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Emergy-based comparative analysis of urban metabolic efficiency and sustainability in the case of big and data scarce medium-sized cities: A case study for Jing-Jin-Ji region (China)

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A B S T R A C T

Emergy-based Urban Sustainability Assessment Framework (EmUSAF) is an effective and widely advocated method to evaluate the general condition at city-scale. However, applying this framework to medium-sized cities has encountered obstacles owing to the data scarcity and inconsistency problem. One the one hand, a range of data such as detailed import-export goods data are only compiled at provincial level therefore for prefectural cities the lack of data is very common. On the other hand, the original environmental data provided by local government is usually not uniform and well-formatted, meaning that the data inventory disclosed by the environmental data compilation administration in different cities are not identical, leading to the difficulty of comparison. Meanwhile, for a given year, not all elements needed in the emergy synthesis inventory are available due to the difference compilation and disclosure timelines of different statistics reports. These facts hinder both city-specific research at local scale and regional research. To address this lingering issue, we developed a methodology for deriving substitute data from extant available data of upper-level administration division and for integrating them into the EUSAF. With a case study on Jing-Jin-Ji region, covering 11 medium-sized prefecture cities, we conducted an emergy analysis of the whole region and examined the methodology discussing its uncertainties and limitations.

This study contributes to emergy synthesis in four aspects: (1) Provide a solution to the enduring data scarcity and inconsistency problem of emergy-based urban sustainability assessment; (2) Establish the deduction method which can deduce data at larger scale to smaller scale when lacking physical data at smaller scale instead of using monetary estimates, and also the accuracy of the deduced data can be identified by using uncertainty analysis; (3) Investigate the strategically essential Jing-Jin-Ji region as a case, applying the new approach to get the data for prefectural cities and carrying out an emergy analysis. We found that the indicators, reflecting the specific development traits of each city, are well confirmed by the status quo in the region. This fact proves that our new method framework is affordable and could be extended in the future study of medium-sized cities suffering from data scarcity. (4) Demonstrate the significant gap between using money value and physical amount to calculate emergy of imported goods, proving the importance of physical amount data in the Emergy-based comparative analysis of urban metabolic efficiency and sustainability.

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Nomenclature

EBS	Energy Balance Sheet
ELR	Environmental Load Ratio
emergy/$	Emergy Money Ratio
EP	Emergy Used Per Capita
ESI	Environmental Sustainability Index
F	Imported Fuels
G	Imported Goods
GACPRC	General Administration of Customs of the People Republic of China
GDP	Gross Domestic Product
GIS	Geographic Information System
HS	Harmonised System
IEGT	Import-Export Goods Table
IOAS	Input and Output Accounting System
IOSs	Input-Output sheets
Jing-Jin-Ji	Metropolitan Region or Jing-Jin-Ji (JJJ) Beijing-Tianjin-Hebei
MPI	Money Paid for Imports N Local Non-renewable Resource
NBSC	National Bureau of Statistics of China
NEAD	National Environmental Accounting Database
NEAS	National Economy Accounting System
PR	Population Report
R	Local Renewable Resource
SF	Service Flow
TF	Tourism Flow
TR	Total Receipt
U	The Total Emergy Used
UEVs	Unit Emergy Values
WRR	Water Resource Report

1. Introduction

The ability of statistical authorities to organize environmental and social economic surveys at urban level is the key to providing reliable and stable estimates of the urban metabolic efficiency and sustainability in China and elsewhere in the world. Obviously, it is not an easy task in the case of such a huge and economically diverse country as China. However, without establishing a reliable country-wide monitoring system, it does not make sense to calculate any urban measures of sustainability. China still has a long way to go in building a data collection system, ensuring quality and data consistency and constructing relatively long time-series of environmental and social economic data for big and middle size cities. So far, the developments in official statistics can be summarized as a mix of good intentions with slow-paced improvements and a lack of transparency (Plekhanov, 2016).

The “fog” surrounding official statistics has started to disperse recently, albeit rather slowly. Recently, the 19th conference of Chinese Communist Party, held in Beijing in October 2017, gave high priority to *Ecological Civilization*, *i.e.* the sustainable interaction between economy and ecosystem. This topic showed that the central government is now paying more attention to environmental and social economic stability issues. Sustainability as a policy concept is about solving the tension between the aspirations of mankind towards a better life and the limitations imposed by nature (Kulman and Farrington, 2010). Effective and comprehensive environmental management over the country is crucial in the pursuit of *Ecological Civilization.* Consequently, monitoring developments in related areas are getting more important than ever. To achieve this goal, an institution for management and supervision of natural resources and ecosystem is going to be established. Based on the available data of the whole nation, this institution should be able to plan and implement policies from a comprehensive perspective, thereby boosting the overall environmental management efficiency. Apart from the optimization of the data-based official management process, integration of some cutting-edge technology can also contribute to the realization of sustainability. For example, Amini et al. (2018) introduced smart cities as a prominent example of sustainable interdependent networks that could collaborate together to achieve sustainability in terms of upgrading the infrastructures to more intelligent and efficient systems. Mohammadi et al. (2018) presented a decentralized decision-making algorithm for collaborative operation of electricity transmission system operators (TSOs) and distribution system operators (DSOs) optimal power flow (OPF) implementation that could improve the economy and reliability of the entire power system.

However, analysis of government data has always posed a challenge for China urban watchers. The existing key problem lies in the process of acquiring correct and detailed urban data. Due to the limitation of current statistics compilation system, data scarcity and inconsistency is common for medium-sized or small-size cities, which hinders urban ecosystem research. The administrative division of China consists of five levels: provincial; prefecture; county; township; village. Until 2017, national statistics were collected from each division and compiled at different administrative scales. International trade statistics, provided by the General Administration of Customs of the People Republic of China (GACPRC), are collected by each province and for several important port cities, such as Dalian and Qingdao. Comprehensive information is recorded from a provincial perspective, while, at prefecture level, public import and export data are usually given as total amounts in yearbooks. The Energy Balance Sheet (EBS), compiled at the provincial level, reflects the condition of energy production, sale, storage and consumption, incorporating the primary data collected by each department. Corresponding management departments or industry associations are in charge of energy and electricity consumptions accounting of four transportation sectors (i.e.: railway, airway, roadway and water way). Among other included items, manufacturing, wholesale and retail industries are assigned to the provincial affiliation of National Bureau of Statistics of China (NBSC). The provincial-level EBSs are published monthly and annually through provincial statistics report, China Energy Statistics Annual Report and also via the official website of NBSC. National Economy Accounting System (NEAS) defines the Input and Output Accounting System (IOAS), which also includes Gross Domestic Production (GDP) accounting. Unlike EBS, other reports are compiled every five years and published two years later than the accounted year. Every basic input and output sheet is compiled in 2nd and 7th year of each decade, while the extended sheet is compiled in 0th and 5th year of each decade (which results in the inconsistency of the statistics). IOAS reports three kinds of sheet: the input and output sheet; the supply sheet; the utilization sheet. Specifically, the input and output sheet displays the input resources and the output destinations in a matrix form, illustrating the flows of resources among different economic sectors and revealing how they interact each other.

Urban general information statistics accounting system is applied in China only for higher-level cities. It covers a wide range of socio-economic aspects. In particular, they include: the administrative division, land area, water resources; population and labor market; transportation, telecommunication and energy; industry; domestic and international trade and tourism; fixed assets investment; education, technology, culture and sanitation; public welfare and environmental protection. Although each involved city collects information for all the above-mentioned aspects, the elaboration doesn't follow any fixed form on data collection and reporting. Consequently, data quality is variable and not guaranteed. Scaling down to county-town level, data for general information statistics, which are also given, have even more vague quality, contributing to a further data inconsistency and also to the present incomparability among cities.

Data scarcity and inconsistency, observed for medium- and small-sized cities, derive from three sources. The first is that the majority of the data, needed to perform detailed inventory analysis, such as emergy analysis, are only provided at provincial level. The second is that data are unformatted and not properly supported by meta-data, which would guarantee their quality, depending on the choices of each local administration. The last is that different primary data are compiled with different time frames. The combination of these gaps leads to a final input data incoherence when applied to emergy analysis as one of the inventory analysis methods.

Emergy analysis, which was introduced by H.T. Odum, currently is one of the most important methods in environmental accounting. Emergy represents the cumulative energy availability, expressed in equivalent-solar units (sej), supplied by the ecosystem for any of its component or process (either natural or human-made) during its formation or production. Its application to urban metabolism analysis derives from the National Environmental Accounting Database (NEAD), which reports detailed information for over 150 countries for the full array of resources, that underlie economies (Odum et al., 1987; Doherty et al., 1993; Ulgiati et al., 1994; Brown and Ulgiati, 2002; Odum et al., 2000; Tilley and Swank, 2003).

The first version of NEAD was produced in 2006 referred to year 2000 (Sweeney et al., 2006), a second version was released in 2012, with additional countries included, as well as years 2004 and 2008, while a third version is now avaliable online (www.emergy-nead.com). Unit Emergy Values (UEVs) were also updated according to new research, changing the numerical results relative to the first NEAD release. Many studies were developed applying NEAD data (King et al., 2007; Cohen et al., 2007a,b; Giannetti et al., 2013; Lei et al., 2014; Coscieme et al., 2014a, b; Pulselli et al., 2015; Liu et al., 2017a, b). Some of them, in particular, tried to downscale the same approach to the urban level, such as Macao, Beijing and other cities in China (Su et al., 2009; Zhang et al., 2011; Liu et al., 2011; Zhang et al., 2011; Lei et al., 2014), Montreal in Canada (Vega-Azamar et al., 2013), Uppsala in Sweden (Russo et al., 2014) and Rome in Italy (Ascione et al., 2008, 2009, 2011; Zucaro et al., 2014).

Detailed data inventories, which are required to develop an accurate emergy synthesis, especially in medium-sized cities, are often not available. However, their availability would be important in the case of China, since medium-sized cities are the key control points of resources metabolism. Moreover, these urban centers are facing extremely difficult management challenges and opportunities for improving urban sustainability. In fact, the design of local policies, as well as the realization of *Ecological Civilization*, is centered on cities, where the majority of global population lives. Moreover, urban centers represent pivotal points of present economic, political, cultural and social development. Therefore, accurate quantitative evaluations would be necessary for assessing the urban metabolism, where economy and ecosystem interact with each other.

Alternative solutions were proposed, aiming to mitigate the effect of data scarcity. Money value often was used as a substitute estimate of emergy flows associated to production of different goods in many previous studies (Yu et al., 2016). In particular, emergy amounts are often derived from money values, since they are combined with production processes and flows. As a reliable alternative, LCA approach can be applied (Liu et al., 2014; Wang et al., 2014). Finally, GIS (Geographic Information System) based emergy data analyses can be applied in different ways to compensate the incompleteness of the primary data (Brown and Vivas, 2005; Huang et al., 2007; Agostinho et al., 2008; Pulselli, 2010; Lin et al., 2013; Coscieme et al., 2014a,b; Li and Luo, 2015), allowing also the spatially explicit representations and visualization of emergy.

The metrological problem, associated to monitoring techniques, as well as measuring units and uncertainty sources, are key points of any data-based modelling and science. From the experimental side, intense multi-sensor data collection methods, such as nowcasting in meteorology, or hierarchical monitoring approaches, which were developed in the last decades, are offering a big opportunity for the future (Casazza et al., 2008, 2017; Lega et al., 2010; Gargiulo et al., 2013; Lega and Persechino, 2014; Errico et al., 2015; Casazza, 2016; Wang et al., 2016). However, persisting challenges remain, especially when data collection is poor, to make integrated sustainability assessment based on emergy method.

