four megacities and domestic regions was gathered from the official statistical yearbook and previous research. The data about sectors of international regions was obtained from the WIOD database. Comprehensive details are shown in the Supplementary Information, and supporting data can be found in the Supplementary Data.

3. Results

3.1. Urban energy–water–land flow and structure analysis

In general, the total EWL flows from the consumption-based accounting were larger than those from the production-based accounting in the four megacities (Fig. 2). Local, peri- and tele-coupling provided the essential EWL nexus for these four megacities. According to the production-based accounting, the four megacities' direct EWL resources were mostly utilized for local consumption, except Tianjin, which used 44%, 43%, and 44% of direct EWL resources for domestic exports, respectively. At the industrial level, the direct water and land use were highly concentered on the *agricultural* sector. Specifically, the direct water and land resources were mostly used for local consumption in Beijing and Shanghai, whereas these same resources in Tianjin and Chongqing were mainly used for domestic exports (Supplementary Data Table S1). For the four megacities, the *electricity, gas & water* sector was completely controlled by energy resource, as with the *others* sector, where the direct energy resource was mainly used for domestic exports and local consumption. The above analysis reflects the predominance of energy in urban production activities.

From the consumption-based accounting, domestic imported flows were the primary source of embodied EWL flows for these four megacities, except for Chongqing, where 55%, 46%, and 35% of embodied

