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Abstract

Unprecedented pace of urbanization and industrialization caused a massive increase in China's urban metabolic pressure. The trend presents an urgent challenge for detailing the long-term changes and disparities in urban metabolic performances in a wide range of cities. Here, we present empirical evidence of 283 China's cities from 2000 to 2018 based on emergy analysis indicating that China's urban metabolic performance gradually becomes worse. For example, the environmental sustainability index decreased by 81.64% between 2000 and 2018. In addition, emergy-based performances among China's cities show considerable differences. Agricultural cities and light manufacturing cities have better sustainability; energy production cities face high environmental pressure. Scenarios for 2025 show that total emergy use would experience slower growth; and most cities continue their decline in emergy metabolism. To ensure overall progress on urban metabolic performance, heavy manufacturing cities and energy production cities should give more attention in adjusting emergy structure.

Introduction

Cities have become the predominant habitat of contemporary humanity, with a little more than half of the global population residing in urban areas, estimated to reach 66% by 2050 [1]. As a result, human activities in cities are significant drivers of global resource consumption. Nearly three-quarters of global materials and four-fifths of global energy are consumed in cities to meet the needs of human activities [2]. This is particularly the case in China's cities, which have experienced unprecedented urbanization in the past decades [3]. For instance, Chinese primary energy consumption increased by nearly a factor of 25 from 1965 to 2019 [4]. Massive energy and resource consumption have triggered a high metabolic pressure, accompanied by irreversible environmental degradation [5]. Therefore, urban metabolic processes and structures of China's cities are needed to be evaluated to reduce resource consumption and alleviate urban metabolic pressure on the environment.

There is an extensive literature using the concept of urban metabolism to depict the interactions and circulation of energy and materials in an urban system [6,7]. Urban metabolism originated from biology conceptualizing cities as living organisms that require biological metabolic processes to support the activities of a system [8]. Urban metabolism is defined as "*the total sum of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste*" (Kennedy et al., 2007, pp. 44)[9]. Previous research on urban metabolism focused on the interactions of biophysical flows between the system and its hinterland [10,11], urban metabolic structures [12], and driving factors of metabolic activities [13]. The major accounting methods for urban metabolism are based on material-based analysis and energy-based analysis [14]. Material-based analysis follows the principle that the mass of input resources should equal the mass of output [15]. Energy-based analysis derived from thermodynamics includes emergy and exergy analysis [16].

Existing studies of urban metabolism cover global [17], national [18], and regional scales [19], as well as specific sectors [20], communities [21], and households [22]. At the city level, differences in climatic conditions, demographics, socioeconomic development, and resource endowment would cause significant variations in material and energy consumption, which can also cause differences in urban metabolic performance among cities. China's cities show significant differences in socioeconomic and environmental characteristics. Literature on urban metabolism investigated temporal changes or urban disparities in the context of China. For example, Chen and Chen [23] tracked the long-term historical trajectory of carbon flows to monitor Beijing's metabolic changes in the period 1985-2012. Xu, et al. [24] identified the metabolic types of the Chinese cities in 2017 using a comprehensive classification method. However, there is still a lack of analysis and comparison detailing long-term changes and disparities of urban metabolism of China's cities.

Emergy analysis, introduced by systems ecologist H.T. Odum, is regarded as a useful method in environmental accounting by linking ecology, thermodynamics, and general system theory [25]. Emergy is defined as the total available energy that is required in the production of goods and services [8]. Different from the concept of energy, it represents the cumulative energy availability (embodied solar energy) from primary solar radiation to final activities[26,27]. In emergy analysis, a system's operation requires materials and energy from local indigenous resources (including renewable and non-renewable resources) and the surrounding hinterland. In return, products and services, and waste are produced and consumed locally or exported to the surrounding system. A 'good' urban metabolic performance based on the emergy framework usually indicates that an urban system depends more on indigenous renewable resources than non-renewable resources to maintain a self-sustained state [28]. Emergy analysis has been widely used in accounting of urban metabolic performance [21,29]. Therefore, emergy analysis can provide a holistic and conceptual understanding of urban metabolic performance, as it integrates various types of resource use exhibited in environmental, economic, and social subsystems.

Here, we aim to detail the changes and disparities in urban metabolic performance of China's cities. In our study, urban metabolic structures, metabolic flows, and environmental influence of 283 prefecture-level cities in China from 2000 to 2018 are investigated based on emergy analysis [8]. We investigate future urban metabolic performance considering the impact of a five-year development policy to highlight the potential improvement. Our study sheds light on urban ecological-economic performance by considering resource and energy use patterns and metabolic flows. Delineating long-term changes and disparities in urban metabolic performance in a wide range of cities could be instrumental in customizing sustainable resource utilization strategies in accordance with local characteristics. Outcomes obtained in our study can provide references to cities elsewhere of similar social, economic and environmental characteristics.

Urban metabolism within the urban system can be further divided into input and output components, including renewable resources, non-renewable resources, imported resources, outputs, and waste. For the input components, renewable and non-renewable resources are from indigenous production, whilst imported resources come from the outside system. Goods and services (urban value added) and waste belong to output. Discussions of the urban metabolic performance that underlie emergy indices are conducted, including the environmental sustainability index (ESI), the environmental investment ratio (EIR), the environmental load ratio (ELR), and the territory emergy yield ratio (EYR_t), to reflect the system's sustainability, dependence on the surrounding environment, environmental pressure, and competitiveness in emergy, respectively. In emergy indices, a 'good' urban metabolic performance usually means a high ESI and low ELR [30]. Detailed explanations and calculation processes of emergy indices are presented in the methods and materials.