A practical alternative calculation mechanism is crucial for such cases, where limited data and information hinders further investigations on urban metabolism characteristics. This problem was already explored by previous studies, which displayed different evaluation 'dimensions' (i.e.: data vs. Simulation-based evaluation and local vs. Regional approaches). Even if recent advancement in data collection can support the definition of urban scenarios, the relevance of such data is crucial, if they need to be converted into meaningful information for local scale assessments and future planning. In parallel, the question on how to generate locally relevant data in the case data scarce contexts still remains open.

With respect to environmental and social economic information, data can be gathered from different available validated databases. Although these datasets contain information about key environmental or social economic features, most of them tend to have a lower level of accuracy and/or high uncertainties at local scale, which need to be taken into account when used for decision making. Another approach is to simulate environmental data. Simulations can both generate missing data and evaluate their quality, in particular at larger geographic scales, either where original data are unavailable or for exploring alternative scenarios, such as future energy/water use or land-use type changes. However, both database and simulation derived data depend on the quality of inputs, so that no clear distinction can be really made. Indeed, also many inputs are obtained through a complex processing flow. For example, stream flow is almost never measured directly, instead relying upon a stage – discharge model to convert water level into discharge (Beven and Alcock, 2012).

The same difficulties occur considering local vs. Regional approaches. Some researchers developed tools, that allow an assessment of the hierarchical and multiscale structure of ecological systems from either a spatial (Dray et al., 2006; Blanchet et al., 2008) or a temporal perspective (Keitt and Fischer, 2006; Angeler et al., 2009). Most spatial studies provide only single 'snapshots' of community structures across spatial scales, that limit the understanding of the dynamic component of the space-time duality (Angeler et al., 2013). For example, regional monitoring strategies frequently employ a nested sampling design, where intensive samplings occur in several sites located within a finite set of selected study areas. This sampling protocol naturally lends itself to a hierarchical analysis, to account for dependence among subsamples (Miller and Campbell Grant, 2015).

Since simulation is becoming a prominent practice to produce outputs at policy-relevant scales, it is crucial to integrate and incorporate socio-economic data into simulation processes. Here again, data scarcity problem arises, together with the problem of getting affordable inputs from higher-scale levels. Any chosen procedure inevitably introduces errors and uncertainties, which need to be taken into account, when simulations are used to inform decision-making.

This paper is aimed at proposing a feasible simplification mode and data distribution approach in the case of data scarcity. In parallel, this method is applied for the assessment of urban metabolic efficiency and sustainability through the emergy approach. In particular, the attention is focused on big cities and data-scarce medium-sized cities. With this respect, uncertainty of different data distribution approaches are discussed. Even though the discussion is applied to China, as a case study, the same approach can also be adapted to different countries, due to the existing common methodological problems. In summary, this study contributes to emergy synthesis in three aspects: (1) Provide a solution to the enduring data scarcity and inconsistency problem of emergy-based urban sustainability assessment; (2) Establish the deduction method which can deduce data at larger scale to smaller scale when lacking physical data at smaller scale instead of using monetary estimates, and also the accuracy of the deduced data can be identified by using uncertainty analysis; (3) Investigate the strategically essential Jing-Jin-Ji region as a case, applying the new approach to get the data for prefectural cities and carrying out an emergy analysis. We found that the indicators, reflecting the specific development traits of each city, are well confirmed by the status quo in the region. This fact proves that our new method framework is affordable and could be extended in the future study of medium-sized cities suffering from data scarcity. (4) Demonstrate the significant gap between using money value and physical amount to calculate emergy of imported goods, proving the importance of physical amount data in the Emergy-based comparative analysis of urban metabolic efficiency and sustainability.

2. Methods

2.1. Data preparation

Data for Chinese cities at any administrative division level can be derived from inventories at upper level division. Fig. 1 synthesizes the methodology framework applied to Chinese cities at any administrative division level, starting from a detailed data inventories acquisition for emergy analysis from upper level division's statistics, that are usually more comprehensive and accessible. In fact, when local statistics are not available, the emergy analysis inventory can still be reasonably constructed by distributing the statistics of its upper division level. As shown in the same figure, statistics of resources are mainly made of four standardized reports (i.e.: Water Resource Report (WRR), Energy Balance Sheet (EBS), Import-Export Goods Table (IEGT), Population Report (PR)). For each standardized report, we design a corresponding distribution index to deduce with. For some cities, emergy analysis inventory data can be partially acquired directly from local statistics. In this case, we adopt the original data. Note that, for cities of the same division level that have no available local data and need distribution from upper division level, the calculation is based on the resource amount diminished by the existing available data, to make sure that the sum of this level meets the original data of its upper level.

2.1.1. Renewable resources

Raw data of renewable resources are available in the statistical year book. Details about emergy of renewable resources calculation are given in Appendix 1.

2.1.2. Energy balance sheet

The Energy Balance Sheet (EBS) is an aggregate summary of energy production, transformation and final consumption in one area expressed as physical or monetary amounts (Qiu, 1995). The detailed energy balance sheet for Jing-Jin-Ji region is included in Appendix 1. Energy inflows and outflows of the system are divided into different categories (i.e.: total primary energy supply; indigenous production; import from other countries; import from other provinces; export to other countries; export to other provinces). Due to the lack of available data, the present energy balance sheet was compiled at the provincial level. Instead, Beijing and Tianjin have available original data, while the prefecture cities in Hebei province do not have data. Energy flows statistics for these data-scarce cities were deduced through GDP values. In particular, a linear correlation is assumed, as demonstrated in a previous research, where a significant linear regression relationship exists between the total GDP and the total carbon emissions from energy consumption (Tong and Ke-Ming, 2011).

In particular, any city-province percentage, P_i, is defined in Eq. (1), which can be derived through different indexes, such as industrial outputs and population. This equation represents the percentage relation between a city and its province.

$$P_i = index_{city_i} \Big/ index_{province} \times 100\% \quad (1)$$

Given P_i, Eq. (2) shows how to scale down any provincial energy balance sheet, using its GDP (GDP_i, as it is referred to the i-th province), to the city level and also fixing a province-scale universal coefficient, k:

$$GDP_i = k_i \times \text{energy flow} \quad (2)$$

Total GDP, made of the sum of its components, I, is equal to the sum of every energy flow (EF hereafter), as written in Eq. (3):

$$\sum_i GDP_i = k \times \sum_i EF_i \quad (3)$$

At city level, the i-th component of EF is accounted through Eq. (4):

$$EF_{i,\,\text{city}} = \left(\frac{GDP_i}{k}\right)_{\text{city}} = P_i\left(\frac{GDP_i}{k}\right)_{\text{province}} \quad (4)$$

The obtained value is, then, multiplied by a corresponding UEV, which converts the obtained value into an emergy amount, depending on the used fuel, as provided by NEAD[1] (Pan et al., 2017). Adding up all the categories, the emergy sum of imported and exported fuels are obtained.

For energy supply, the local (i.e., city) GDP ratio to provincial GDP is used to deduce the primary energy supply at city level. To avoid double counting, all data are derived from primary energy supply, since all other terms derive from primary energy. Table A1in Appendix 2 details the obtained energy values, which are accounted through Eq. (5):

$$P_i = \frac{gdp_i}{GDP} \quad (5)$$

where, gdp_i is the gross regional product for the i-th prefecture level city; GDP is the gross provincial product; P_i is the gross

[1] https://www.emergy-nead.com/home.

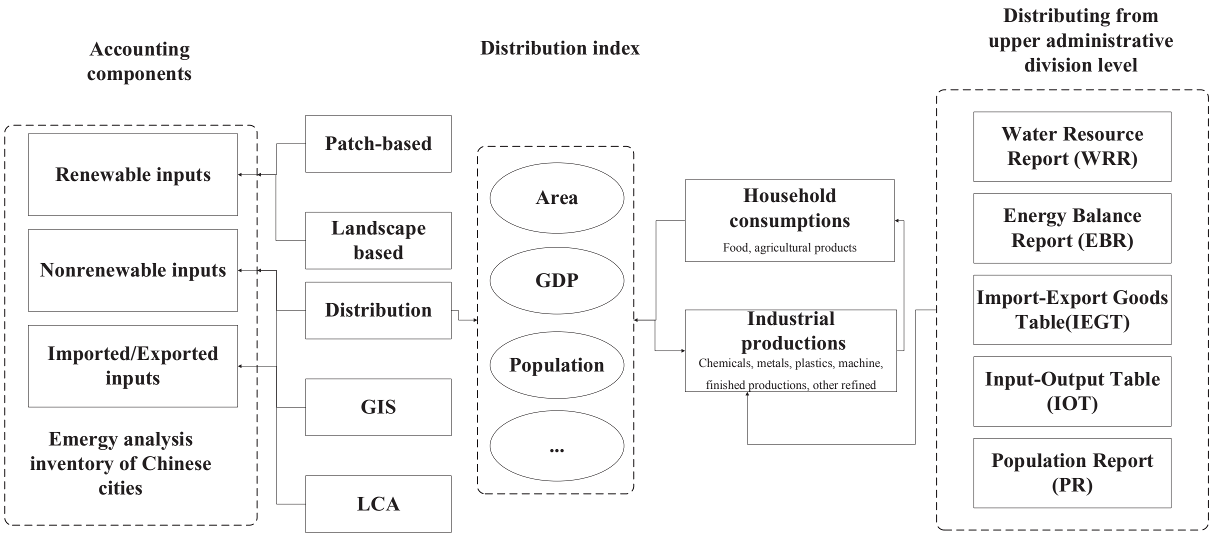

Fig. 1. Inputs, available indexes and accounting components, according to the Chinese official statistical databases, used for emergy analysis.

Table 1
Principle of data distribution.

No.	Imported/Exported Goods	Distribution index
1–1	Food & agricultural products	Population
1–2	Livestock, meat, fish	Population
1–3	Other refined goods	Population
1–4	Finished products	GDP
1–5	Machinery, transportation equipment	GDP
1–6	Metals	GDP
1–7	Minerals	GDP
1–8	Chemicals	GDP
1–9	Plastics & synthetic rubber	GDP

product ratio for the i-th city to its upper province. The i-th primary energy supply at city level, e_i, is accounted according to Eq. (6):

$$e_i = P_i * E_i \tag{6}$$

where P_i is the same indicator as Eq. (1) and E_i is the ith primary energy supply at provincial level.

2.1.3. Import-export

Apart from imported and exported fuels, urban system also imports and exports a considerable amount of goods. GACPRC compiles the import-export goods table annually. It summarizes 1000 types of imported goods, as well as the export of commodity goods. Then, it classifies them into 98 categories, following the international standard, known as the Harmonised System (HS). Among the 98 categories, one category covers coal, oil and their respective products, which coincides with part of the fuels included in the EBS. In order to avoid duplicated calculation, we dropped these items from the imported-exported goods table. For the remaining 97 categories, most are presented with both physical quantity (weight) and money value, while others only have money values. Two methods are defined to calculate their emergy value correspondingly. To illustrate the goods structure more clearly, 97 categories are grouped into 9 classes, as shown in Table 1.

Different and inhomogeneous data are generally found. In particular, different cases are possible:

- Case 1. Both physical quantity and money value are presented. Group 1-1 (Food & agricultural product), Group 1–2 (Livestock, meat, fish), Group 1–4 (Finished products), Group 1–6 (Metals), Group 1–7 (Minerals), Group 1–8 (Chemicals) and Group 1–9 (Plastics & synthetic rubber), fall under this case. We adopt the physical quantity multiplied by the UEV provided in NEAD, instead of using the money value.
- Case 2. Only money values are presented. Group "Machinery, transportation equipment" and "Other refined goods" are in this case. We proposed a LCA-based method to obtain physical quantity, specifically weight data, from the money value provided (obtained data are provided in the tables within Appendix 2). First, all the goods in the "Machinery & transportation equipment" were grouped into two parts: transport equipment and computer technology. We assumed that all the transport equipment and computer technology-relevant goods are cars and personal computers, respectively. For each part, we calculated the total emergy of their different material composition. The transition from money value to physical quantity is obtained dividing the total monetary amount by the average price of the good to get the total number of considered items. Having both the total number of items and their material composition, an estimate of total materials contained in each item is obtained. Then, this is multiplied by transformity to get the total emergy.