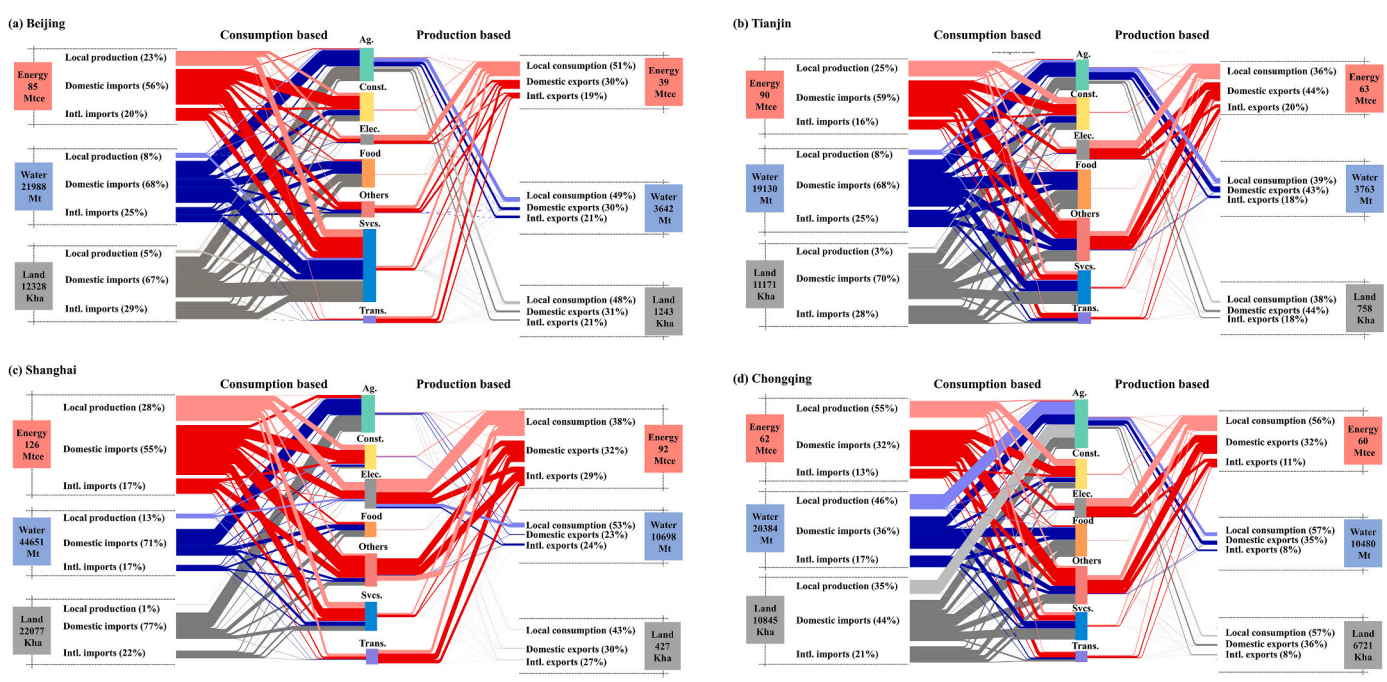

Fig. 2. Urban EWL nexus induced by sector and the spatial distribution. Each resource group flow has a width corresponding to the total value supplied beside it. As energy, water, and land use were all calculated in different units, their relative magnitude is meaningless. Intl. is an abbreviation for international. Local coupling exists in local production and consumption. Domestic exports and imports form a peri-coupling, and international exports and imports generate a tele-coupling.

EWL flows for local production. At the industrial level, the *services* sector had a typical EWL balance utilization for the four megacities, with domestic imported EWL flows accounting for a significant portion of the EWL consumption flows (Supplementary Data Table S1). The *agriculture* and *food & tobacco* sectors were typically dominated by water and land, of which domestic imported flows were the main source of embodied water and land flows for these four megacities. Whereas the embodied water and land flows in the *agricultural* sector of Chongqing relied more on local production. Although *construction*, *electricity, gas & water*, *others*, and *transport* sectors were concentrated on EWL, energy was still the absolute controlling resource in these sectors, and domestic imported energy flows were the main source. Because EWL resources are not the same units, the analysis of urban resource flow and structure from resource provision can show the urban EWL nexus and reflect to some extent which resources are preferred by urban industrial in terms of absolute resource use. However, these analyses do not reflect the significance of each resource's conurbation to the integrated multiple resources of urban industrial activity. Therefore, the UINS and UIPRE are needed to solve the above problems, with flow and structure analysis as the foundation. The UINS and UIPRE for EWL will be analyzed in the next section.

3.2. Urban industrial physical resource efficiency

EWL resources have been calculated using equal weights, showing that each resource receives the same importance. From the production-based accounting (Fig. 3a), nexus strength is associated with each industry's production activity within city boundaries, reflecting the direct use of EWL resources. Therefore, the UINS relates solely to the absolute resource use for each sector. It merits noting that most (nearly 68%) four megacities' sectors were concentrated near the energy vertex, with energy resource efficiency exceeding 60% (energy