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Urban Metabolic Efficiencies and Elasticities of Chinese Cities

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Abstract: Urban metabolism is a complex system of materials, energy, population and environment, which usually can be measured by the Emergy Synthesis (ES) and the Slacks-Based Measure (SBM) approach. In this paper, by employing the two approaches of ES and SBM, as well as metabolic evolution index, urban metabolic stocks, efficiencies and elasticity of 31 Chinese cities are evaluated in a systematic way. The results imply that over the last decade (2000–2010), most of the cities, such as Chongqing, Nanjing, Shijiazhuang, Hangzhou, were experiencing drastic urban metabolic efficiency decline accompanied with a moderate decrease of industrial outputs. By contrast, metropolises and specialized cities have improved their urban metabolic performances, with higher output-input ratio and fewer undesirable outputs. However, their exported emergy experienced a substantial increase as well. It is concluded that local urban management might develop policies to diversify urban renewable supplies and address the undesirable output problems. The urban emergy of renewable resources should be specified as a prime focus for future research. In addition, mechanisms of different urban metabolic models will also be necessary for researchers.

Keywords: urban metabolism; emergy; Slacks-Based Measure (SBM); metabolic elasticity

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1 Introduction

Since the dawn of industrialization, economic growth has been associated with ever increasing use of non-renewable materials and energy, as well as the degradation of renewable resources beyond their regenerative capacities. As the main consumption places of materials and energy, cities are characterized by yet gross inefficiencies in the use of energy, water and materials (Zhang *et al*., 2010a). To achieve the goal of urban sustainable development, it is necessary to study urban systems from a metabolic perspective.

Cities are similar to organisms in that they consume resources from their surroundings and excrete wastes (Kennedy *et al*., 2011). The concept of urban metabolism was firstly introduced by Wolman (1965). He defined the metabolic requirements of a city as all the materials and commodities needed to sustain the city′s inhabitants at home, at work and at play. Urban metabolism is a self-organized system, which circulates materials, energy, resources, and services in urban network interactions (Ulgiati and Brown, 2009), and can be defined as ′the sum total 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). By analyzing the fluxes, stores and efficiencies of the urban metabolic system, it is possible to express, manage and improve the inter-relationship of the urban economic material system and the ecological resource system (Broto *et al*., 2012). A lot of studies

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worldwide have contributed to the quantitative appraisal way of urban metabolisms in terms of fundamental flows or cycles—those of water, materials, energy, and nutrients (Kennedy *et al*., 2007), including Hanya and Ambe (1976), Hendriks *et al*., (2000), Bristow and Kennedy (2013). These metabolic studies provide new insights to urban sustainable development by integrating the accumulation and consumption processes of materials, resources, energy, nutrients and wastes.

Odum first proposed the concept of emergy, which is the amount of energy that is directly or indirectly transferred to flow or storage of energy or matter (Odum, 1971). Emergy evaluation is a method to associate a product with its dependencies on all upstream environmental and resource flows using a common unit of energy (Ingwersen, 2011). Many studies have applied emergy evaluation to a variety of urban sustainable researches and decision-making practices (Odum, 1983; Keller, 1992; Odum, 1996), such as Hong Kong (Newcombe *et al*., 1978), Sydney (Newman *et al*., 1996), Taiwan (Huang, 1998), Shanghai (Zhang *et al*., 2006), Toronto (Forkes, 2007), and Beijing (Zhang *et al*., 2009b). For example, Zhang *et al*., (2009b) and Song *et al*., (2015) measured Beijing′s urban metabolic performances by emergy analysis. Their results showed that Beijing depend excessively on nonrenewable resources than other cities. Ascione *et al*., (2009) also compared urban emergy indicators of Roma with three other cities (Taibei, San Juan and Macao). However, the emergy approach adopted in urban metabolic analysis mostly emphasizes model building of a single city by performance indicators and still lacks of a systematically comparable urban metabolic based on amounts of different cities (Zhang *et al*., 2010b), which will be helpful to understand different mechanisms of urban metabolic structures. More importantly, further studies need to portray the system′s overall metabolic efficiency of resource inputs/production and waste outputs, and distinguish different metabolic efficiencies of various cities by comparing their input-output ratios, in addition to developing urban metabolic model by simply capturing linear accumulations and flows of urban materials. Slacks-Based Measure (SBM) can address this shortcoming by examining both urban input and output technologies in a unified framework.