In terms of imported services, imports cost is multiplied by the global average emergy-to-money ratio. In detail, services embodied in trade flows are human work inputs to the transformations and flows of the materials. This is why human work cost is used to estimate the portion of the emergy in the trade flows associated to human services. In particular, given a certain amount of refers to Money Paid for Imports (in US $), Service Flow (SF), expressed in US $, is defined according to Eq. (7):

$$\mathrm{SF} = \mathrm{MPI}. \tag{7}$$

Any import, for which money was used to calculate emergy, is not included in the services calculation in order to avoid duplicated accounting. Finally, Tourism Flow (TF) values are derived from paid Total Receipt (TR), both expressed in units of US $, according to Eq. (8):

$$\mathrm{TF} = \mathrm{TR} \tag{8}$$

in which any export, from which emergy cost is derived, is not included in the calculation to avoid double accounting. Tourism data are derived from city statistics yearbook.

2.1.4. Input-output sheet

Total emergy data of imported and exported goods were defined. The purpose of this work is to further deepen the analyses, following the suggestion of integrating Input-Output sheets given by Cho (2013), which was never carefully followed before at such a spatial scale. However, the data of goods transported from and to other provinces are absent in the import-export goods table. However, they are necessary to have an accurate esteem of energy flows. To tackle the problem, we designed a method to get the goods flow between provinces from the input-output sheet.

Input-Output sheets (IOSs) describe the multiple sale and purchase relationships among producers and consumers within an economy. All the industries listed, except service industries, are classified into the 9 groups mentioned above. For each group, emergy from other provinces is equal to the associated money value referred to other provinces divided by the money value from other countries times emergy from other countries. It is assumed that, for each goods group, the composition of flows, from and to other countries, is consistent with that of flows from and to other provinces, respectively. To calculate the emergy from other provinces, emergy from other countries is multiplied by the money ratio.

2.1.5. Other inventory items

Immigrate and migrate population for each prefecture city in Hebei province is obtained by scaling down the Hebei province's population change table with corresponding population proportion.

2.1.6. Uncertainty analysis

The uncertainty of a physical quantity is generally measured by errors, which can be produced by instruments. In this study, the errors are the calculated change rate of emergy value based on other methods (population, GDP and area) with respect to the method defined here. The error propagation formula is generally used to calculate the uncertainty of two or more variables. When an estimate is the sum or differences of n estimates, the uncertainty of the estimates is defined according to Eq. (9):

$$U_c = \frac{\sqrt{(U_{s1}{*}\mu_{s1})^2 + (U_{s2}{*}\mu_{s2})^2 + \cdots + (U_{sn}{*}\mu_{sn})^2}}{|\mu_{s1}| + |\mu_{s2}| + \ldots + |\mu_{sn}|} \tag{9}$$

where, U_c is the uncertainty of the sum or differences of n estimates; $\mu_{s1} \ldots \mu_{sn}$ are the estimates; $U_{s1} \ldots U_{sn}$ is the uncertainty of the estimates (%).

2.2. Case study of Jing-Jin-Ji

Jing-Jin-Ji Metropolitan Region or Jing-Jin-Ji (JJJ), also known as Beijing-Tianjin-Hebei, is the national capital region of China. It is the biggest urbanized region in Northern China, that includes an economic region surrounding Beijing, Tianjin, and Hebei, alongside the coast of the Bohai Sea. There are 11 prefectural cities in Hebei province: Shijiazhuang; Baoding; Tangshan; Cangzhou; Langfang; Zhangjiakou; Chengde; Qinhuangdao; Xingtai; Handan. This emerging region is rising as a Northern metropolitan region, rivaling the Pearl River Delta in the South and the Yangtze River Delta in the East. In 2016, Jing-Jin-Ji produced 10% of China's GDP. Jing-Jin-Ji was traditionally involved in heavy industries and manufacturing. Tianjin's strengths have always been in aviation, logistics and shipping. Beijing complements this with strong petrochemical, education and R&D industries. The area is becoming a significant growth cluster for the automobile, electronics, petrochemical sectors, automotive industry, software and aircraft, also attracting foreign investments in manufacturing and health services.

Except the two provincial cities Beijing and Tianjin, all the 11 prefecture cities in Jing-Jin-Ji region are lack of EBS, IOS and IES data, because they are prefectural level cities, for which these three sheets are not compiled, if not at provincial level. Therefore, the distribution methodology is employed to deduce the data of the overall Hebei province.

3. Results

By applying the above defined method, detailed inventories for emergy analysis of cities at any level were inferred. Therefore, the development pattern of any region at the urban scale was investigated. Emergy analysis results of Jing-Jin-Ji region in 2012 are summarized from Figs. 2–7.

Consistent with the existing research about emergy-based urban sustainability assessment framework, on the basis of the quantification of emergy flows, a set of indices for 13 cities were calculated and used to evaluate the sustainable performance of urban system (Odum, 1996): the total emergy used (U), the emergy money ratio (emergy/$), the emergy used per capita (EP) and the Environmental Load Ratio (ELR).

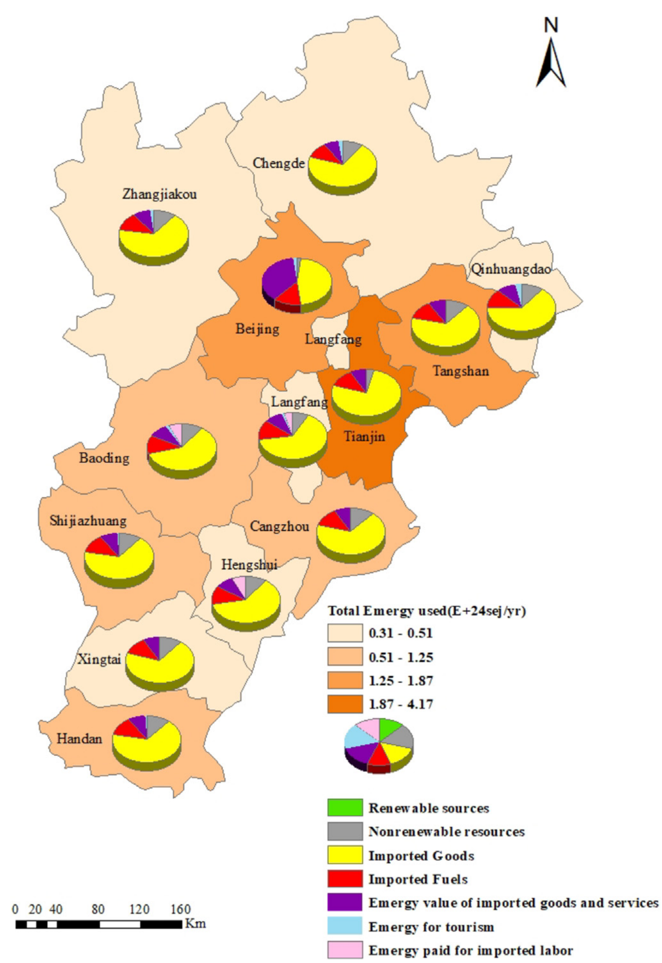

Fig. 2. Total emergy use for JJJ region (China).

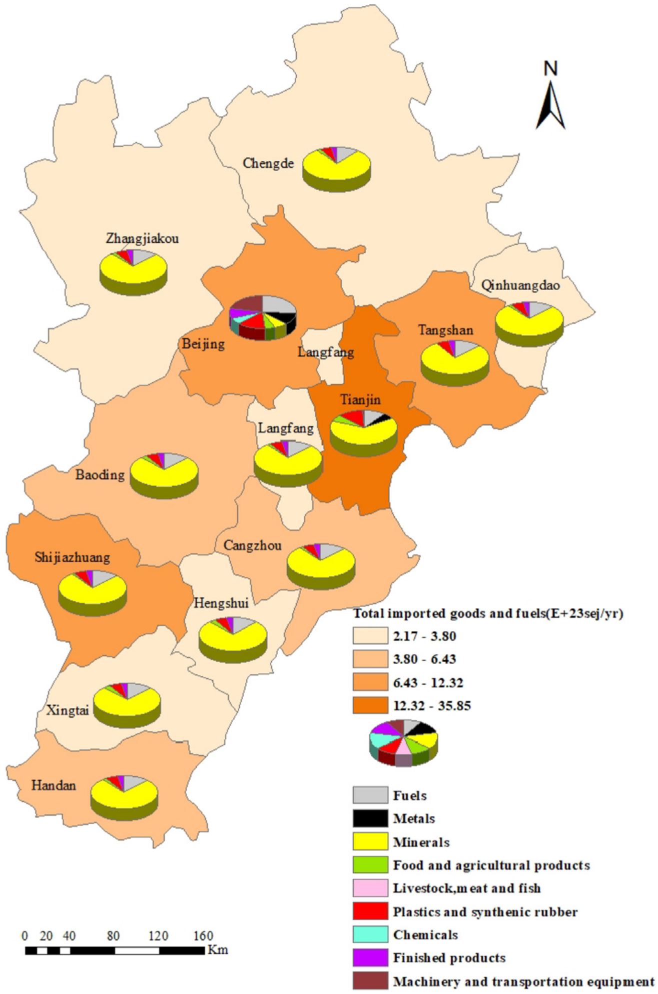

Fig. 3. Emergy input proportion.

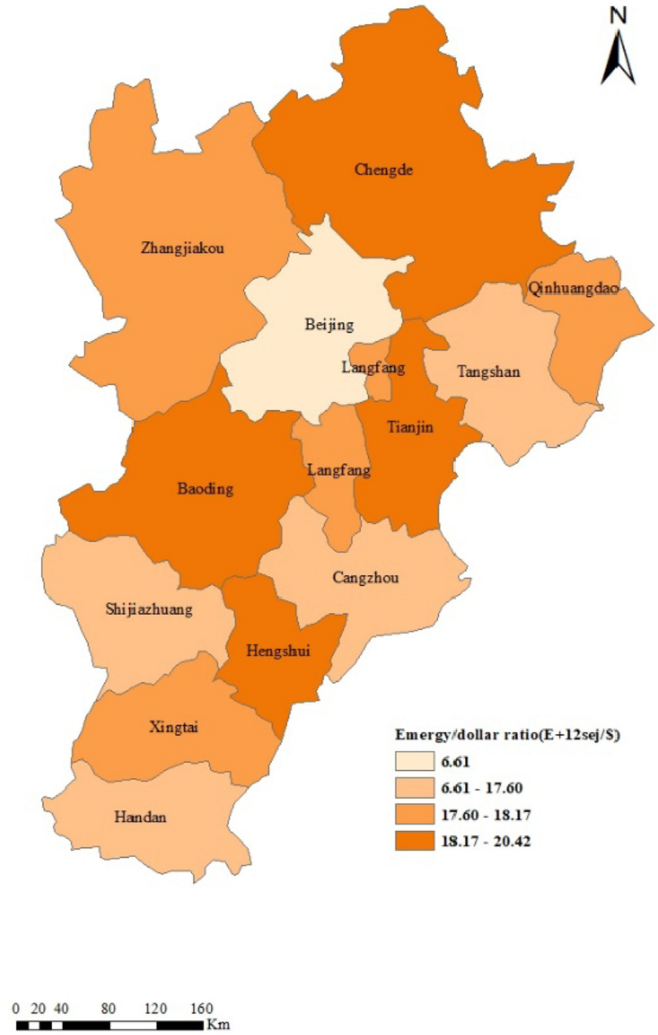

Fig. 4. Emergy/GDP ratio.