accounting for over 60% of the UINS), mainly represented by the *electricity, gas & water*, *others*, *services*, and *transport* sectors, which means that urban development is driven by energy. Additionally, Chongqing, Beijing, and Tianjin's *agriculture* sectors appeared to be strongly interconnected between EWL, with 0.70, 0.68, and 0.67, respectively (Supplementary Data Table S2), maybe because water and land combined had a resource efficiency of nearly 50% (contribution of water and land in UINS). Detailed production-based UINS and UIPRE for each megacity are shown in Fig. SI-2 and Supplementary Data Table S2.

From the consumption-based accounting (Fig. 3b), nexus strength is caused by the final demand for each industry, reflecting the indirect EWL embodied in goods and services along supply chains. Notably, the UINS of all the sectors for the four megacities were distributed along a line that bisected the water axis across the energy vertex (Fig. 3b), which means that sectors along this line have the same share of water and land in UINS, in other words, water and land were equally efficient. We classified these sectors to identify megacities' industrial physical resource efficiency better. Specifically, the EWL balanced sectors (Part I) in the center indicates that EWL resources have a balanced resource efficiency. In other words, the contribution of EWL were balanced, with the three resources accounting for between 30% and 50% of UINS. Particularly in Beijing's *services* sector, the EWL nexus was strong, given its point size's most significant value of UINS, with the proportion of the three resources showing a balanced contribution in this sector. The energy-driven sectors (Part II) are close to the energy vertex, suggesting a sector with a higher energy contribution to UINS. Energy resource efficiency exceeding 50% might be considered an energy-intensive sector, such as the *electricity, gas & water* (energy resource efficiency over 78% in this sector for each megacity), *construction* (over 52%), and *transport* (over 52%) sectors. The water and land control sectors (Part III) are near the water axis, indicating a sector with a higher water and land contribution to UINS. Resource efficiency of above 40% for each water and land might be considered water and land control sectors, such as Beijing's *agriculture* (water and land contribution to UINS above 45% each) and *food & tobacco* (above 47%) sectors. Detailed consumption-based UINS and UIPRE for each megacity are shown in Fig. SI-3 and Supplementary Data Table S2.