Data Envelopment Analysis (DEA), a methodology to evaluate the performance of various organizations in public and private sectors (Sueyoshi and Goto, 2012), has long been applied to analyze the environmental efficiency of regional development, such as Fare *et al*., (1996), Ramanathan (2002), Zaim (2004), Seiford and Zhu (2005) and Zhou *et al*., (2008). However, the DEA model does not measure the slacks (inefficiencies) in inputs and desirable outputs (Boyd *et al*., 2002). By combining the environmental and economic slacks, the SBM can serve as a composite index for analyzing the economic-environmental performance (Zhou *et al*., 2006). In addition to the advantage of modeling desirable and undesirable slacks, other advantages of the model include optimal solution, non-radial and input or output independence. Instead of proportionate reduction in inputs or outputs (radial), the non-radial characteristics aim at obtaining maximum rates of contraction in inputs or outputs, which makes SBM a step forward than the traditional model (Avkiran *et al*., 2008). A number of SBM research efforts focused on the environmental performances evaluation , such as CO_2 emissions, at regional or provincial level, including those by Fare *et al*., (2005), Hu and Kao (2007), Choi *et al*., (2012), Wei *et al*., (2012). It would be helpful to extend the current research by adding more applications of SBM at the urban level. To the best of our knowledge, it is also rare to have SBM and urban metabolic evaluation combined. Moreover, few empirical studies to date have concentrated on the relationship between urban metabolic efficiencies and metabolic yield level of the Chinese cities.

Against the backdrop above mentioned, this paper evaluates the metabolic bases of urban sustainable development by four steps:

(1) The first goal is to establish an urban metabolic system by the emergy flow analysis, which converted all the systematic energy, resources and services into emergy units.

(2) Urban metabolic efficiencies of 31 Chinese cities are examined by applying the Slack-Based DEA (SBM) model. The SBM facilitates judgments of the urban metabolic system′s overall situation by integrating both desirable and undesirable slacks, as well as aiming at obtaining maximum rates of outputs to inputs. The emergy analysis and SBM model for urban metabolism are briefly reviewed followed by analysis of urban metabolic statistical data of sample cities.

(3) Based on the efficiency analysis, an index of ur-

ban metabolic elasticity is creatively constructed to monitor urban metabolic trends. All the 31 sample cities are divided into different metabolic types to help understand the metabolic efficiency and evolution of urban systems in terms of resources, energy inputs and desirable, undesirable outputs.

(4) The main conclusions, method challenges and potential solutions for urban metabolic analysis are discussed. This section tries to show how a simple metabolic model can be used to stimulate the related urban sustainable policies.

Answering all these questions will pave the way for improving the future dynamics of urban sustainable metabolic development and promoting the emergy method, to be a more important and effective urban metabolic evaluation tool.

2 Methodology and Data

2.1 Urban emergy analysis

The concept of ′emergy′ was introduced to measure the quantity of the systematic energy, resources and services in a metabolic process (Odum, 1971). The emergy flow and storage of the urban metabolic system were depicted in Fig. 1. In this paper, an urban metabolic system is an analogy of a prefecture-level city, in which the flows of renewable emergy from outside (R), indigenous renewable emergy (IR) and locally non-renewable emergy (N) are stored, consumed and transferred between different urban components within the system boundary. The system also imports and exports materials, energy, and labor depending on the supply and demand gap (Zhang *et al.*, 2010a). Wastes of the urban system will be discharged with converged endogenous energy. In addition, the solar emergy required to generate a unit of flow or storage of available energy, materials or money is called solar transformity and is expressed as solar emergy joules per joule of output flow (seJ/J, seJ/g, or seJ/$(USD)) (Brown and Ulgiati, 2002). Table 1 is the emergy synthesis table, including emergy items and transformities to summarize the major systematic flows (Song *et al.*, 2015).