3.1. Total emergy flows and their spatial distribution

The detailed inventory, being categorized into corresponding classification and calculated accordingly, supported the accounting of total emergy flows in Jing-Jin-Ji region, which are mapped in Fig. 2.

As shown in the map, the largest emergy is consumed in Tianjin (4.17 E+24sej/yr) followed by Beijing (1.87 E+24sej/yr) which is consistent with previous literature results (Yu et al., 2016). The reason why the emergy of Tianjin is more than twice that of Beijing could be attributed to their different emergy composition structure that are illustrated in the next part. From the map we can also see that Bejing, Tianjin and Tangshan form an agglomeration of considerable amount of Emergy, owing to their traditionally developed industry and economy. Hengshui reports the least total emergy used (3.08 E+23/yr), resulting from the fact that its manufacturing industry is under development.

In order to reveal the geographical distribution characteristics more transparently using GIS technology, all 13 cities in Jing-Jin-Ji region are classified and ranked into four groups, in accordance with the total emergy value used. Tianjin ranks first because of its vast amount of imported goods. Tangshan, the traditional industry base of the Jing-Jin-Ji region and Beijing fall in the second level, due to the concentrated and advanced industry and massive population located there. The third level comprises of four cities: Shijiazhuang, the capital city and political center of Hebei province; Baoding, one major resettlement destination of low-tier industry transferred from Beijing thanks to its geographic advantage and relatively solid industrial infrastructure together with its largest population among Hebei province; Handan, one of the National Old Industrial Bases, and also one of planned destination cities of lower-tier industry of Jing-jin-ji region, owning the second largest population and advanced agriculture with GDP ranking third in Hebei province; Cangzhou, bordering Tianjin with the fifth largest population and fourth highest GDP. Level 4 cities mainly locate in the north part of the Jing-Jin-Ji region, including Zhangjiakou and Chengde whose industry are under-developed despite their advantage of vast geographic area and abundant natural resources compared with other cities, along with tourism-dominated Qinghuangdao, Langfang and two agriculture-oriented cities (Xingtai and Hengshui).

3.2. The emergy composition in Jing-Jin-Ji region

The detailed emergy composition for each city in Jing-Jin-Ji region. In accordance with the emergy synthesis, the total emergy is divided into six parts: local renewable resource (R); local non-renewable resource (N); imported inputs including imported goods (G); imported fuels (F); imported services; imported labor and tourism.

As shown in Fig. 3, imported inputs for all cities in the region, on

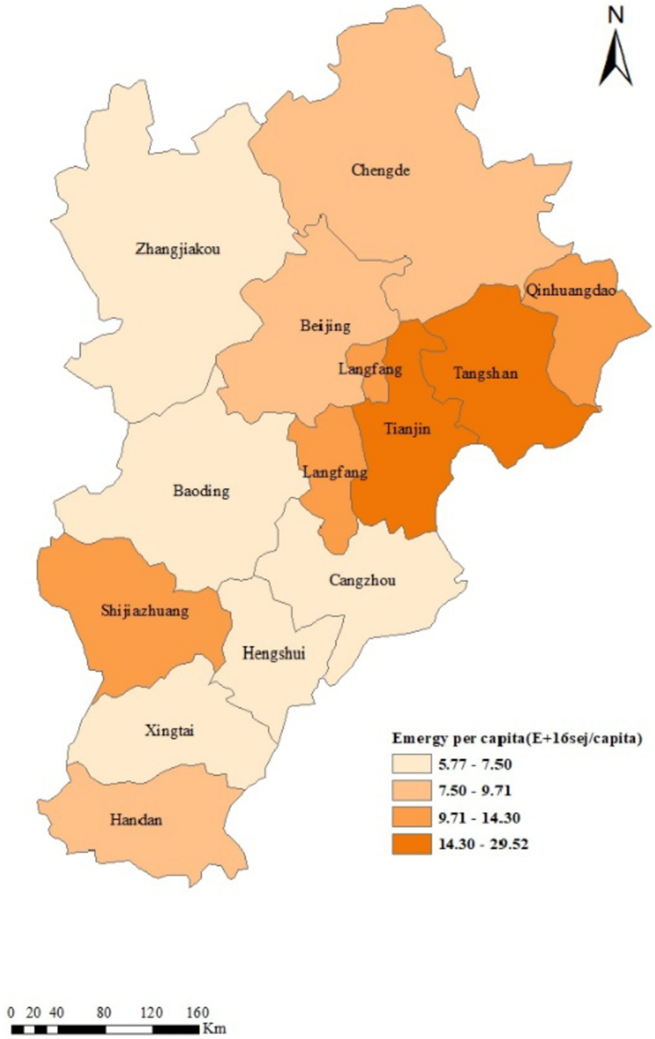

Fig. 5. Emergy use per person.

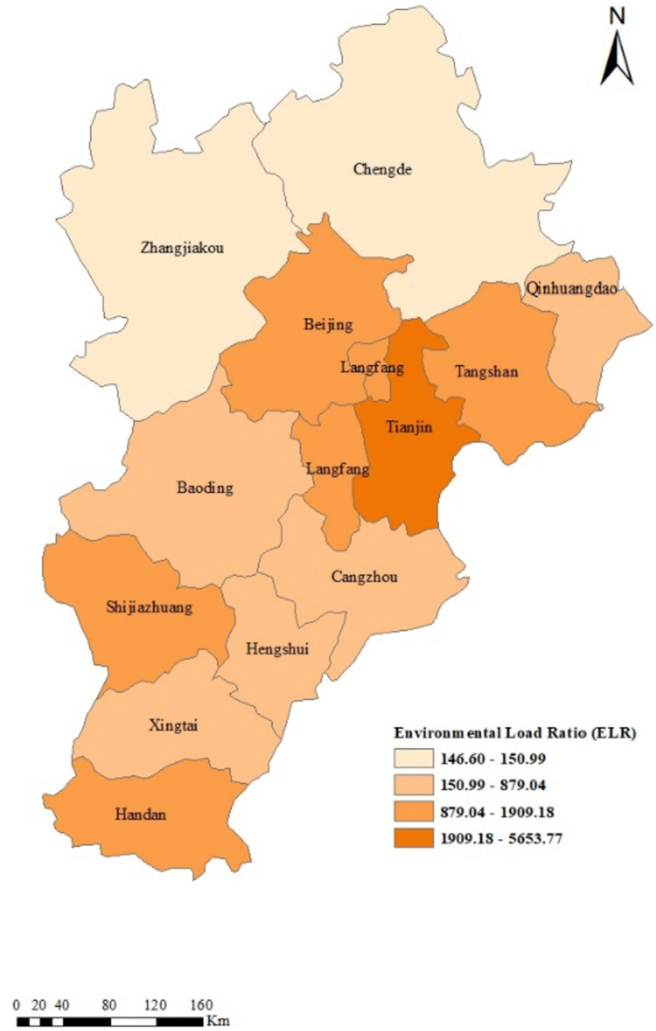

Fig. 6. Environmental load ratio (ELR).

average, occupy more than 85% of the total emergy used (U), implying that the economy relies heavily on the imported resources uniformly over the whole region. Note that except Beijing, the majority of imported input is "imported goods" (G), that constitutes about 75% of the total emergy used. Conversely, local renewable (R) forms such a tiny part of U (less than 0.1%) that it is rarely displayed in the pie chart. This fact was already observed (Cai et al., 2009; Zhang et al., 2011), revealing that the R proposition in Jing-Jin-Tang region (Beijing, Tianjin, Tangshan agglomeration) was decreasing since 1991, owing to the ongoing urbanization. In terms of local nonrenewable resource (N), Beijing has the lowest proportion (2.16%), followed by Tianjin with the second lowest percentage (4.41%). On the other side, the 11 cities in Hebei province share almost the same percentage (about 12%). This implies that Beijing and Tianjin rely little on indigenous exploitation, while cities in Hebei seem to have more balanced resource supply structure. It is also notable that, for Baoding and Hengshui, almost 10% of the total emergy used (U) is attributed to imported labor, reflecting that the system receives considerable support from the immigrate population in the process of urbanization. In addition, it could be observed from the map that tourism also accounts for a relatively significant proportion of U for several cities: Qinhuangdao (3.82%), Chengde (2.55%), Zhangjiakou (2.42%) and Beijing (2.23%). These cities are popular tourist attractions, because of their cultural and natural landscape.

3.3. The composition of imported goods (G) and fuels

To provide further insight on the disparity of internal imported input structure in the region, the 9 subsections, that constitute imported goods (G), are presented in the pie chart in Fig. 3. It is important to mention that, since the imported fuels have already been calculated in the EBS, when calculating the imported goods, in order to avoid duplicate accounting, fuels are excluded. The sums of the total goods and fuels of each city are sequenced into 4 levels to illustrate the geographic distribution pattern.

The difference between Beijing and Tianjin is quite noticeable. For Beijing, among nine categories, Fuels (2.92 E+23) ranks first, occupying 25.62% of the total imported goods and 15.61% of the total emergy used, suggesting that the economy is based on intense energy consumption that are probably caused by the massive population located in Beijing. Note that the imported fuels are about 28 times of locally produced fuels (1.05 E+22), which only accounts for 0.56% of total emergy used. This significant gap confirms that the fuels supply structures are rather unbalanced. Following fuels, stands machinery and transportation equipment (2.56 E+23 sej), sharing 22.46% of the total imported goods. Such a considerable proportion of the total imported goods taken by machinery and transportation equipment is only observed in Bejing, while for the rest of cities in the region, its proportion ranges from 0.12% (Chengde) to 1.01% (Tianjin). The category machinery and

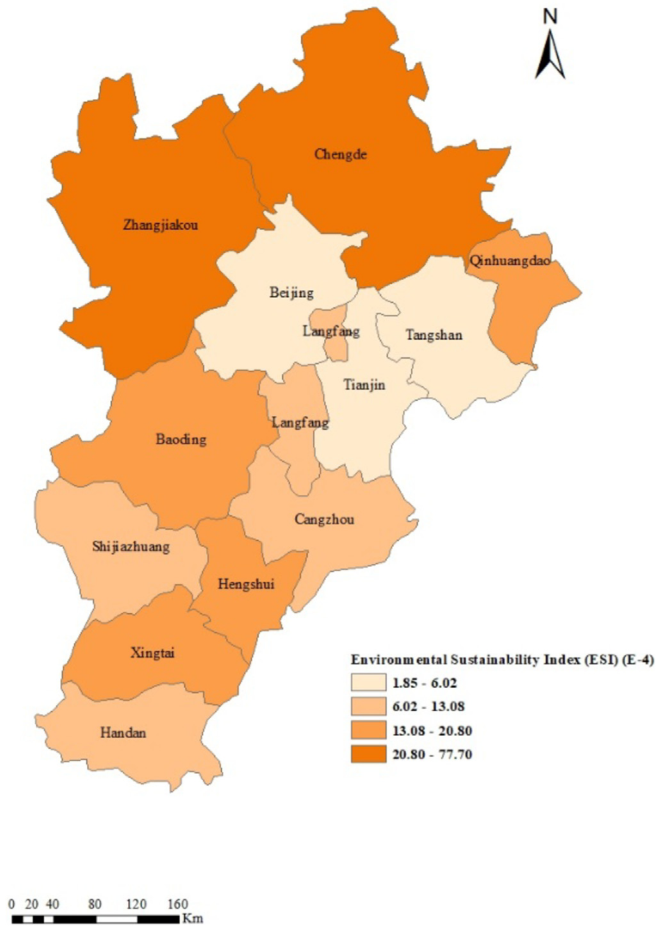

Fig. 7. Environmental sustainability index (ESI).

transportation equipment are mainly high-tech machinery and equipment with high monetary value. Their monetary value are adopted as input in the LCA method when calculating their emergy. In the LCA method, the input (i.e. the monetary value) and the output (i.e. the emergy value) are linear, meaning that the higher the monetary value is, the bigger the emergy will be. Surpassing all the rest of cities in the region, a uniquely significant monetary amount of machinery and transportation equipment are imported into Beijing, which could be explained by the highly advanced and technology-intense industries concentrated in Beijing.