3.3. Urban industrial physical resource efficiency under different weightings

Various weightings had influence on the UINS of EWL, and we took Beijing as an example to further analyze the impact of its diverse characteristics on the results. From the production-based accounting, under all weighting schemes, while the weighting of shadow price (Fig. 4d) was an exception, all sectors except the *agriculture* sector were closer to the energy vertex, reflecting that energy resource efficiency exceeded 83%. Additionally, while the distribution of sectors was dispersed under the shadow prices weighting, most were biased toward the energy vertex, and land contribution to UINS was higher for most sectors. The *agriculture* sector gained positions in the top nexus under equal weights (Fig. 4a), distance-to-target (Fig. 4b), and shadow prices (Fig. 4d) weightings via water and land combinations to UINS (water and land resource efficiency exceeded 96%) (see Supplementary Data Table S3).

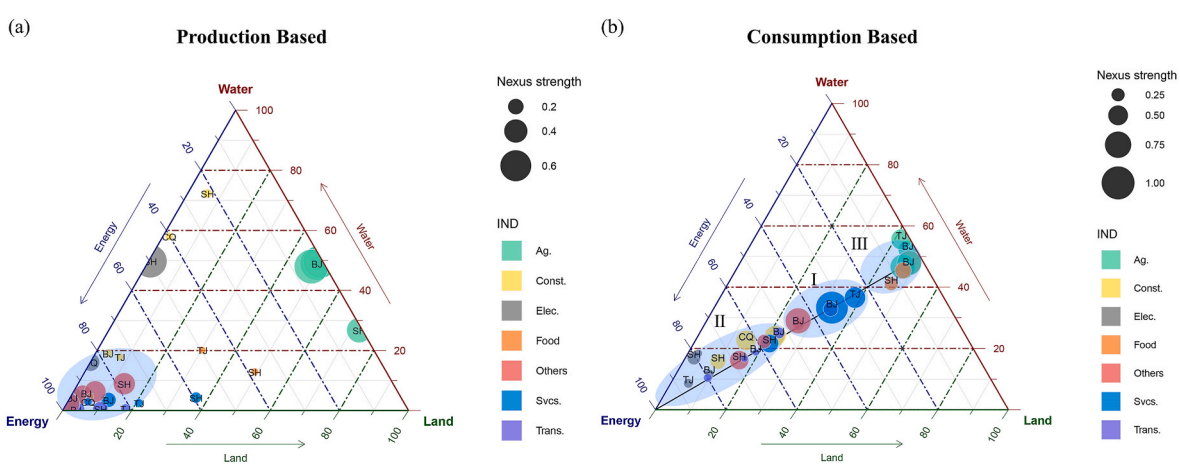

Fig. 3. Urban industrial nexus strength and industrial physical resource efficiency from the production- and consumption-based accounting. (a) The UINS and UIPRE from the production-based accounting. (b) The UINS and UIPRE from the consumption-based accounting. The size of a circle represents the UINS. Colored circle represents the 7 sectors, which are shown by squares in the legend. The abbreviated letters BJ, TJ, SH, and CQ inside the circle represent Beijing, Tianjin, Shanghai, and Chongqing, respectively. Ag., Const., Elec., Food, Others, Svcs, and Trans. are abbreviations for *agriculture*, *construction*, *electricity, gas & water*, *transport*, *others*, *services*, *food & tobacco*.