Four urban emergy indicators were explained in Table 2. U is the total amount of emergy consumed by the city within a year, representing the total net emergy throughput without exports and wastes and consisting of four parts: R, IR, N and IM. Us is the total emergy with exports and wastes, representing emergy sum of both import and export, input and output. R, IR and N are summed as SR, reflecting the amount of resources invested. Furthermore, RYR is the ratio of U to Us, representing the yield rate of the total resource emergy. Further details of the calculations by the four urban emergy indicators are explained below.

2.2 Urban metabolism model based on slacks-based measure

DEA method, invented by Charnes *et al.* (1978), is employed to evaluate the systematic efficiency of a group of decision-making units (DMU) with the same types of

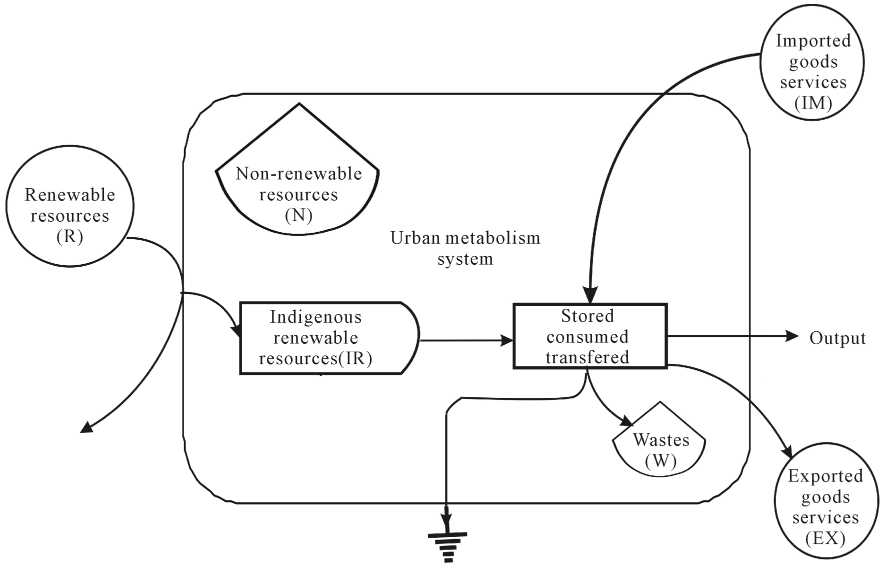

Fig. 1 Emergy flows of the urban material metabolism system (Zhang *et al.*, 2009a)

Table 1 Emergy items and transformity

Emergy item		Item	Unit	Transformity (seJ/unit)	Emergy of Beijing in 2001	Reference of transformity
R	Renewable emergy	Sunlight	J	1	6.71E+19	Odum,1996
		Wind, Kinetic	J	2.45E+03	2.92E+19	Odum *et al*., 2000
		Rainfall (chemical)	J	3.05E+04	2.73E+19	Odum *et al*., 2000
		Rainfall (geopotential)	J	4.70E+04	5.48E+20	Odum *et al*., 2000
		Waves	J	2.59E+04	0	Odum,1996
		Earth cycle	J	5.80E+04	1.37E+21	Odum *et al*., 2000
IR	Indigenous renewable emergy	Water	J	3.05E+04	6.41E+19	Odum *et al*., 2000
		Crops	g	2.43E+11	1.63E+21	Odum,1996
		Livestock	g	1.49E+11	1.70E+20	Odum,1996
		Fisheries	g	1.80E+10	1.33E+18	Odum,1996
N	Locally non-renewable emergy	Topsoil loss	t	1.71E+03	1.32E+22	Huang and Chen, 2005
		Electricity	J	1.60E+05	2.29E+22	Odum,1996
		Steel	g	1.80E+09	1.31E+22	Odum,1996
		Raw coal	J	4.00E+04	2.7E+22	Odum,1996
		cement	g	3.3E+10	2.67E+23	Huang and Hsu,2003
		Gasoline	J	1.11E+05	6.41E+21	Odum,1996
		Diesel fuel	J	1.11E+05	3.76E+21	Odum,1996
		Liquid petroleum gas	J	4.80E+04	1.59E+21	Odum,1996
		Fuels oil	J	6.25E+04	2.31E+21	Odum *et al*., 2000
		Fertilizer	t	8.28E+06	2.79E+20	Ascione *et al*., 2009
IM	Imported emergy	Goods	$(USD)	9.37E+12	3.72E+23	Jiang *et al*., 2007
		Service	$(USD)	9.37E+12	3.11E+22	Jiang *et al*., 2007
		Fuel	J	8.55E+04	2.82E+22	Odum,1996
		Tourism income	$(USD)	1.66E+12	1.60E+23	Jiang *et al*., 2007
EX	Exported emergy	Goods	$(RMB)	6.34E+12	7.47E+22	Jiang *et al*., 2007
		Service	$(RMB)	6.34E+12	4.70E+22	Jiang *et al*., 2007
W	Waste emergy	Rubbish	J	1.80E+06	1.29E+22	Huang and Chen, 2005
		Sewage	J	6.66E+05	6.98E+20	Huang and Chen, 2005
		Emission	J	6.66E+05	1.30E+20	Huang and Chen, 2005