Results

Trends in China's total emergy use

Total emergy use of 283 cities shows an overall increase with some fluctuations (shown in Figure 1a). Total emergy use in 2000 was estimated at 1.12E+25 solar emjoules (sej), growing to 2.71E+25 sej (increased 141.51%) in 2014, but the annual growth rate slowed down. In 2015, total emergy use decreased 2.22% to 2.65E+25 sej, after that, it fluctuated and reached 2.68E+25 sej in 2018.

Total emergy use among China's cities shows considerable differences. For example, the maximum of total emergy use among 283 cities is more than 9 times the average value in 2018. To reflect characteristic differences, cities have been divided into six groups, service-based cities (n=24), high-tech cities (n=70), light manufacturing cities (n=78), heavy manufacturing cities (n=57), agricultural cities (n=31), and energy production cities (n=23), according to the dominant sector's share of urban GDP [31]. Energy production cities occupied the highest position of emergy per capita in 2018 (shown in Figure 2) reflecting high intensity as well as resource utilization. The economy of cities with high emergy intensity relies more heavily on resource-intense and energy-intensive industries with low population, such as the coal-based sectors. For example, Shuozhou (2.14E+17 sej/person, Shanxi province) occupied the highest position of emergy per capita, followed by Ordos (1.59E+17 sej/person, Inner Mongolia) and Yulin (1.09E+17 sej/person, Shaanxi province). Service-based cities have the highest value of the emergy density (shown in Figure 2). Some service-based cities with a high value of total emergy use per unit of land, such as Shenzhen (2.14E+14 sej/m^2) and Shanghai (1.35E+14 sej/m^2), occupied the top positions of emergy density. Cities like these usually suffer from constraints of land resources. How to retain cities' metabolic activities with limited land may become a major challenge during rapid urbanization.

Emergy structure of urban metabolism

Figure 3a shows the emergy structure of 283 cities from 2000 to 2018. Local renewable and non-renewable resources play dominant roles in total emergy use for most of the cities. Emergy of renewable resources increased between 2000 and 2018 (shown in Figure 3b). However, the share of renewable resources in total emergy use has declined from 57.31% to 40.45% (shown in Figure 3a). The emergy flow of non-renewable resources has dominated total emergy use since 2010, with the share of annual total emergy use ranging from 37.73% to 46.12% during this time frame. Similarly, the emergy flows from imported resources of the metabolic system show an overall increase. The value in 2018 was more than three times the emergy of 2000. Changes in the emergy structure may be related to the accession to the World Trade Organization in 2001. After that, China succeeded in attracting external investment to support national economic development based on a relatively inexpensive workforce and abundant natural resources. This process accelerated the transformation of China's economic development trajectory from agriculture (renewable resources) to energy-intensive manufacturing (non-renewable resources) and service sectors.

Coal played a dominant role in non-renewable resources with a share of 67.5% in 2018 (shown in Figure 3c), although the share of non-renewable resources from coal shows a decline. This is likely due to the improvement in the utilization efficiency of coal and the development of clean energy. Most cities with high shares of coal are distributed mainly in energy-rich regions, such as the Shanxi-Inner Mongolia coal base and the Huainan-Huaibei coal base, where urban development and economic growth are overwhelmingly dependent on energy-intensive industries. Steel also contributed markedly to non-renewable resources, with the contributions reaching 21.17% in 2018. In industrial cities that are well endowed with iron and steel resources, such as Tangshan and Handan (both in Hebei province), steel consumption generally maintains a high level coinciding with local industrial development. Emergy flows from vegetables and dairy products were the main contributors, together accounting for 69.8% of local renewable resources during the investigation period (shown in Figure 3d). Populous cities, such as Chongqing, consumed large amounts of food, which caused high demands for renewable resources in the local metabolic system. As shown in Figure 3e, imported goods and services contribute the most to imported resources, representing average 81.63% of imported resources during the entire investigation period. Developed and eastern coastal cities such as Beijing and Shanghai are top consumers of imported resources reflecting the high dependence on the outside system.

Emergy-based performance of the urban metabolic system

A downward trend in the environmental sustainability index (ESI), to reflect the system's sustainability, of 283 cities was observed. The ESI decreased by 81.64% over the past 19-year study period (shown in Figure 1b). The decline is mainly due to the national metabolic system's reliance on local non-renewable and imported resources, rather than using renewable resources. The environmental investment ratio (EIR), to demonstrate the system's dependence on the surrounding environment shows an overall increase with some fluctuations from 2000 to 2018 (shown in Figure 1a). The increase in EIR of the 283 cities indicates that more imported resources were required to support national metabolic activities. Such a result is further confirmed by changes in the national emergy structure of metabolic inflows. Our analysis shows that the environmental load ratio (ELR), to measure the environmental pressure, of the 283 cities has increased nearly twofold since 2000 (Figure 1a). To maintain high-speed economic development over the past years, exploiting non-renewable resources and importing external resources have caused a significantly high pressure on the natural environment. Territory emergy yield ratio (EYR_t) reflects the metabolic system's competitiveness in emergy. The EYR_t ranges from 4.76 to 9.37 between 2000 and 2018. The EYR_t shows a decline between 2000 and 2006; after that, it increased and reached a peak in

2016 (presented in Figure 1b). The initial decline indicates that the system's competitiveness in emergy was increasing, and it can benefit more from imported metabolic activities. A huge amount of external resources are adopted to sustain the Chinese metabolic activities.