Unlike Beijing, for Tianjin the biggest part of imported goods are minerals (61.03%) rather than fuels (13.33%), owing to their different industrial structures. Notably, a significant amount of metal ores with large UEVs such as iron ores, manganese ores, copper ores, nickel ores are imported to Tianjin to be utilized in manufacturing industry. Meanwhile, plastics and synthetic rubber (14.60%) is the second biggest part of imported goods because of the concentrated oil processing industry in Tianjin. Taking almost the same proportion as plastics and synthetic rubber, metals (13.33%) ranks third, indicating the intensity and dynamic of Tianjin's manufacturing industry.

For the 11 cities in Hebei province, it is not a coincidence that they report almost the same pattern because most of the distribution index we used when applying the methodology on the provincial data of Hebei province are GDP index and for each prefectural city in Hebei province, the difference between GDP index and population index is rather indistinguishable. Therefore, the internal composition structure of imported goods and fuels for the 11 prefectural cities are visually uniform. Analyzing the visually uniform pattern that are quite similar to Tianjin, we can find that minerals (71.05% on average) together with fuels (14.71% on average) dominate the imported goods. Same as Tianjin, for the 11 cities in Hebei, the largest proportion is also occupied by Minerals.

With respect to the study of Tian et al. (2017), the present research improves the quality of data, increasing their resolution. Moreover, the importance of imported goods in determining the variability of overall emergy accounting results is confirmed here. Finally, it is confirmed that imported goods are becoming a relevant component for JJJ overall development processes.

3.4. Efficiency indicators

Two indices, namely, resource use efficiency (emergy/dollar ratio) and direct resource availability for human activities (emergy per capita), are employed to analyze the resource efficiency in the region from different perspectives. The emergy/dollar ratio represents the relationship between the emergy used and GDP, thus can indicate the level of process efficiency of a city to some extent (Zhang et al., 2011). Emergy per capita is the ratio of the total emergy driving a system to the population in the system. This ratio can be used as a measure of the potential mean standard of living of the population. In particular, large values indicate a high level of metabolic intensity per capita (Zhang et al., 2011). Significant disparity is illustrated in Figs. 4 and 5.

Fig. 4 shows that Beijing has the lowest emergy/$ ratio (6.61 E+12 sej/$), indicating that Beijing is the most efficient city to transform resources into economic value, benefiting from its superior industrial structure with highly competitive and productive tertiary industry, such as finance industry and IT industry. Therefore, it appears as the most advanced and prosperous city. Meanwhile, Tianjin ranks top of the region with an emergy/dollar ratio (2.42 E+13 sej/$) more than triple that of Bejing. Because Tianjin has the largest total emergy in the region while its GDP ranks after Beijing. This means that Tianjin's GDP growth is heavily reliant on resources consumption, echoing the fact that Tianjin's economy relies on energy-consuming and resource-intense heavy industries that yield low value-added, such as steel industry and petrochemical industry, while the high value-added tertiary industry develops rather slowly.

Tianjin also has the highest Emergy per capita ratio (2.95E+17 sej/ca), followed by Tangshan (2.18 E+17 sej/ca) and Shijiazhuang (1.43 E+17 sej/ca). Tianjin has a higher ratio than Beijing since Tianjin has larger amount of U and much smaller population than Beijing. In fact, in year 2012, the population of Beijing reached 20.69 million, while Tianjin had 14.13 million people. For Tangshan, from Fig. 2, its total emergy used falls the same level as Beijing while in 2012 its population (7.42 million) is only a third that of Bejing, which results in its Emergy per capita ratio ranking second. In accordance with the function of Emergy per capita ratio, cities that rank top in terms of this indices usually tend to have high average living standard and also serve as the industrial and exchange center of the region. The lowest level consists of five cities: Baoding (7.14E+16 sej/ca) and four agriculture-dominant cities, Hengshui (6.97E+16), Cangzhou (6.62E+16) and Xingtai (5.77E+16), Zhangjiakou (7.50E+16), consistent with their economic sequences in the region.

3.5. Sustainability evaluation

ELR is calculated by dividing the sum of imported input emergy and indigenous nonrenewable emergy (N) with the local renewable resources emergy (R). A large ratio suggests a high metabolic load on the environment (Ulgiati et al., 1994).

As shown in Fig. 6, this is the case for Tianjin, which has the highest ELR in the region. This depends on its intense industry combined with limited local renewable resources. Therefore, it is urgent to optimize the industrial structure to reduce the existing environmental pressure. The two cities, lying in the North of the region (i.e. Zhangjiakou and Chengde), are in the group of the lowest ELR. With relatively broad geographic area accompanied by adequate local natural resources, including dense forests and big reservoirs, they are designated to be the ecological barriers of Beijing to prevent sandstorm from the Northwestern deserts of China. As a result, larger proportion of the economic growth is attributed to the utilization of indigenous renewable resources, thereby inducing less pressure on the environment. This kind of development mode is more sustainable, which is further confirmed by the results presented in the following Environmental Sustainability Index (ESI) analysis part. Moreover, the higher sustainability and ecological sustainability of Northern areas is confirmed by a recent study by Yang et al. (2018).

ESI represents the system output efficiency per emergy unit. It can be used to measure the coordination degree between social economic development and ecological environment with the urban metabolism system. ESI is associated with the definition of sustainability used by H.T. Odum (Odum, 1996; Liu et al., 2017), different from previous sustainability concepts, which were based on stationary state systems (e.g.: Harte and Socolow, 1971). ESI is a more comprehensive indicator, since it takes both ecological compatibility and economic compatibility into account. The larger the ESI, the higher the sustainability of a system (Jiang et al., 2007; Ascione et al., 2009; Qi et al., 2017). In detail, renewable emergy source especially affects the recorded values of ESI (Yu et al., 2016).

Chengde and Zhangjiakou have the highest ESI value, profiting from the strict environmental policies and balanced resource utilization structure mentioned above. Moreover, these areas have a higher proportion of tourism and lower proportion of industry. Beijing, instead, relies heavily upon imported inputs and nonrenewable resources, while Tianjin and Tangshan possess intensely aggregated industry, which inevitably harms the long-term sustainability. This is why these three cities rank lowest among the region sequenced by ESI index. Our analysis confirms the results of Yu et al. (2016) with respect to ESI. Note that our emergy total values are different from Yu et al. (2016), since we improved the data quality by introducing a larger number of industrial sectors and a detailed Input-Output table to better define the biophysical and economic resources flows.

4. Discussions

4.1. Uncertainty analysis

Emergy analysis is based on an inventory of products derived from different activities and, in parallel, on Unit Emergy Value (UEV), which are influenced by the complexity of the system under study. Consequently, the uncertainty might origin from these two sources. In this study, the majority of data are original and directly acquired from official and validated statistics resources, with the exception of the 11 prefectural cities in Hebei provinces, for which the activity data of energy and commodities were deducted from Hebei's provincial data. Potential errors and biases during the statistical compilation process were already taken into consideration and controlled in an acceptable scale, satisfying our data quality requirement.

The latest verified baseline and UEV, provided by NEAD, were used to avoid errors and minimize the uncertainty of UEV (Odum et al., 2000). These data were already checked, based on the framework defined by Ingwersen (2010). Consequently, the uncertainty mainly comes from the total amount distribution process.

In particular, the process of distributing the total amount with a set of indexes has a considerable level of uncertainty, depending on which index is applied. Analyzing the uncertainty underlying the chosen distribution, appropriate correction factors could be applied. A sensitivity analysis on each index of statistical distribution was performed. In particular, the measure of output uncertainty with respect to different sources was tested. In detail, GDP, population and area are used, as indexes, to be compared with respect to the change of Total emergy used (U). It is worth underlying that, GDP, population and area can affect the calculation of imported goods and fuel of each prefectural city in Hebei province. This is another reason for selecting these three factors to identify the uncertainty of different deduction methods Results are presented in Table 2. In Eq. (10) and Eq. (11), the index are: population, GDP and area.

$$\textit{Change rate}_{index} = \left(U_{index} - U_{average(Population,GDP,Area)}\right) \times \Big/ U_{average(Population,GDP,Area)} \tag{10}$$

U for each city is calculated with four combination of distribution index. As shown in Table 2, the "G-rank" (GDP is used as the sole distribution index) and the "T-rank" (a set of distribution indexes are used as designed in the methodology part) are the same because the majority of imported goods are distributed by GDP in the adopted method. When population is used as the sole distribution index, the "P-rank" are almost consistent with "T-rank". Several cities report rather low change rate in all three ways, such as Qinhuangdao, Cangzhou and Baoding. Chengde and Zhangjiakou experience dramatic leap under Area distribution index, increasing to 81.33% and 72.44% respectively, as a result of their above-average land area. Variance is used as indicator to test which index set best reflects the development disparity among different areas. However, even if the rank fluctuates, the U amount changes at an acceptable scale. Therefore, when selecting the distribution index, we need to take the significantly above- or under-average situation into consideration and select the most correlated index.

The uncertainty of these five deduction methods, defined in Eq. (9) and supplemented in Eq. (11), was assessed. The individual uncertainty of a city under certain distribution index method, or μ_{sn} in Eq. (9), is defined in Eq. (11). The index are: Population, GDP and Area.

$$\mu_{sn} = \textit{Uncertainty}_{index} = \left(U_{index} - U_{this\ study}\right) \Big/ U_{this\ study} \tag{11}$$

The results are shown in Table 3. From the perspective of individual uncertainty, the largest individual uncertainty was recorded in Chengde, whose uncertainty under Area distribution method reached 207.39%, resulting from its excessively broad administrative division in the region. For Zhangjiakou, where the second largest individual uncertainty is reported, it is the similar case. As for the smallest individual uncertainty, under any of the three distribution index method, the individual uncertainty of Qinhuangdao is always smaller than 5%, which reveals that population, GDP and area stay in a quite consonant state in Qinhuangdao. From the perspective of distribution index method, the Comprehensive uncertainty of Average distribution method is the smallest, followed by area, GDP and population. The reason could be that the average value of population, GDP and area carries the most of information that could reflect the comprehensive traits of a city.

Table 2
Change rate based on different data distribution rules.