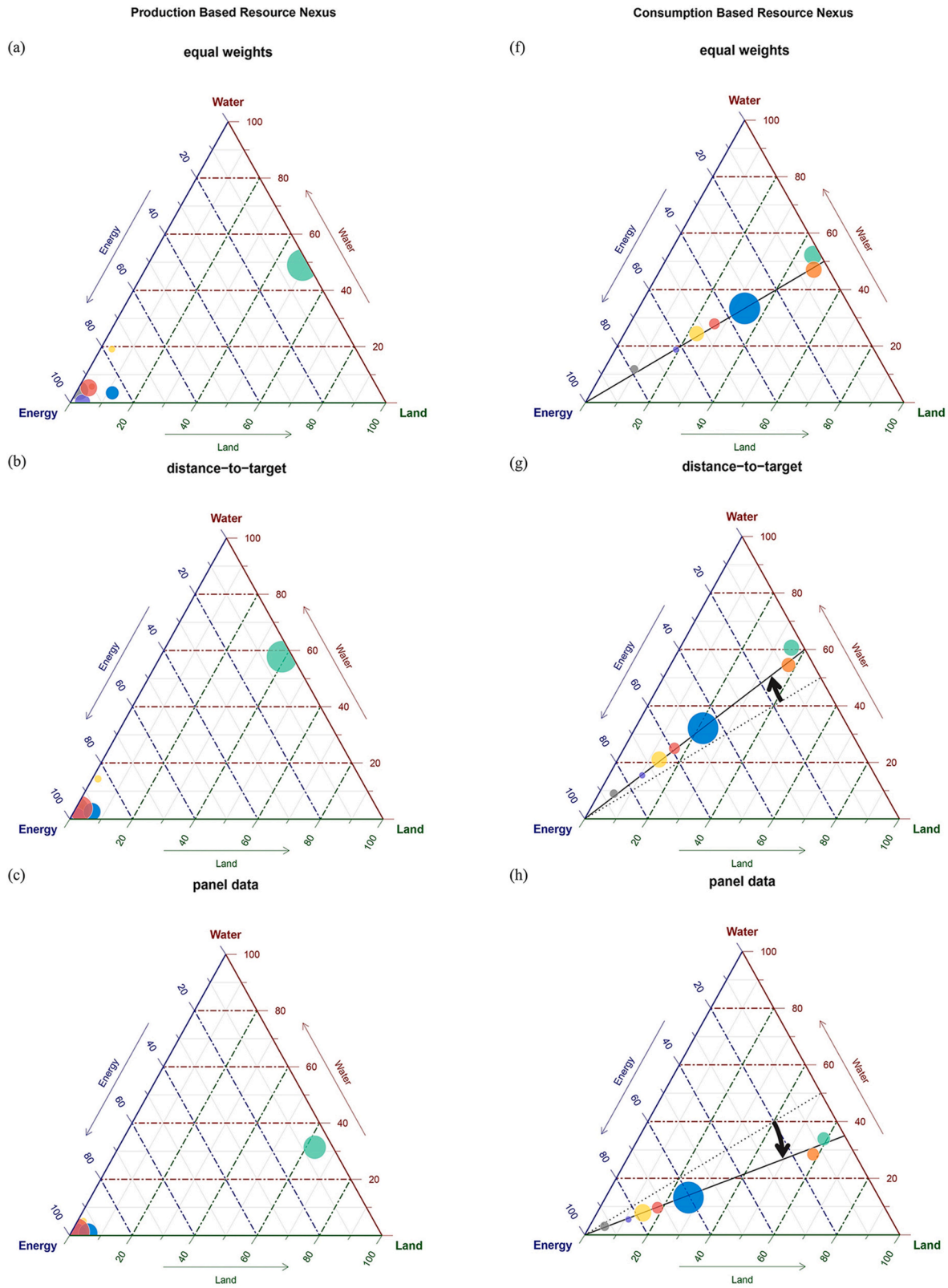

Fig. 4. Urban industrial nexus strength and industrial physical resource efficiency under various weightings. The left part is the UINS and UIPRE under various weighting schemes from the production-based accounting. The right part is the UINS and UIPRE under various weighting schemes from the consumption-based accounting. The size of a circle represents the UINS. The color of a circle represents the 7 sectors, which are shown by squares in the legend. Panels (a–j) share the same legend.