Figure 4a shows the spatial variation of ESI for prefectural-level cities in 2018. Agricultural cities and light manufacturing cities have better ESI performances, followed by high-tech cities and service-based cities, while heavy manufacturing cities and energy production cities are at the bottom. Agricultural cities and light manufacturing cities, such as Wuwei (Gansu province) and Bazhong (Sichuan province), have the largest share of emergy flows from renewable resources with 94.6% and 92.54% in 2018, respectively. In these cities, local economic development heavily depends on agriculture and the light manufacturing industry given their abundant sunlight, water, and agricultural products. In contrast, service-based cities usually depend to a larger extent on imported resources and services to support urban metabolic activities. Typical examples are, Shenzhen and Beijing, where imported resources accounted for 59.1% and 53.5% of the total emergy use in 2018, respectively. The metabolic system of service-based cities would be vulnerable in the case of imported resources' scarcity. Service-based cities need to bolster domestic autarky to face metabolic challenges through increasing the share of indigenous renewable resources and improving the metabolic efficiency of the urban metabolic system. Heavy manufacturing cities and energy production cities are usually those whose urban economic development benefit more from local abundant non-renewable resources. For example, Tongling (Anhui province) is well-endowed with mineral resources, which provide a foundation for the development of local ore extraction and processing and metallurgical industries. A large amount of non-renewable resources (e.g. fossil fuel) are consumed in manufacturing processes. It is worth noticing that non-renewable resource depletion, environment pollution, and lagging economic performance have gradually become major challenges for heavy manufacturing cities and energy production cities along with the rapid urban economic development over the past few years. Adjustment of local industrial structure and development of alternative industries could be adopted to increase the share of local capital- and knowledge- intensive industries in local economy and reduce dependence on non-renewable resources.

Service-based cities are considered to depend more on external investment and have strong competitiveness in emergy with the highest EIR (0.70) and lowest EYR_t (33.57) in 2018. Service-based cities usually account for large fractions of external resource input, small fractions of indigenous renewable environmental inputs, and relatively lower outputs to the external system. Note that service-based cities located in the top positions of EIR (e.g. Shenzhen and Beijing, shown in Figure 4b) need to balance the metabolic flows of internal and external resources to reduce over-reliance on the outside system and replace it with indigenous resources. Similar to the roles in the food chain of an ecosystem, service-based cities with strong competitiveness in emergy (shown in Figure 4c), such as Beijing, Dongguan, and Shanghai, are regarded as 'predators' or net consumers, making more economic profits from imported metabolic activities. In contrast, agricultural cities show weak competitiveness in emergy, which deplete local resources to contribute to the metabolic activities of predators.

Energy production cities occupied the top position of the ELR. As shown in Figure 4d, the ELR of Yangquan (Shanxi province) and Wuhai (Inner Mongolia) exceeded other cities in 2018. The ELR of these two cities in 2018 also grew significantly compared with 2000. This is mainly because local industrial manufacturing activities consumed abundant coal resources, and thus markedly increased non-renewable resource consumption. Therefore, the observed cities with high ELR should draw attention to decreasing coal consumption and improving efficiency by adjusting the local coal-based energy structure. In general, cities with relatively large land areas and abundant agricultural resources tend to have low ELR, such as Ziyang (Sichuan province) and Guilin (Guangxi province).

Future urban metabolic performance (2021-2025)

Given the strong influence of policy instruments on metabolic activities of cities, we investigate potential future urban metabolic performance considering the policy impact. The 14th Five-Year Plan (14th FYP) released by the Chinese central government plays a critical role in guiding the next five-year development strategies (from 2021 to 2025) for the social, economic, and environmental aspects of China. The Chinese central government has assigned a series of social and economic targets to provinces and municipalities that are directly responsible for the achievement. To achieve these targets, national and local governments need to understand the potential implications of the policy before launching relevant policies. Therein, investigating urban metabolic performance under the guidance of the 14th FYP is instrumental in tailoring policies to advance urban sustainability.

Total emergy use would increase to 3.23E+25 sej in 2025 (shown in Figure 5a), but it would experience a slower growth with an average of 2.72% compared to 4.95% between 2000 and 2018. As shown in Figure 5b, the share from non-renewable resources and imported resources will grow to 47.69% and 13.59%, while the share of local renewable resources will decline to 38.73% of total emergy use in 2025. One of the reasons for the result is that the future trajectory of national economic development will still rely on energy-intensive manufacturing and service industries. It is worth noticing that policies to encourage electricity generation by using clean energy will cause a significant improvement in the emergy flows of renewable resources. According to Figure 5a, ESI would decline, whereas EIR, ELR, and EYR_t would increase till 2025. Policies to attract foreign investment, encourage import, and develop tourism would be instrumental in increasing the emergy flows of imported resources for the national metabolic system. Imported resources could further speed up industrial development leading to an increase in the consumption of indigenous non-renewable resources. As a result, the national metabolic system's dependence on the outside system and environmental pressure would increase.

Most cities would experience continuous decreasing in urban metabolic performance in the next five years. Cities with better metabolic performance are usually located in western Chinese provinces (e.g., Gansu and Sichuan). Policies to increase the amount of local renewable resources, such as encouraging agricultural production and promoting renewable energy for electricity generation (including hydropower, wind power, and solar power), could improve the urban metabolic performance. For example, Suihua and Yichun (both in Heilongjiang province), plan to increase agricultural products including grains, vegetables, milk, meat, and aquatic products. Consequently, urban metabolic performance of these cities will improve in 2025.