SCENARIO	This study	T-Rank	Average (POPULATION,GDP,AREA)	Ave-rank	POPULATION	P Change rate	P-rank	GDP	G Change rate	G-rank	AREA	A Change rate	A-rank	Variance
Tianjin	4.17E+24	1	4.17E+24	1	4.17E+24	0	1	4.17E+24	0	1	4.17E+24	0	1	0
Beijing	1.87E+24	2	1.87E+24	2	1.87E+24	0	2	1.87E+24	0	2	1.87E+24	0	2	0
Tangshan	1.61E+24	3	1.20E+24	3	1.06E+24	−11.78%	4	1.63E+24	35.89%	3	9.08E+23	−24.11%	5	1.39E+47
Shijiazhuang	1.25E+24	4	1.04E+24	4	1.02E+24	−1.91%	5	1.26E+24	20.72%	4	8.46E+23	−18.81%	7	3.96E+46
Handan	8.43E+23	5	7.96E+23	6	9.49E+23	19.19%	6	8.41E+23	5.66%	5	5.98E+23	−24.84%	9	2.20E+46
Baoding	8.36E+23	6	9.39E+23	5	1.09E+24	15.71%	3	8.30E+23	−11.61%	6	9.00E+23	−4.10%	6	1.44E+46
Cangzhou	7.76E+23	7	7.19E+23	7	7.58E+23	5.55%	7	7.76E+23	8.01%	7	6.21E+23	−13.56%	8	5.62E+45
Langfang	5.11E+23	8	4.44E+23	11	4.73E+23	6.36%	9	5.11E+23	15.09%	8	3.49E+23	−21.46%	12	5.89E+45
Xingtai	4.31E+23	9	5.11E+23	10	6.42E+23	25.68%	8	4.26E+23	−16.58%	9	4.64E+23	−9.11%	10	1.05E+46
Chengde	3.66E+23	10	6.21E+23	8	3.71E+23	−40.20%	12	3.65E+23	−41.13%	10	1.13E+24	81.33%	3	1.44E+47
Zhangjiakou	3.52E+23	11	6.15E+23	9	4.35E+23	−29.25%	10	3.50E+23	−43.19%	11	1.06E+24	72.44%	4	1.18E+47
Qinhuangdao	3.28E+23	12	3.21E+23	13	3.14E+23	−2.05%	13	3.28E+23	2.31%	12	3.20E+23	−0.25%	13	4.56E+43
Hengshui	3.08E+23	13	3.57E+23	12	4.15E+23	16.28%	11	3.06E+23	−14.23%	13	3.50E+23	−2.05%	11	2.59E+45

4.2. Gap between using money value and physical amount to calculate emergy of imported goods

As shown in Fig. 2, for all the cities in the region except Beijing, the emergy value calculated using physical amount (Imported Goods in yellow plus Imported Fuels in red), weighs about 8 times of the emergy based on money value (Emergy value of imported goods and services in purple). Table 4 displays the percentage of physical-amount- based emergy of commodities.

On average, more than 70% of the total emergy used is attributed to the emergy of imported fuels and goods measured through physical amount (i.e. measure of physical resources flows instead of human services). Therefore, it is undoubtedly necessary to acquire the data of the physical amount of imported goods. Using physical amount to calculate is more accurate than the money-based value because the high proportion of imported goods is machinery, of which the transformity per dollar cannot reasonably represents the real environmental costs underpinning.

5. Conclusions

This work presented an emergy-based comparative analysis of urban metabolic efficiency and sustainability in the case of big cities and data-scarce medium-sized cities. A simple downscaling method was defined to obtain substitutes for missing data for medium-sized cities and the reliability of this method is verified. Enhanced spatial-scale data, with more comprehensive details with respect to industrial sectors was introduced. Consequently, more details of the productive performance and sustainability condition about China were inferred. In particular, the method was tested here with the case of Jing-Jin-Ji region (China), taking into consideration both the existing problems of originally unavailable data in many medium-sized cities, and the potential impacts that improved data would have on the policies and roadmaps towards cleaner productions and ecological security for the whole area.

In conclusion, the main findings of this study are: (1) This study proposed a methodology to get substitutes for missing data using extant data at higher administrative level for medium-sized cities suffering from data scarcity and inconsistency. (2) We integrated uncertainty analysis to complement the methodology in order to improve its reliability. (3) We verified the methodology by applying it in the case of Jing-Jin-Ji region. We find that the methodology is feasible to acquire substitutes for missing data items needed in the emergy synthesis inventory. (4) The metabolic and economic patterns revealed by the substitute data are well confirmed by the status quo in the region and are also in line with previous literature, indicating that the methodology is practical and could be applied to a wider range of data-scarcity cities. (5) The uncertainty analysis part shows the importance of prudence in the choice of distribution index that contributes to the uncertainty of final results. (6) Unlike previous study, enhanced spatial-scale data, with more comprehensive details with respect to industrial sectors was introduced in this work. Specifically, the emergy calculation of the imported and exported commodities is rather elaborate based on the detailed physical amount of each item, making the results more convincing. We also demonstrated the significant gap between using money value and physical amount to calculate emergy of imported goods, proving the importance of physical amount data in the Emergy-based comparative analysis of urban metabolic efficiency and sustainability.

Emergy-based indicators show that Beijing and Tianjin, with massive population, rely heavily on imported goods and fuels to satisfy their intense economic activities, thereby contributing to the high environmental load there. For Hebei province, our results indicate that the two cities in its North-Western part (i.e. Chengde

Table 3
Uncertainty analysis of total emergy (U) in Beijing-Tianjin-Hebei area according to different distribution methods.

Area	Distribution methods								
	This study	Pop.		GDP		Area		Ave.(Pop, GDP, Area)	
		U	*Uncert.* [a]	*U*	*Uncert.* [a]	*U*	*Uncert.* [a]	*U* [b]	*Uncert.* [a]
Tianjin	4.17E+24	4.17E+24	0	4.17E+24	0	4.17E+24	0	4.17E+24	0
Beijing	1.87E+24	1.87E+24	0	1.87E+24	0	1.87E+24	0	1.87E+24	0
Tangshan	1.61E+24	1.06E+24	−34.57%	1.63E+24	0.78%	9.08E+23	−43.72%	1.20E+24	−25.84%
Shijiazhuang	1.25E+24	1.02E+24	−18.41%	1.26E+24	0.42%	8.46E+23	−32.46%	1.04E+24	−16.82%
Handan	8.43E+23	9.49E+23	12.49%	8.41E+23	−0.28%	5.98E+23	−29.07%	7.96E+23	−5.62%
Baoding	8.36E+23	1.09E+24	30.02%	8.30E+23	−0.68%	9.00E+23	7.75%	9.39E+23	12.36%
Cangzhou	7.76E+23	7.58E+23	−2.23%	7.76E+23	0.05%	6.21E+23	−19.93%	7.19E+23	−7.37%
Langfang	5.11E+23	4.73E+23	−7.43%	5.11E+23	0.17%	3.49E+23	−31.65%	4.44E+23	−12.97%
Xingtai	4.31E+23	6.42E+23	48.99%	4.26E+23	−1.11%	4.64E+23	7.75%	5.11E+23	18.54%
Chengde	3.66E+23	3.71E+23	1.37%	3.65E+23	−0.21%	1.13E+24	207.39%	6.21E+23	69.52%
Zhangjiakou	3.52E+23	4.35E+23	23.87%	3.50E+23	−0.54%	1.06E+24	201.90%	6.15E+23	75.07%
Qinhuangdao	3.28E+23	3.14E+23	−4.18%	3.28E+23	0.09%	3.20E+23	−2.41%	3.21E+23	−2.16%
Hengshui	3.08E+23	4.15E+23	34.52%	3.06E+23	−0.78%	3.50E+23	13.31%	3.57E+23	15.68%
U_c			43.79%		43.07%		41.46%		39.73%

Notes. A: abbreviation of uncertainty, corresponding to μ_{s1} in Eq. (9); b: the total emergy of this column is the average of the total emergy of population, GDP and area column. U_c is the Comprehensive uncertainty of a certain distribution index. The index could be Population or GDP or Area.

Table 4
The gap between using money value and physical amount to calculate emergy of imported goods.

% U	Beijing	Tianjin	Baoding	Cangzhou	Chengde	Handan	Hengshui	Langfang	Qinhuangdao	Shijiazhuang	Tangshan	Xingtai	Zhangjiakou
Physical amount	49.0%	85.9%	73.1%	65.0%	74.5%	75.3%	74.0%	65.2%	70.0%	70.9%	73.9%	74.2%	73.0%
Money value	34.3%	9.5%	10.0%	8.8%	9.6%	8.5%	9.8%	8.8%	9.8%	9.9%	10.0%	9.5%	9.2%
Gap	1.43	9.04	7.31	7.42	7.79	8.89	7.58	7.39	7.16	7.18	7.37	7.79	7.91

and Zhangjiakou) are the most sustainable, thanks to their relatively substantial proportion of renewable resources utilization compared with other cities. Besides, the cities benefiting significantly from imported labor are also revealed (i.e. Baoding, Hengshui and Langfang). Our results have confirmed the findings of previous literature findings, but more importantly, the data underlying is more detailed and comprehensive to support the convincing results. Such results can be applied to improve the existing planning options toward a cleaner production and consumption system within Jing-Jin-Ji region. In this sense, this method offers a possibility of obtaining an augmented quantitative perspective to measure the sustainability conditions for a larger scale of medium-sized cities.

In general, this improvement can be applied to other areas, where locally targeted policy-making and overall sustainability planning would be highly desirable. Limitations still remain to be further investigated and solved. As discussed previously, the results of downscaling should be scrutinized carefully and more comprehensive robustness tests would be recommended. The choice of the most suitable index, based on its characteristics for each single item, remains an open topic. The metrological approach to data acquisition also remains open. In fact, without a suitable and affordable metadata collection and integration system, the quality and reliability of the final outputs for decision-making would remain poor. Appropriate integrated hierarchical environmental monitoring techniques would partially mitigate this problem. However, the crucial question is how to define and validate a measure in the absence of original data. Apart from traditional statistical methods, machine learning methods could be one potential solution to support the detection of underlying data patterns. This would pave the way for more precise and tailored solutions, based on the quantification of semi-empirical parameters to build accurate sets of data.

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Appendix 1

In this paper, UEVs are based on the latest geobiosphere emergy baseline (GEB) of 12.0E+24 seJ/yr (Brown and Ulgiati, 2016). The UEVs, which initially were not based on this GEB, were modified accordingly. The specific calculation methods of renewable resources emergy are as follows:

1 Solar energy:

Area: statistics year book (m^2).
Insolation = statistics year book ($J/cm^2/y$)
Albedo = 30.00 (% of insolation) (Brown and Ulgiati, 2016)
Carnot efficiency = 0.93 (Brown and Ulgiati, 2016)
Solar energy (J) = (area)*(avg insolation)*(1-albedo)*(Carnot efficiency)

2 Earth cycle:

Area: statistics year book (m^2).
Heat flow = 2.00E+06 $J/m^2/v^1$ (International Heat Flow Database, 2010)
Carnot efficiency = 9.50% (Brown and Ulgiati, 2016)
Earth cycle energy (J)= (area) (heat flow) (Carnot efficiency).

3 Wind energy:

Area: statistics year book (m^2).
Density of air = 1.23E+00 kg/m^3

Drag coefficient = 1.64E−03 (Garratt, 1992).
Wind velocity absorbed: statistics year book (m/s).
Wind energy (J)= (land area) (air density) (drag coefficient) (wind velocity absorbed)^3

4 Rain, chemical potential energy:

Area: statistics year book (m^2).
Rainfall: statistics year book (m/y).
Transpiration rate = 75%
Gibbs energy of rain = 4.72E+03 J/kg.
Rain, chemical potential energy (J)= (land area) (rainfall) (% transpired) (Gibbs energy of rain).

5 Runoff, geopotential energy:

Area: statistics year book (m^2).
Runoff rate = 25% (Brown and Ulgiati, 2016).
Rainfall: statistics year book (m/y).
Avg. elevation: statistics year book (m).
Gravity = 9.8 m/s^2

Runoff, geopotential energy (J)= (land area) (% runoff) (rainfall) (avg elevation) (gravity).