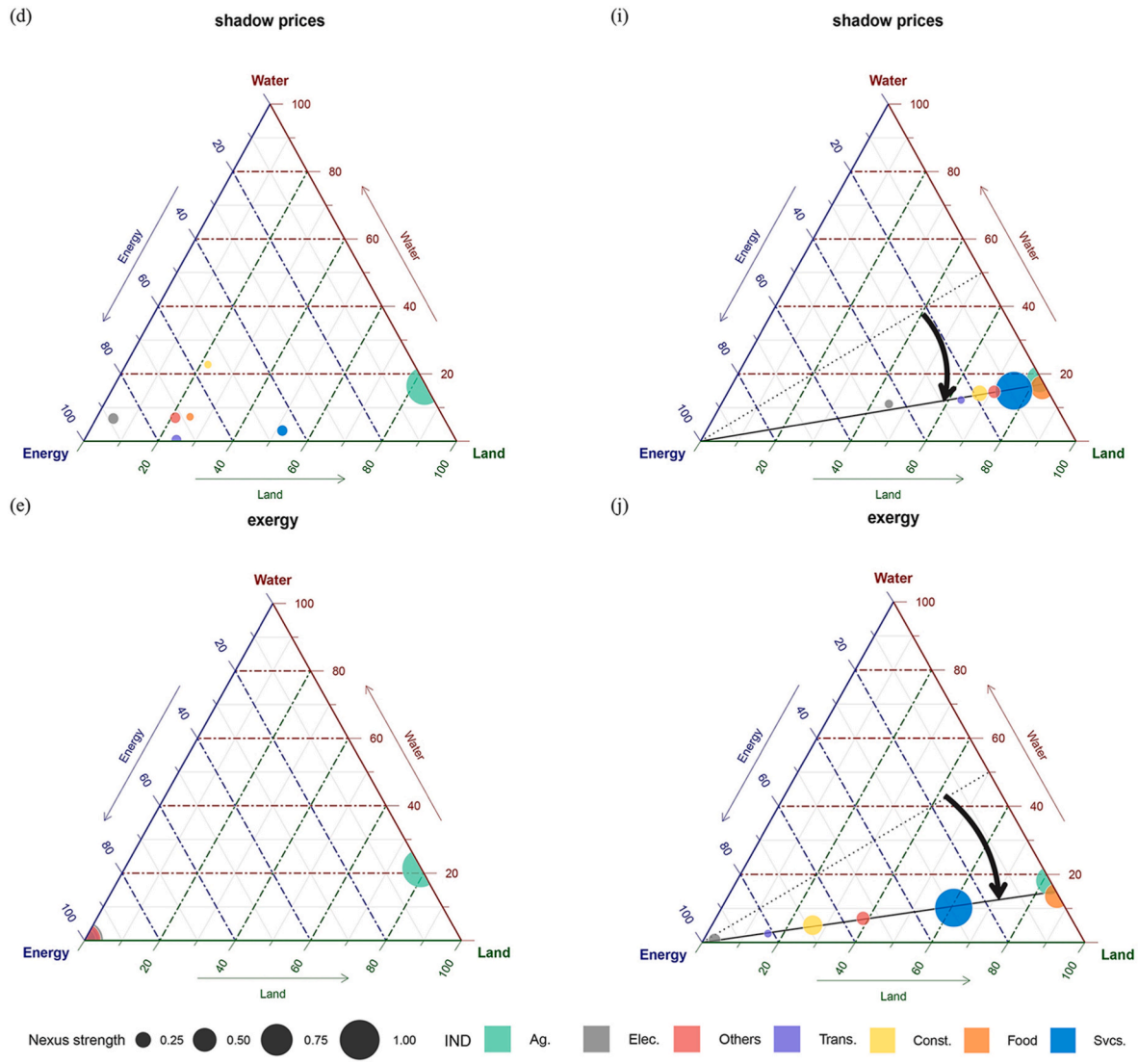

Fig. 4. (*continued*).

From the consumption-based accounting, the UINS shows distinct characteristics from that of the production perspective. In general, the *services* sector, with a value close to 1, gained positions in the top nexuses under these different weightings (Fig. 4f–j), indicating that the EWL were highly used and were strongly associated with this sector. Notably, sectors were distributed along the line that passed through the energy vertex in the same order, indicating that energy resource efficiency in each sector decreases in the order of *electricity, gas & water*, *transport*, *construction*, *others*, *services*, *food & tobacco*, and *agriculture* with different weights and that the water and land contribution to UINS are constant. Under physical weightings (i.e., equal weights, distance-to-target, and panel data), most sectors were mainly biased towards the energy vertex, while under economic weightings (i.e., shadow prices and exergy), they were biased towards the land axis. Specifically, under the distance-to-target weighting (Fig. 4g), the line over the energy vertex was biased upward toward the water axis, indicating the resource efficiency ratio of water to land was 1.5, as in the case of the *agriculture* and *food & tobacco* sectors, with water resource efficiency over 54% (see Supplementary Data Table S3). The line of the energy vertex under the other four weightings was increasingly biased downward to the land axis, indicating that land has an increasing share in water and land contribution to UINS, and the resource efficiency ratio of water to land were 0.6, 0.2, and 0.18, respectively. Furthermore, the *agriculture* and *food & tobacco* sectors under these various weights were dominated by the water–land resources, with resource efficiency of water and land above 86%.

4. Discussion and conclusion

4.1. Significance of the methodological framework

This study provides a new methodological framework that fits into UTMDN framework as provided before (Wang et al., 2022). By combining this methodological framework with the previously proposed UTMDN, we can thoroughly analyze the flow patterns of multiple resources, taking into account the economic and environmental correlations between sectors in urban economic and social subsystems, and quantitatively analyze the structural characteristics and the efficiency of multiple resources. Despite their inherent simplifications, the above two frameworks enable a step-by-step analysis of urban multiple resources and highlight a comprehensive and complete picture of the local, peri- and tele-coupling among the urban natural-economic-social subsystems induced by anthropogenic activities (Liu et al., 2015).

This methodological framework for urban resource management quantifies the direct and indirect resource use and allocation of urban goods and services along the supply chains using the EE-MSIO model in

terms of flows, structures, and efficiencies. It integrates different resources into a comprehensive and systematic nexus framework to optimize the use of resources in urban systems for sustainable management of urban resources and ultimately for sustainable urban development, such as Sustainable Development Goal 11 (SDG11) that aims to "make cities and human settlements inclusive, safe, resilient, and sustainable (United Nations, 2015)." This study focuses on urban resource efficiencies. Multiple resources of different units are integrated to look at the physical resource efficiency at the urban sectoral level. Moreover, this framework considers resource characteristics and scarcity, assigns weights according to various meso and macro policies (Liu et al., 2015), and identifies the key sectors under diverse policy interventions from a nexus approach for specific regulation and control. Our framework can be applied to other natural resources and other pollutants involving carbon dioxide (CO_2). Understanding urban resource flows in a multi-scale economy as well as analyzing the urban resource nexus strength and resource efficiency is the basis for urban sustainable resource management (Tan et al., 2021).