Conclusions

The urban metabolic performance of 283 Chinese prefecture-level cities from 2000 to 2018 was evaluated based on emergy analysis. The China's urban metabolic performance gradually becomes worse between 2000 and 2018. Total emergy use shows an overall increase, whilst its annual growth rate declined. Local renewable and non-renewable resources play dominant roles in total emergy use. The emergy structure has changed from 2000 to 2018, with the share of renewable resources in national total emergy use declining, whilst the share of non-renewable resources and imported resources was increasing. The metabolic system is losing its sustainability and competitiveness in emergy, whilst the system's dependence on the outside system and environmental pressure continues to increase. According to the analysis of future urban metabolic performance, total emergy use would increase to 3.23E+25 sej in 2025 with a slower growth rate.

Total emergy use of cities show considerable differences. Energy production cities occupy the highest position of emergy per capita in 2018, service-based cities show the highest level of the emergy metabolic density. Agricultural cities and light manufacturing cities have better sustainability (higher environmental sustainability index), followed by high-tech cities and service-based cities, while heavy manufacturing cities and energy production cities are at the bottom. Service-based cities depend more on the outside system and have strong competitiveness in emergy. Energy production cities tend to face high environmental pressure (higher environmental load ratio). Heavy manufacturing cities and energy production cities should give more attention in adjusting emergy structure.

Materials And Methods

Overview of the emergy analysis framework

Emergy analysis is a measure of how much solar energy is required, both directly and indirectly, for manufacturing a product or making a service within a system [32]. Solar radiation is considered the ultimate power of all materials, energy, and nutrient flows on the earth. Flows from geothermal heat and gravitational potential (from a non-solar source) are also transformed into solar equivalent energy based on the transformation coefficient. In the context of emergy theory, all metabolic flows induced by metabolic activities make it possible to compare them by a common unit (the equivalence of the solar emjoules, sej) based on the transformity. Transformity (sej/unit) is defined as the amount of emergy used to produce one unit of product or service. The lower the value of transformity, the more efficient is the conversion process [33].

The emergy analysis of our study includes three steps: definition of system boundary, emergy structure, and major metabolic flows, calculation of emergy metabolic flows, and evaluation of emergy-based indices. Figure 6 details the emergy accounting diagram of urban components and metabolic flows to visualize the major social, economic, and environmental activities within an urban system. To compare intercity differences, the urban system boundary in our study is defined as the administrative boundary that coincides with official statistical publications.

The renewable resources (R) include the emergy from renewable resources of the natural environment (R_1) and local renewable resources (R_2) (see Supplementary Table 1). To avoid double-counting for renewable resources of the natural environment, the largest emergy flow among sun, wind, rain, and earth cycle is adopted as R_1 [34]. The non-renewable resources in our study are the emergy obtained within the study area including indigenous topsoil loss, fossil fuels, electricity, and steel. Imported resources mainly contain foreign direct investment, imported goods and services, and tourism from the outside system. Outputs refer to goods and services quantified by gross domestic product (GDP) [35]. Wastewater, waste gas, and solid waste constitute waste. Wastewater includes domestic sewage discharged and industrial wastewater discharge. Solid waste includes common industrial solid waste generated and domestic waste removed and transported. The global emergy baseline conducted in this study was 1.20E+25 sej/year (Brown and Ulgiati, 2016).

Emergy indices

Similar to previous studies on emergy [25,29], several emergy indices are characterized to evaluate emergy intensity and metabolic performance of urban systems (see Supplementary Table 2). Total emergy use represents emergy consumption of all goods and services within an urban metabolic system in a given period. Intensity indicators (emergy per capita, and emergy density) that target resource conservation per unit are applied to reflect the economic, social, and environmental intensities of the urban metabolic system. ELR is designed to reflect the system's environmental pressure, which reflects the intensity of indirect resources (embodied human-made and natural capital loss) contributing to a metabolic system [36]. A higher ELR indicates that system's metabolic activities depend heavily on indirect resources, which cause a greater pressure on local environmental resource. ESI can be used to reflect the sustainability of a system. It is an aggregate indicator by considering the effect of imported resources on local urban system and the environmental loading. EIR makes it possible to reflect the dependence of local metabolic system on the surrounding environment. EYR_t provides insights on a system's competitiveness in emergy; a lower value indicates that the urban metabolic system benefits more from the trading relationships compared with its surrounding environment [29,30].

Study area, data compilation, and scenarios

Our study urban metabolic analysis includes 283 cities at the prefectural level in 30 Chinese provinces, due to accessibility and completeness of the metabolic data at the city level. To describe changes in urban metabolic properties, the urban metabolic performance of 283 cities was analyzed for the time range 2000-2018. The types of data required to detail urban metabolic properties are summarized including meteorological information, consumption of resources and services, monetary outputs, and waste generation (see Supplementary Table 1). The urban metabolic datasets in our study were derived from official statistics, including the China Statistical Yearbook, the China City Statistical Yearbook, the China Urban Construction Statistical Yearbook, and the Municipal Statistical Yearbook of each city in the corresponding years. Historical meteorological data of renewable resources of the natural environment missing from the statistical yearbooks were obtained from the China Meteorological Administration (http://data.cma.cn). Because China has a high coal share in electricity generation, to avoid double counting for emergy flows, the electricity data in our study excluded coal-fired electricity. The ratio of coal-fired electricity for regional power grids in China, namely North China Grid, Northeast China Grid, Northwest China Grid, East China Grid, Central China Grid, and South China Grid, were considered to reflect the regional differences on the accommodation ability of electricity consumption. In addition, all prices and costs were converted into 2000 constant prices. Unavailable data for specific years were interpolated.