Appendix 2

Emergy Accounting of 13 cities in Jing-Jin-Ji

Tangshan is taken as example of prefectural city in Hebei province. We obtained the city-level data required for emergy analysis by applying the methodology mentioned in the second section of this paper. First, provincial data of Energy Balance Sheet were distributed into the municipal level by GDP ratio. Because the energy consumption increases as GDP grows in terms of the Import-Export Goods data, first we classified the whole 98 categories into 10 categories and used different distribution ratios, corresponding to different features of every category. For goods falling in the categories, we used the GDP ratio, since it is highly related to the industry process. For the other categories, which are mainly related to domestic consumptions, population ratio was used, being more appropriate.

Table A1
Emergy Calculation Table of Tangshan City in 2012. Notes.

Items	Units	Raw amount	UEV (seJ/unit)	Refs. For Transformity	Emergy
1.Renewable Input (locally available)					
Sun	J/yr	5.77E+19	1	By definition	5.77E+19
Wind (Kinetic Energy)	J/yr	4.00E+16	2.51E+03	After Odum et al., 2000	1.00E+20
Rainfall (Geopotential Energy)	J/yr	8.01E+10	1.74E+04	After Odum et al., 2000	1.40E+15
Rainfall (Chemical Potential)	J/yr	1.71E+16	3.05E+04	After Odum et al., 2000	5.22E+20
Geothermal Heat	J/yr	1.47E+16	5.76E+04	After Odum et al., 2000	8.45E+20
2.Nonrenewable Input (locally available)					
Hydroelectricity	J/yr	3.73E+14	3.36E+05	After Odum et al., 2000	1.25E+20
Stream flow	J/yr	8.81E+15	3.05E+04	After Brandt-Williams,2001, Folio # 4	2.69E+20
Top soil (erosion, wheathering)	0	5.20E+10	1.23E+05	Brown M.T. and Arding J.,1991, uppdate after Odum et al., 2000	6.41E+15
Fuels input from local region					
Coal	J/yr	8.26E+17	6.69E+04	After Odum,1996	5.52E+22
Oil	J/yr	5.54E+16	9.08E+04	After Odum et al., 2000	5.03E+21
Natural gas	J/yr	1.27E+16	9.85E+04	After Romitelli, 2000	1.25E+21
Constructed local input					
Limestone	g/yr	3.39E+13	1.68E+09	After Brandt-Williams,2001, Folio # 4	5.68E+22
Sand and gravel	g/yr	2.26E+13	1.68E+09	After Brandt-Williams,2001, Folio # 4	3.79E+22
Iron ore	g/yr	3.61E+13	1.44E+09	After Odum,1996	5.18E+22
copper ore	g/yr	0.00E+00	1.39E+09	NEAD, 2012	0.00E+00
aluminum ore	g/yr	0.00E+00	3.38E+07	NEAD2012	0.00E+00
3.Imported Input					
Imported Fuels					**1.85E + 23**
Imported Goods					
Food & agricultural products					1.08E+22
Livestock, meat, fish					1.79E+19
Chemicals					2.55E+21
Finished products					5.49E+22
Machinery, transportation equipment					1.73E+21
Metals					5.39E+21
Minerals					8.83E+23
Plastics & synthetic rubber					8.83E+22
Other refined goods					–
Import human labor	$/yr	1.42E+08	3.11E+12	Country Emergy/$ ratio	4.43E+20
Services associated to imports					
From other provinces	$/yr	4.95E+10	3.11E+12	Country Emergy/$ ratio	1.54E+23
From other countries	$/yr	6.16E+09	1.29E+12	World Emergy/$ ratio	7.95E+21
Tourism	$/yr	3.26E+09	3.11E+12	Country Emergy/$ ratio	1.01E+22
4.Exported output					
Exported Fuels					7.39E+22
Exported Goods					
Food & agricultural products					4.93E+21
Livestock, meat, fish					8.45E+19
Chemicals					2.69E+21
Finished products					1.34E+22
Machinery, transportation equipment					6.34E+21
Metals					8.73E+23
Minerals					1.35E+22
Plastics & synthetic rubber					2.11E+23
Other refined goods					–

(*continued on next page*)

Table A1 (*continued*)

Items	Units	Raw amount	UEV (seJ/unit)	Refs. For Transformity	Emergy
Export human labor	$/yr	1.84E+08	1.74E+13	This study	3.20E+21
Services associated to Exports					
to other provinces	$/yr	4.87E+10	1.74E+13	This study	8.47E+23
to other countries	$/yr	4.32E+09	1.74E+13	This study	7.51E+22

Notes.

1	Sun Solar energy received = (avg. Insolation, J/m2/yr) (area, m2) = 7.22E+19 J/yr Albedo 2.01E-01 (% given as decimal) (Zhang et al., 1986) Solar energy received = 5.77E+19 J/yr
2	Wind (Kinetic Energy of Wind Used at the Surface) Wind energy = (air density, kg/m3) (drag coeff.) (geostrophic wind velocity, m/s)^3 (area, m2) (sec/year) = Air density = 1.30E+00 kg/m^3 Wind velocity (average 2012) = 2.50E+00 m/s http://cdc.cma.gov.cn/shishi/climate.jsp?stprovid=河北 Geostrophic wind = 4.17E+00 m/s (observed winds are about 0.6 of geostrophic wind) Drag coeff. = 1.00E-03 #Miller, 1964 quoted by Time frame = 3.15E+07 Wind energy on land = 4.00E+16 J/yr
3	Rainfall (Geopotential Energy) Total Agricultural area of Beijing Region = 564691 m^2 Rain (annual average) = 5.90E-01 m/yr http://cdc.cma.gov.cn/shishi/climate.jsp?stprovid=河北 Avg. Elev = 4.35E+01 m http://cdc.cma.gov.cn/shishi/climate.jsp?stprovid=河北 Runoff rate = 56.40% 0.00E+00 (Zhu, 2002) Energy(J)=(area) (rainfall) (% runoff) (avg elevation) (gravity) = 8.01E+10 J/yr
4	Rainfall (Chemical Potential Energy) Rain (average temperate areas) = 5.90E-01 m/yr http://cdc.cma.gov.cn/shishi/climate.jsp?stprovid=河北 Water density 1.00E+06 g/m^3 Mass of rainfall water = 7.95E+15 g/yr water Fraction of water that is evapotranspired 4.36E-01 Evapotranspired rain water 2.57E-01 m/yr Mass of evapotranspired water 3.47E+15 g/yr Free energy of water=(evapotranspired water,g/ha/yr) (Gibbs free energy per gram water, J/g) = Gibbs free energy of water 4.94E+00 J/g [Odum, 1996] Energy of evapotranspired rain water 1.71E+16 J/yr
5	Geothermal Heat Heat flow through earth crust contributing to uplift replacing erosion. Average heat flow per area = 3.50E-02 J/m^2/s [Hu et al., 2011] Energy (J/yr) = (land area, m^2) (heat flow per area, J/m^2/yr) = 1.47E+16 J/yr
6	Hydroelectricity Hydroelectricity = 1.04E+08 kwh Energy of hydroelectricity = 3.73E+14 J/yr
7	Stream flow upstream inflow = 1.78E+09 m^3 coefficient = 4.94E+06 (J/cu.m) Energy of Stream flow = 8.81E+15 J/yr Water density = 1.00E+06 g/m3 Total weight = 1.78E+15 g/yr
8	Net Loss of Organic Matter in Topsoil Soil Erosion rate = 8.15E+02 g/m^2/yr Farmed area = 564691 m^2 Net loss of topsoil = (farmed area, m^2) (erosion rate, g/m^2/yr) = 4.60E+08 g/yr Average % organic in soil (w.m.) = 1.80E-02 Organic matter in topsoil used up = =(total mass of topsoil) (% organic) = 8.28E+06 g/yr (w.m.) Water content in organic matter 7.00E-01 (Our assumption, average value) Dry organic matter lost with erosion 2.49E+06 g/yr d.m. Energy content of dry organic matter 5.00E+00 kcal/g d.m. (Average value for dry organic matter) Energy loss= (loss of dry organic matter) (5 kcal/g) (4186 J/kcal) = 5.20E+10
9	Fuels input from local region Coal = 2.60E+07 t = 2.60E+13 g/yr Coal energy density = 3.18E+10 J/t Coal energy = 8.26E+17 J/yr oil = 1.29E+06 t = 1.29E+12 g/yr Oil energy density = 4.30E+10 J/t Oil energy = 5.54E+16 J/yr Natural gas = 2.95E+08 m^3 Density = 7.17E-01 kg/m^3 = 2.11E+11 g/yr Natural gas density = 4.30E+07 J/t 1.27E+16 J/yr Total energy of Fuels input from local regain = 8.94E+17 J/yr
10	Constructed local input Limestone = 3.39E+07 t = 3.39E+13 g/yr Cement quantity of production = 2.83E+07 t = 2.83E+13 g/yr Sand and gravel = 4.52E+07 t = 2.26E+13 g/yr Iron ore = 3.61E+07 t = 3.61E+13 g/yr

Table A2
Summary of flows of the 13 cities in Jing-Jin-Ji in 2012.