4.2. Consumption perspective complements production perspective

Cities are intricately connected to global trade networks, which facilitate the exchange of products and services from around the world. Consequently, a resource nexus based on a consumption perspective can be clarified as a necessary complement to a production-based perspective. This analysis can help final or intermediate consumers determine the impact of their purchases on the supply chain. The supply chain-wide analysis based on EE-MSIO modeling can be applied in understanding how these vital natural resources are interconnected in the urban system, and uncovering the critical sectors along the supply chain. For example, based on our results, we can conclude that the four megacities depend heavily on imports to meet local demand. The *agriculture* and *food & tobacco* sectors were typically dominated by water and land, with imported flows being the main source of embodied water and land flows for these four megacities. Meanwhile, the simultaneous interactions among multiple sectors, domestic trade, and international trade should be considered while formulating policies (Romero-Lankao et al., 2017; Yang et al., 2020). Cities frequently act outside of their national context, and many decisions affecting global development are made at this sub-national level. Analyzing resource flows and efficiency at the urban scale is essential for solving global resource challenges.

4.3. Urban resource efficiency requires various policy considerations

Given that UINS provides a weight of one-third to the EWL in relation to the average weight, the results exhibit similarities to those obtained by structural analysis. Additionally, we considered the variability of UINS under different weightings for EWL resources. From the production-based accounting, sectors other than the *agriculture* sector were near the energy vertex under all weightings except the shadow prices, reflecting that energy resource efficiency exceeded 83%, which means urban economic sectors rely on energy for production. Therefore, it is necessary to pay attention to the energy input of each urban production sector, which can identify key sectors to specifically implement the national energy consumption dual control policy for regulation (Li et al., 2018). Besides, it is necessary to advocate for multiple targets for governance. For example, reducing energy use in each sector will lead to the reduction of energy-related emissions such as carbon dioxide, which can help achieve the reduction of pollution and carbon at the industrial level (Qian et al., 2021; Tian et al., 2022). Because the scarcity of land resources was taken into account and the land weights were set higher (76%), under the shadow price weights, sectors were characterized by a decentralized distribution near the energy vertex and a high weighting of land in water and land in UINS. In attempting to address one of humanity's greatest challenges, both sides of the coin-production and consumption-need to be addressed, with the goal of keeping their impact on the Earth's resources within planetary boundaries (Wiedmann and Lenzen, 2018). Promoting internal linkages between producers and consumers within the same urban system is vital in the context of limited resources to maintain ecological balance and circulation between cities (Tan et al., 2021).

The UINS, based on the consumption perspective, can account for the resource use that occurs in various sectors along the supply chains, thereby identifying stronger and more complex resource connections. This finding is consistent with the conclusions reported by Font Vivanco et al. at the national scale (Font Vivanco et al., 2018). From the consumption-based accounting, although different weightings were set for each resource, sectors were distributed in the order of *electricity, gas & water, transport, construction, others, services, food & tobacco,* and *agriculture* on a line with energy as the apex under all weightings, and sectors changed from being dominated by energy to being dominated by water and land. The changing dominance of resources at the sectoral level can clearly show the different use shares of different resources in different sectors and facilitate policy decisions by decision-makers. Regarding policy design, we provide a scientific basis for decision-making based on quantitative analysis. Cities as a regulatory unit for different resources under different weighting designs, such as distance-to-target bias to energy and water resources, panel data bias to energy and land, and shadow prices and exergy bias to land, indicating that policy has a greater impact on the UINS and UIPRE of cities, so the government should make relevant policies according to different industries in different cities, for city management cannot adopt a one-size-fits-all approach. The management and regulation of resources will be different, and different designs will be made according to different cities with different comparative advantages in production technologies and natural endowments, which can optimize the overall use of natural resources. For example, for cities with scarce water resources, imports from water-deficit cities should be reduced, less water-intensive products should be imported, or policies could be developed with an appropriate weighting of water resources so that these cities can reduce their water consumption to maintain local sustainable development (Qian et al., 2019; Zhang et al., 2021). Determining weights under diverse meco and macro policies is more scientific than determining weights under a single consideration (Müller et al., 2021).