Future performance of urban metabolism in Chinese prefectural-level cities was discussed in our study. The national and regional 14th FYP (including 22 provinces, 4 municipalities, and 4 autonomous regions) were collected from the National Development and Reform Commission and local governments. The emergy flows of renewable resources, non-renewable resources, imported resources, and outputs in 2025 can be estimated by the targets of food production, energy consumption, and economic development based on the 14th FYP. Given the lack of the 14th FYP at the city level, we assumed that city-level metabolic flows in 2025 coincided with the share of GDP of cities in the corresponding province. Renewable resources were assumed to be constant for this short time period. The average emergy flows of renewable resources of the natural environment from 2016 to 2018 have been applied as the emergy value for future urban metabolic analysis.

Limitations

Some limitations and potential future extensions are worth noting. First, detailed emergy data reflecting different metabolic processes such as the production of light industrial products, construction materials, and services are ignored due to data availability in a wide range of Chinese cities. Second, the transformities used in our study were collected from different sources without considering regional differences. The lack of region-specific transformity data causes uncertainty for accurate emergy calculation.

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Declarations

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Author contributions

J.H., Y.S., K.H., and M.T. conceptualized and designed the study. R.X, F.R, and W.W. contributed to reviewing and discussing the manuscript. M.T. performed the calculations and prepared the manuscript. M.T., J.H., Y.S., and K.H. contributed to writing the manuscript.

Figures

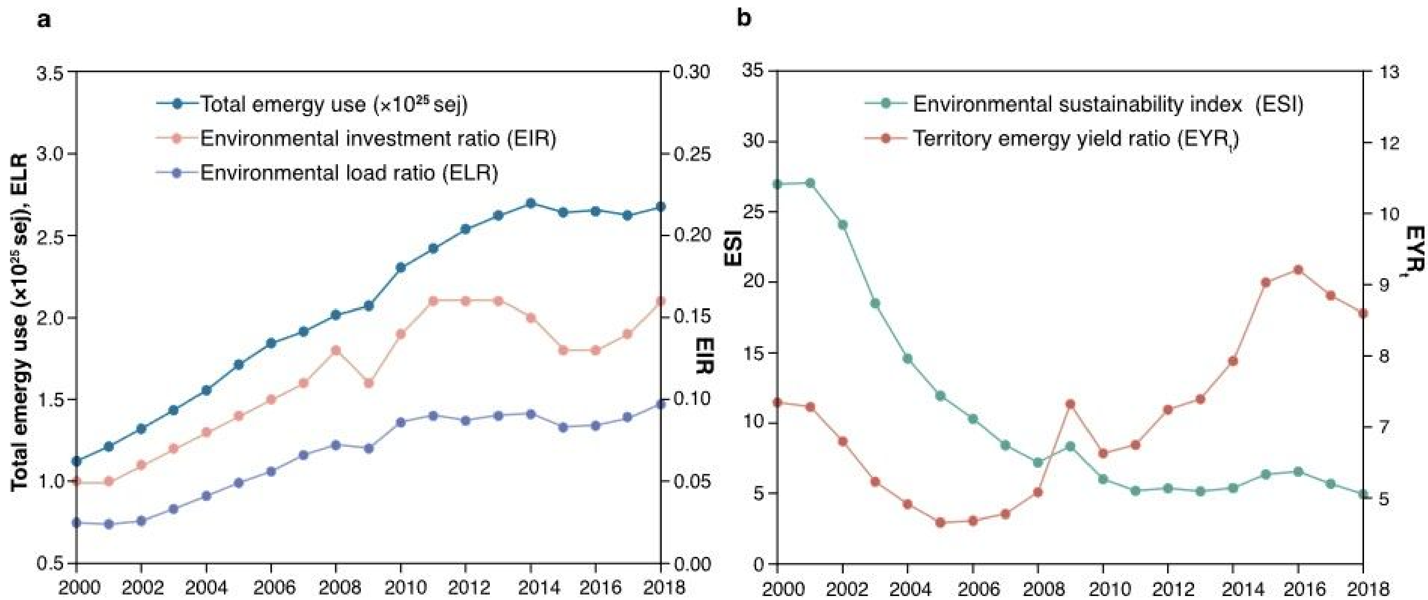

Figure 1

Development of emergy indices in China over the period 2000-2018. a, The blue line shows total emergy use, the pink line shows the environmental investment ratio, and the violet line shows the environmental load ratio. b, The green line shows the environmental sustainability index and the red line shows the territory emergy yield ratio.