Table 2 Urban emergy indicator

Indicator	Formula	Indication
U	U = R + IR + N + IM	Total emergy without exports and wastes
U_S	Us = U + EX + W	Total emergy with exports and wastes
SR	SR = N + IR + R	Total amount of resource emergy
RYR	RYR = U/U_S	Resource yield rate of urban metabolic system

inputs and outputs. In view of the application of DEA to urban negative environmental indicators such as waste outputs and emissions, the undesirable outputs orientation DEA model (Tyteca, 1996) provides an standardized efficiency method (greater than 0 but less than or equals to 1) for measuring environmental performance (Zhou *et al*., 2006). It is particularl significant to integrate these environmental inefficiencies into the total performance evaluation, by SBM in the traditional DEA framework (Cooper *et al*., 2000; Tone, 2001).

In this paper, the evaluation of urban metabolic performance comes from the emergy analysis and the SBM model. This not only expresses the urban metabolic stock and flow by emergy analysis, but it also estimates the urban metabolic efficiency by weighting the proportion of the inputs and outputs. Thus, it clearly improves efficiency by reducing the resourse input and the output slacks using SBM, especially by reducing undesirable outputs rather than increasing desirable outputs. As for the database of SBM model combing emergy theory, this paper employs the total renewable emergy (R', he sum of R and IR) and total non-renewable emergy (N) as inputs. The output data are divided into the desirable (Y^g) and undesirable outputs (Y^b). Desirable economic outputs GDP (Y^g) is accompanied with undesirable emergy of wastes (Y^b), including sewages, emissions and solid wastes, as outputs.

In urban metabolism model based on SBM, the vectors of input, desirable output and undesirable output in decision-making units (DMU) of the metabolism system are expressed as, $y^g \in R^{s_1}$, $y^b \in R^{s_2}$; λ is a weight vector**.** X is a ($m \times n$) matrix of emergy inputs, Y^g is a ($s_1 \times n$) matrix of desirable outputs, Y^b is a ($s_2 \times n$) matrix of undesirable emergy outputs, and X, Y^g, Y^b>0. A production possibility set under constant returns to scale P is defined as follows:

$$P=\left\{\left(x,y^g,y^b\right) \mid x \geq X\lambda,\ y^g \leq Y^g\lambda,\ y^b \geq Y^b\lambda,\ \lambda \geq 0\right\} \tag{1}$$

By integrating both economic inefficiency (desirable outputs′ slacks) and environmental inefficiency (undesirable outputs′ slacks), the urban metabolic SBM is defined as follows:

$$\rho = \min \frac{1-\left(1/m\right)\sum_{i=1}^{m} s_i^- x_{i0}}{1+\dfrac{1}{s_1+s_2}\left(\sum_{r=1}^{S_1} S_r^g / y_{r0}^g + \sum_{r=1}^{S_2} S_r^b / y_{r0}^b\right)}$$

$$s.t: x_0 = X\lambda + s^-; y_0^g = Y^g\lambda - S^g; y_0^b = Y^b\lambda + S^b; \qquad \lambda \geq 0, S^- \geq 0, S^g \geq 0, S^b \geq 0 \tag{2}$$