4.4. Urban physical resource efficiency needs to be considered

Traditional resource efficiency, measured as the ratio between the added value and the environmental impacts of the product or service by resources, is considered separately from the economic perspective (Yu et al., 2013). We use the same normalized approach as in the physical perspective to compute economic resource efficiency and give one-third weighting to each EWL, resulting in a different distribution from that of the physical resource efficiency. Detailed information about urban industrial economic resource efficiency was shown in Supplementary Section 3-3. The UIPRE presented in this study exhibits distinct characteristics and has the potential to serve as a valuable complement to economic resource efficiency. The use of the UIPRE metric may provide a more comprehensive evaluation of the sectors' resource nexus.

The analysis of urban resources allows for resource reallocation at the urban industrial level in order to redirect resources to where they are most needed based on the overall resource effectiveness of the system, thus maximizing the use of all available resources. Intercity cooperation may improve resource efficiency by integrating the diverse strengths of cooperating cities. The urban scale provides an essential methodological basis for how the whole range of the human-nature nexus affects national and global sustainable resource management. Additionally, urban resource management is a dynamic process (Batty, 1971; Krueger et al., 2022), and its development and formation must have deeply rooted laws. Each city has different types and functions (Brelsford et al., 2017), and there is no such thing as a standardized development pattern, so its

resource management is bound to adopt its consistent development pattern. Urban industrial resource management is essential for cities to achieve sustainable production and consumption (SDG14) and resource management (SDG11) (United Nations, 2015).

4.5. Limitations and future directions

One of the primary limitations of this research is the use of data from 2010, which, while not the most current year, remains to provide valuable insights into the issue of urban resource efficiency. Second, it is important to acknowledge that the research is subject to the inherent limitations of input-output tables (Wiedmann, 2009). Last, the sectors have been extensively aggregated for the sake of this research, resulting in a small margin of error that does not significantly affect the outcomes (Hu et al., 2020a).

Future research should first improve data tracking and updating, then explore the changing patterns of urban resource use and consumption across multiple years, thereby predicting future resource nexus. Second, consider more socioeconomic factors, such as resource endowment, geopolitics, economic development, population growth, and other factors; incorporate more cross-scale evaluation indicators; improve the research methodology and analytical framework; assess the relationship between resources and socioeconomics in urban systems more systematically and comprehensively; and explore the driving factors of urban resource flows. Third, in-depth research is conducted on urban resource use patterns and mechanisms with different development conditions and urban spatial units to propose reasonable and precise measures based on scientific conclusions of resource analysis and provide scientific support for decision-making on urban resource management. Fourth, link resource nexus with SDGs at the city scale to analyze how different actions to advance one SDG have varied impacts on other SDGs (Fuso Nerini et al., 2019), and systematically distinguish between local and international impacts (Engström et al., 2021). Fifth, a systematic nexus of planetary boundaries, sustainable development, urban resources, and environmental elements should be conducted in the future (Wiedmann and Allen, 2021). A major transition is occurring away from consumption-based monetary growth toward one that values and makes decisions based on the non-exceedance of critical environmental thresholds (Koch, 2020). Thus, efficiency cannot be viewed from a strictly economic resource perspective but should be based on ecological constraints, environmental health, and human well-being, fostering effective social and ecological benefits (McPhearson et al., 2021).

Credit authors statement

Meng, Liu and Yang initiated the idea for the paper and designed the research; Meng and Wang performed the research, ran the models and calculations, conducted the analysis, visualized the figures, and wrote the original draft; Giannetti, Agostinho and Almeida contributed ideas for the analyses and give comments on the draft; Liu and Yang revised and provided critically important content, and supervised the research. All authors actively contributed to the draft review.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 72174028, 71804023).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118849.

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