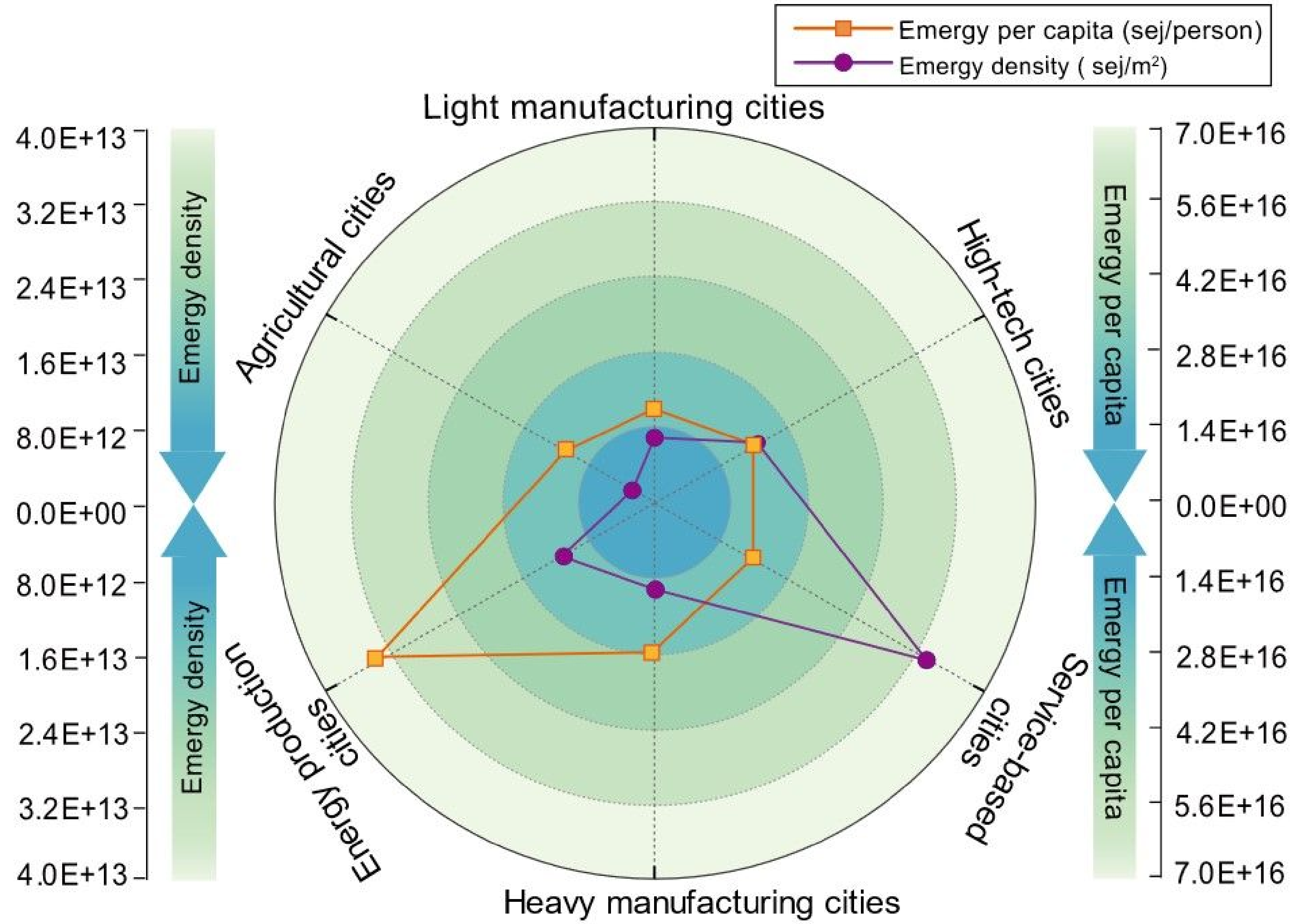

Figure 2

Results of intensity indicators for six city groups. The orange dots show the emergy per capita for six city groups in 2018 (including agricultural cities, energy production cities, heavy manufacturing cities, service-based cities, high-tech cities, and light manufacturing cities). The purple dots show the emergy density for six city groups in 2018. The left and right axis shows the range of emergy density and emergy per capita, respectively.