Item		Beijing	Tianjin	Shijiazhuang	Baoding	Cangzhou	Chengde	Handan	Hengshui	Langfang	Qinhuangdao	Tangshan	Xingtai	Zhangjiakou	Unit
R =	Renewable sources (rain, tide, earth cycle)	1.03E+21	7.38E+20	9.94E+20	1.39E+21	8.81E+20	2.48E+21	7.57E+20	5.54E+20	4.03E+20	4.89E+20	8.45E+20	7.80E+20	2.31E+21	seJ/yr
N =	Nonrenewable resources from within Country	4.04E+22	1.84E+23	1.60E+23	9.70E+22	1.00E+23	4.22E+22	1.08E+23	3.62E+22	4.88E+22	4.07E+22	2.08E+23	5.47E+22	4.41E+22	seJ/yr
N0 =	Dispersed Rural Source	2.51E+19	4.99E+19	6.59E+15	8.98E+19	8.62E+15	3.80E+15	7.50E+15	6.48E+15	4.28E+15	2.07E+15	6.41E+15	7.34E+15	9.79E+15	seJ/yr
N1 =	Concentrated Use	4.04E+22	1.84E+23	1.60E+23	9.69E+22	1.00E+23	4.22E+22	1.08E+23	3.62E+22	4.88E+22	4.07E+22	2.08E+23	5.47E+22	4.41E+22	seJ/yr
G =	Imported Goods	8.48E+23	3.11E+24	8.08E+23	4.98E+23	5.08E+23	2.43E+23	5.48E+23	1.85E+23	3.24E+23	2.06E+23	1.05E+24	2.82E+23	2.25E+23	seJ/yr
F =	Imported Fuels	2.92E+23	4.78E+23	1.42E+23	8.60E+22	8.89E+22	3.74E+22	9.56E+22	3.20E+22	5.67E+22	3.60E+22	1.85E+23	4.85E+22	3.90E+22	seJ/yr
I =	Dollars paid for imports goods	2.64E+11	1.67E+11	4.36E+10	2.43E+10	2.40E+10	9.99E+09	2.78E+10	9.06E+09	1.73E+10	1.15E+10	5.56E+10	1.36E+10	1.05E+10	$/yr
I2 =	Dollars for tourism	1.34E+10	1.03E+09	4.83E+09	4.73E+09	1.01E+09	3.00E+09	2.77E+09	6.30E+08	1.80E+09	4.02E+09	3.26E+09	1.27E+09	2.74E+09	$/yr
I3 =	Dollars paid for imported labor	1.80E+09	7.98E+08	1.93E+08	2.11E+10	1.35E+08	6.51E+07	1.72E+08	8.15E+09	8.24E+09	5.61E+07	1.42E+08	1.33E+08	8.16E+07	$/yr
P2I =	Emergy value of imported goods and services	6.43E+23	3.96E+23	1.25E+23	7.32E+22	7.41E+22	3.10E+22	8.24E+22	2.73E+22	4.99E+22	3.24E+22	1.62E+23	4.11E+22	3.25E+22	seJ/yr
P2I2 =	Emergy for tourism	4.18E+22	3.19E+21	1.50E+22	1.47E+22	3.15E+21	9.34E+21	8.61E+21	1.96E+21	5.61E+21	1.25E+22	1.01E+22	3.95E+21	8.51E+21	seJ/yr
P2I3 =	Emergy paid for imported labor	5.61E+21	2.48E+21	6.00E+20	6.56E+22	4.18E+20	2.02E+20	5.37E+20	2.54E+22	2.57E+22	1.75E+20	4.43E+20	4.15E+20	2.54E+20	seJ/yr
B =	Emergy Value of Goods and Fuels Exports	2.36E+24	6.93E+23	8.66E+23	5.28E+23	5.43E+23	2.26E+23	5.85E+23	1.96E+23	3.46E+23	2.20E+23	1.13E+24	2.98E+23	2.39E+23	seJ/yr
P1E3 =	Emergy Value of labor and services exported	5.46E+24	3.50E+24	7.91E+23	1.06E+24	4.47E+23	1.97E+23	4.72E+23	4.17E+23	5.10E+23	2.19E+23	9.25E+23	2.48E+23	1.92E+23	seJ/yr
X =	Gross Domestic Product	2.83E+11	2.04E+11	7.13E+10	4.31E+10	4.46E+10	1.87E+10	4.79E+10	1.60E+10	2.84E+10	1.80E+10	9.29E+10	2.43E+10	1.95E+10	$/yr
P3 =	World emergy/$ ratio, used in imports	1.29E+12	1.29E+12	1.29E+12	1.29E+12	1.29E+12	1.29E+12	1.29E+12	1.29E+12	1.29E+12	1.29E+12	1.29E+12	1.29E+12	1.29E+12	seJ/$
P2 =	Country Emergy/$ ratio	3.11E+12	3.11E+12	3.11E+12	3.11E+12	3.11E+12	3.11E+12	3.11E+12	3.11E+12	3.11E+12	3.11E+12	3.11E+12	3.11E+12	3.11E+12	seJ/$
Use per person	U/population	9.05E+16	2.95E+17	1.43E+17	7.13E+16	6.62E+16	9.71E+16	8.49E+16	6.97E+16	1.18E+17	1.13E+17	2.18E+17	5.77E+16	7.50E+16	seJ/unit
P1 =	Ratio of use to GDP, emergy/dollar ratio P1=U/GDP	6.61E+12	2.04E+13	1.76E+13	1.94E+13	1.74E+13	1.96E+13	1.76E+13	1.93E+13	1.80E+13	1.82E+13	1.74E+13	1.78E+13	1.80E+13	seJ/$

Table A3
Indices using emergy for overview of the 13 cities in Jing-Jin-Ji in 2012.

Indicator	Expression	Beijing	Tianjin	Shijiazhuang	Baoding	Cangzhou	Chengde	Handan	Hengshui	Langfang	Qinhuangdao	Tangshan	Xingtai	Zhangjiakou	Unit
Renewable emergy flow	R	1.03E+21	7.38E+20	9.94E+20	1.39E+21	8.81E+20	2.48E+21	7.57E+20	5.54E+20	4.03E+20	4.89E+20	8.45E+20	7.80E+20	2.31E+21	seJ/yr
Flow from indigenous nonrenewable reserves	N=N0+N1	4.04E+22	1.84E+23	1.60E+23	9.70E+22	1.00E+23	4.22E+22	1.08E+23	3.62E+22	4.88E+22	4.07E+22	2.08E+23	5.47E+22	4.41E+22	seJ/yr
Flow of imported emergy	F + G + P2I + P2I2+P2I3	1.83E+24	3.99E+24	1.09E+24	7.37E+23	6.75E+23	3.21E+23	7.35E+23	2.72E+23	4.61E+23	2.87E+23	1.40E+24	3.76E+23	3.05E+23	seJ/yr
Total emergy used, U	R + N + F + G + P2I + P2I2+P2I3	1.87E+24	4.17E+24	1.25E+24	8.36E+23	7.76E+23	3.66E+23	8.43E+23	3.08E+23	5.11E+23	3.28E+23	1.61E+24	4.31E+23	3.52E+23	seJ/yr
Total exported emergy	N2+B + P1E3	7.83E+24	4.19E+24	1.26E+24	2.18E+24	9.61E+23	4.61E+23	1.23E+24	8.73E+23	7.77E+23	4.15E+23	1.13E+24	8.96E+23	5.68E+23	seJ/yr
Fraction emergy use derived from home sources	(N0+N1+R)/U	2.22E-02	4.43E-02	15.76%	9.05E-02	1.33E-01	12.05%	11.43%	8.85%	10.40%	13.11%	19.81%	8.63%	10.65%	
Imports minus exports	(F + G + P2I + P2I2+P2I3)-(N2+B + P1E3)	−6.00E+24	−2.03E+23	−4.01E+23	−1.19E+24	−3.03E+23	−1.35E+23	−3.90E+23	−4.95E+23	−3.54E+23	−1.41E+23	−2.81E+23	−3.09E+23	−1.79E+23	seJ/yr
Ratio of exports to imports	(N2+B + P1E3)/(F + G + P2I3)	4.28E+00	1.05E+00	146.56%	2.20E+00	1.46E+00	141.33%	146.44%	230.78%	183.56%	151.78%	133.15%	152.72%	145.91%	
Fraction used, locally renewable	R/U	5.50E-04	1.77E-04	0.08%	1.67E-03	1.14E-03	0.68%	0.09%	0.18%	0.08%	0.15%	0.05%	0.18%	0.66%	
Fraction of use purchased	(F + G + P2I3)/U	9.78E-01	9.56E-01	87.14%	8.82E-01	8.70E-01	87.79%	87.14%	88.10%	90.37%	87.44%	87.04%	87.14%	86.81%	
Fraction imported service	P2I/U	3.43E-01	9.50E-02	10.01%	8.76E-02	9.56E-02	8.48%	9.77%	8.83%	9.77%	9.88%	10.03%	9.53%	9.24%	
Fraction of use that is free	(R + N0)/U	5.63E-04	1.89E-04	0.08%	1.77E-03	1.14E-03	0.68%	0.09%	0.18%	0.08%	0.15%	0.05%	0.18%	0.66%	
Ratio of concentrated to rural	(F + G + P2I3 +N1)/(R + N0)	1.77E+03	5.30E+03	1.26E+03	5.63E+02	8.79E+02	1.47E+02	1.11E+03	5.56E+02	1.27E+03	6.69E+02	1.91E+03	5.52E+02	1.51E+02	
Use per unit area, Empower Density	U/(Area mˆ2)	1.14E+14	3.55E+14	7.90E+13	3.77E+13	5.52E+13	9.26E+12	6.99E+13	3.49E+13	7.94E+13	4.20E+13	1.20E+14	3.47E+13	9.53E+12	seJ/mˆ2
Use per person	U/Population	9.05E+16	2.95E+17	1.43E+17	7.13E+16	6.62E+16	9.71E+16	8.49E+16	6.97E+16	1.18E+17	1.13E+17	2.18E+17	5.77E+16	7.50E+16	seJ/unit
Renewable carrying capacity	POPULATION =	2.07E+07	1.41E+07	8.76E+06	1.17E+07	1.17E+07	3.77E+06	9.93E+06	4.42E+06	4.33E+06	2.91E+06	7.42E+06	7.48E+06	4.68E+06	
at present living standard	(R/U) (Population)	1.14E+04	2.50E+03	6.95E+03	1.95E+04	1.33E+04	2.55E+04	8.91E+03	7.95E+03	3.42E+03	4.34E+03	3.88E+03	1.35E+04	3.08E+04	
Ratio of use to GDP, emergy/dollar ratio	P1=U/GDP	6.61E+12	2.04E+13	1.76E+13	1.94E+13	1.74E+13	1.96E+13	1.76E+13	1.93E+13	1.80E+13	1.82E+13	1.74E+13	1.78E+13	1.80E+13	seJ/$
Environmental load ratio (ELR) (with L&S)	(F + G + P2I + P2I2+P2I3+N)/R	1.82E+03	5.65E+03	1.26E+03	5.99E+02	8.79E+02	1.47E+02	1.11E+03	5.56E+02	1.27E+03	6.69E+02	1.91E+03	5.52E+02	1.51E+02	
Emergy investment ratio (EIR) (with L&S)	(F + G + P2I + P2I2+P2I3)/(R + N)	4.41E+01	2.16E+01	6.78E+00	7.49E+00	6.68E+00	7.19E+00	6.78E+00	7.40E+00	9.39E+00	6.96E+00	6.71E+00	6.78E+00	6.58E+00	
Net emergy yield ratio (EYR) (with L&S)	Y/F	1.02E+00	1.05E+00	1.15E+00	1.13E+00	1.15E+00	1.14E+00	1.15E+00	1.14E+00	1.11E+00	1.14E+00	1.15E+00	1.15E+00	1.15E+00	
Emergy self-support ratio (ESR) (with L&S)	(R + N)/U	2.22E-02	4.43E-02	12.86%	1.18E-01	1.30E-01	12.21%	12.86%	11.90%	9.63%	12.56%	12.96%	12.86%	13.19%	
Environmental sustainability index (ESI) (with L&S)	EYR/ELR	5.63E-04	1.85E-04	9.11E-04	1.89E-03	1.31E-03	7.77E-03	1.03E-03	2.04E-03	8.75E-04	1.71E-03	6.02E-04	2.08E-03	7.63E-03	
Ratio of use to GDP, emergy/dollar ratio (without L&S)	P1=U/GDP	4.17E+12	1.85E+13	1.56E+13	1.58E+13	1.57E+13	1.74E+13	1.57E+13	1.59E+13	1.51E+13	1.57E+13	1.55E+13	1.59E+13	1.59E+13	seJ/$
Environmental load ratio (ELR) (without L&S)	(F + G + P2I + P2I2+P2I3+N)/R	1.15E+03	5.11E+03	1.12E+03	4.89E+02	7.91E+02	1.30E+02	9.92E+02	4.57E+02	1.06E+03	5.77E+02	1.71E+03	4.94E+02	1.33E+02	
Emergy investment ratio (EIR)) (without L&S)	(F + G + P2I + P2I2+P2I3)/(R + N)	2.75E+01	1.94E+01	5.90E+00	5.93E+00	5.91E+00	6.28E+00	5.93E+00	5.91E+00	7.74E+00	5.86E+00	5.89E+00	5.96E+00	5.69E+00	
Net emergy yield ratio (EYR)) (without L&S)	Y/F	1.04E+00	1.05E+00	1.17E+00	1.17E+00	1.17E+00	1.16E+00	1.17E+00	1.17E+00	1.13E+00	1.17E+00	1.17E+00	1.17E+00	1.18E+00	
Emergy self-support ratio (ESR)) (without L&S)	(R + N)/U	3.51E-02	4.90E-02	1.45E-01	1.44E-01	1.45E-01	1.37E-01	1.44E-01	1.45E-01	1.14E-01	1.46E-01	1.45E-01	1.44E-01	1.49E-01	
Environmental sustainability index (ESI)) (without L&S)	EYR/ELR	9.03E-04	2.06E-04	1.05E-03	2.39E-03	1.48E-03	8.90E-03	1.18E-03	2.56E-03	1.06E-03	2.03E-03	6.86E-04	2.37E-03	8.83E-03	

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