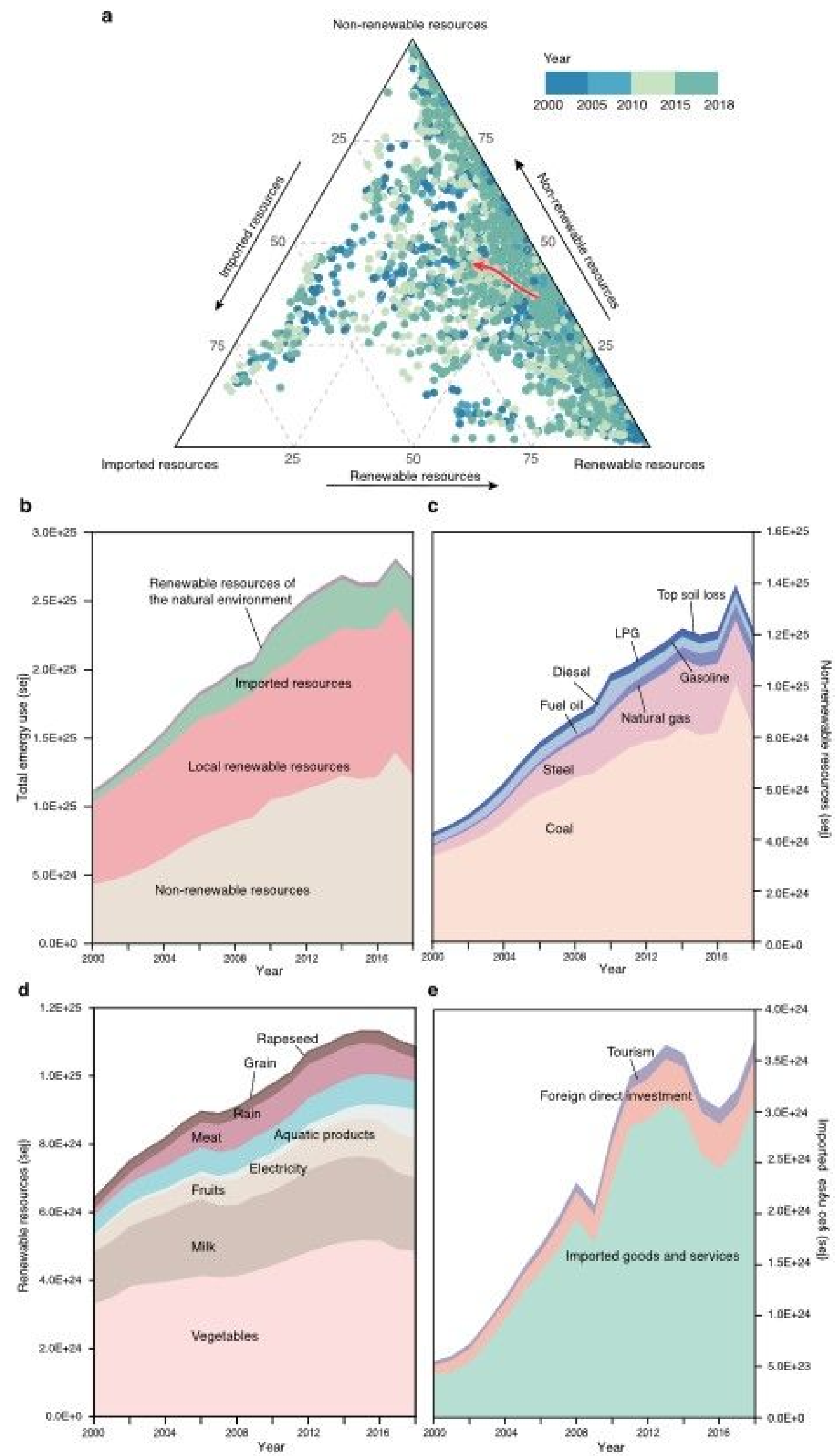

Figure 3

Emergy inflows for urban metabolism. a, Urban metabolic inflow diagram of renewable resources, non-renewable resources, and imported resources during the study period. The colored dots represent the urban emergy structure in different periods. The pink dots represent the national emergy structure from 2000 to 2018. b, Emergy flows for total emergy use from 2000 to 2018. c, Emergy flows for non-renewable resources. LPG refers to liquefied petroleum gas. c, Emergy flows for renewable resources. d, Emergy flows for r imported resources.

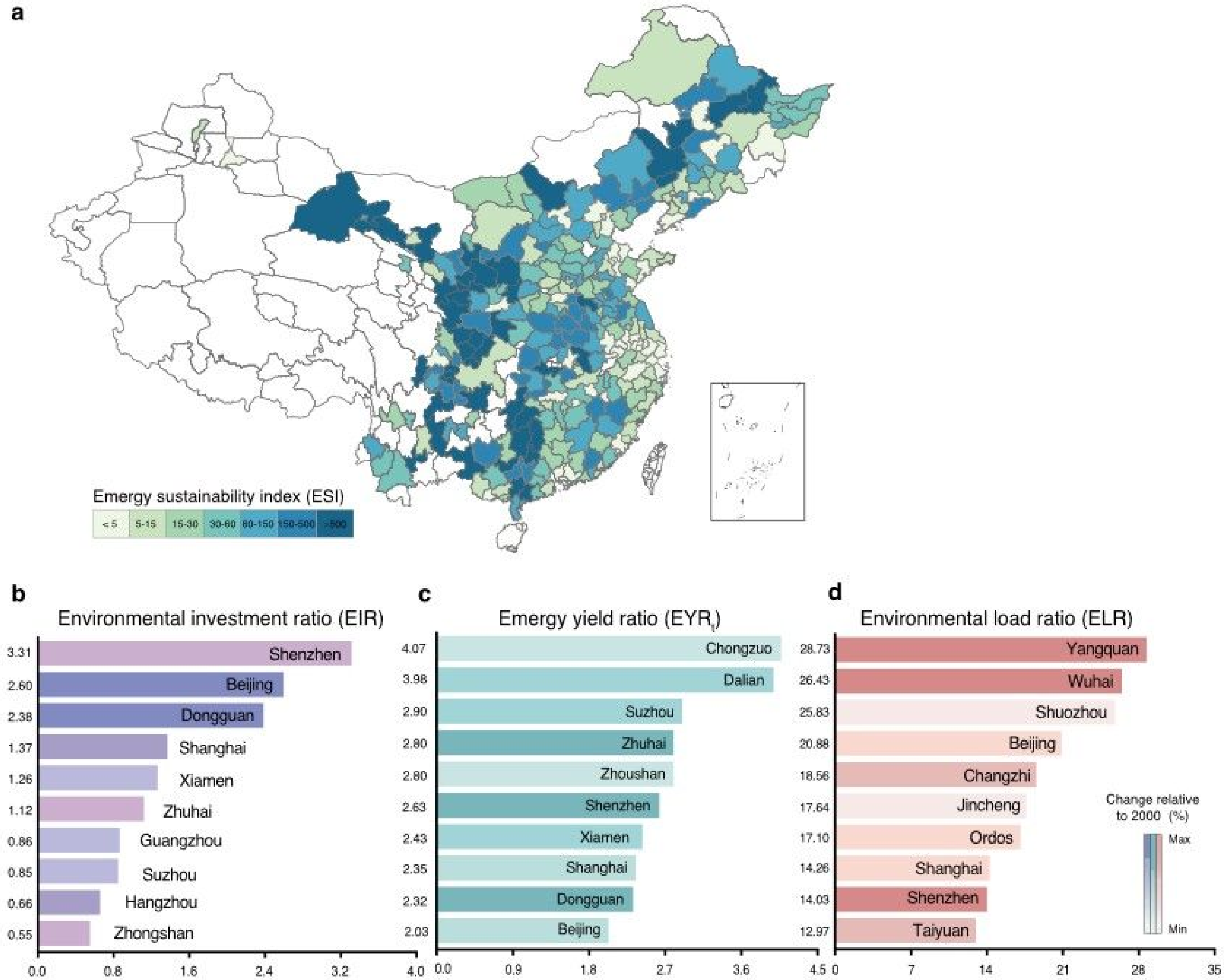

Figure 4

Emergy-based performance of the urban metabolic system. a, Mapping ESI performance across the urban metabolism of the 283 cities in 2018. b and c, Environmental investment ratio (EIR) and environmental load ratio (ELR) of the top 10 cities in 2018. b, Emergy yield ratio (EYR_t) of the bottom10 cities in 2018. The color bars (light to dark) represent the change rate of emergy indices compared with 2000.

Figure 5

Urban emergy performance in China from 2000 to 2025. a, Changes of emergy indices. The green line shows the environmental sustainability index, the pink line shows the territory emergy yield ratio, the red line shows the environmental investment ratio, the violet line shows environmental load ratio, and the blue line shows the total emergy use. b, Emergy structure of urban metabolism. The colored dots represent the urban emergy structure in different periods. The purple, green, and orange axis shows the imported resources, renewable resources, and non-renewable resources, respectively.

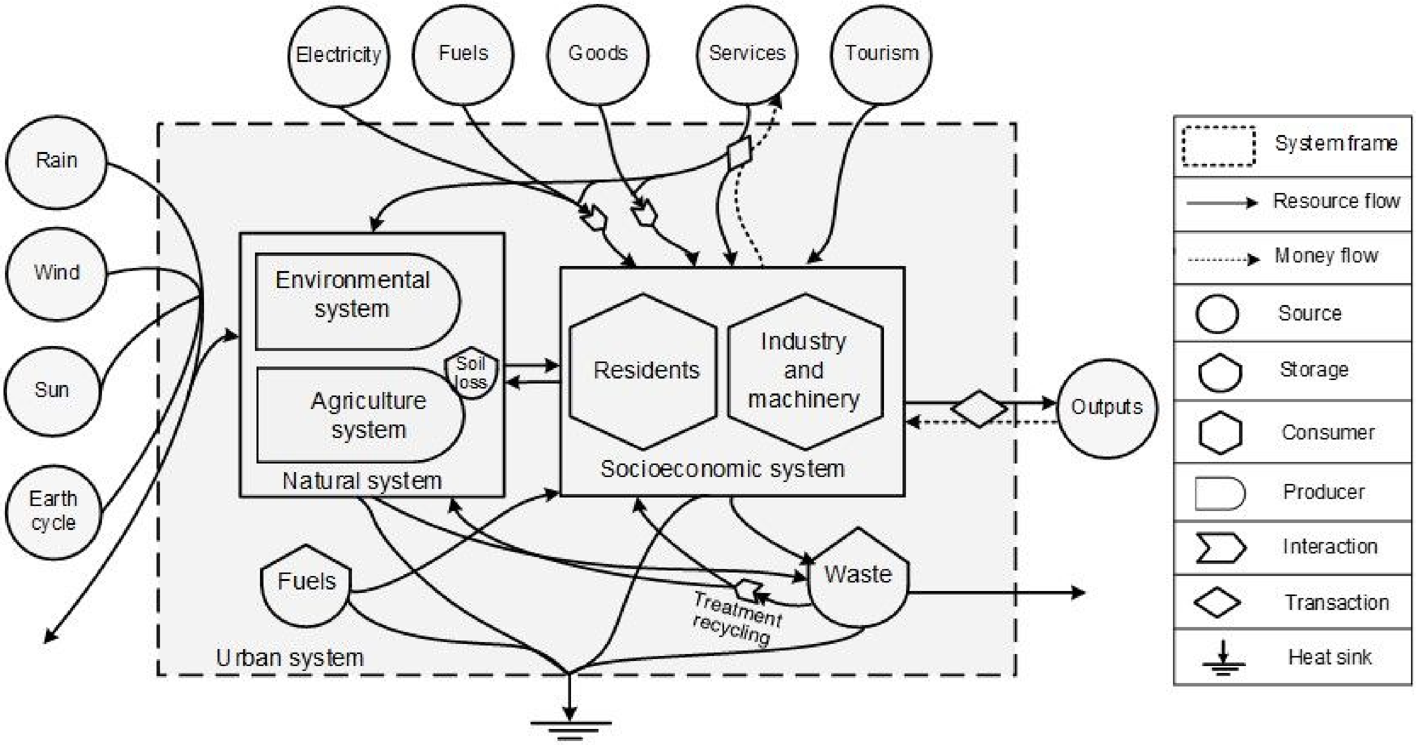

Figure 6

Emergy analysis diagram of the urban metabolism

Supplementary Files

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- SupplementaryInformation.docx