The equations above are linear programs with undesirable slacks (Tone, 2004). The vectors $s^- \in R^m$, $S^g \in R^{s_1}$, and $S^b \in R^{s_2}$ correspond to slacks in inputs, desirable outputs, and undesirable outputs, respectively. The computed value of ρ is the overall technical efficiency score for a urban metabolic system after its input and output slacks are adjusted to their minimum levels (Li and Hu, 2012). Only if ρ = 1, the corresponding decision-making unit (DMU, urban metabolic system) is effective; i.e. S^- = 0, S^g = 0, S^b = 0 (maximum desirable outputs, minimum resource inputs and undesirable outputs) are efficient. If $0 < \rho < 1$, the DMU is ineffective, indicating that the DMU is inefficient. For the inefficient DMU_0 (x_0, y_0^g, y_0^b) to improve its urban metabolic performances towards its efficient projection unit DMU_0' (x_0', $y_0^{g\prime}$, $y_0^{b\prime}$) in the frontiers, it is needed by reducing the emergy input slacks S^-, the undesirable emergy output slacks S^b or increasing the desirable output slacks S^g.

Finally, an index of urban metabolic intensity based on SBM is as following:

$$UM = \rho\sqrt[3]{(1-S^- / x_{ij})\times(1-S^g / y_{ij}^g)\times(1-S^b / y_{ij}^b)} \tag{3}$$

Where UM = comprehensive metabolic intensity of the corresponding DMU (urban metabolic system); S^- is slacks in input (maximam slack of R' and N), x_{ij} is actual input, S^g is slacks in desirable output, y_{ij}^g is actual desirable output, S^b is slacks in undesirable output, and y_{ij}^b is actual undesirable output. The UM is a comprehensive index to measure urban metabolic intensity by the product of overall technical efficiency score (ρ) and the geometric mean of the input, desirable output and undesirable output efficiency considering the efficient DMU in the frontiers. This indicator is usefully applicable to measure urban metabolic efficiency both in the input excesses and the output shortfalls. Higher UM characterizes both economic output and environmental efficiency, while lower UM means the urban metabolic system has to improve the environmental and economic efficiency during energy and resource consumption/ conversion processes.

2.3 Urban metabolic evolution index

In an attempt to monitor urban metabolic trends and correlate changes in the urban metabolic efficiency with changes in the comprehensive yield level, the paper borrows the index of environmental elasticity (Rogers *et al.*, 1997) and builds up an index of urban metabolic elasticity (ME). The index is defined as the percentage change in an urban metabolic efficiency as a function of a 1 percent change in an urban metabolic yield rate (RYR), or:

$$ME = UMc/RYc \tag{4}$$

Where UMc is aggregate UM change (normalized values of changed percent); RYc is aggregate RYR change (normalized values of changed percent).

Figure 2 graphically illustrates the four possible quadrants in which a city can be located in the metabolic efficiency-yield space.

Quadrant I (both metabolic efficiency and yield capacity changes are positive) is the most preferred situation and Quadrant III (both the metabolic efficiency and yield capacity changes are negative) is the least preferred situation. Cities in Quadrant II (positive metabolic efficiency change but negative yield capacity change) witness the improvement of urban metabolic efficiencies and growth in exported and wasted emergy. They need to put more focus on endogenous economic development. By contrast, cities in Quadrant IV (positive yield capacity change but negative metabolic efficiency) have regressed in improving urban metabolic efficiences. More efforts in renewable energy, green-industrial development, *etc.*, goes a long way toward improving metabolic performances.

2.4 Samples and statistical data

In this paper, 31 major Chinese cities are chosen to serve as cases. Among all the cities, Beijing, Shanghai, Chongqing and Tianjin are municipalities whose total gross domestic product (GDP) reached 4.84 × 10^{13} yuan (RMB) in 2010, with a total population of 8.448 × 10^7. Other 27 cities, such as Harbin, Suzhou, Dalian, Shenzhen, Guangzhou, *etc.*, are provincial capitals or prefecture-level cities. GDP of these 31 sample cities arrived at 1.54 × 10^{14} yuan (RMB) in 2010, accounting for 35.99% of the national GDP of the same year. These cities covered total area of 460 856 km^2 (4.8% of China's land area) and had a population of 2.624 × 10^7 in 2010 (19.4 % of China's total population). Among them, 14 sample cities are located in Eastern China, 8 in Western China, 5 in Middle China, and 4 in Northeastern China, as shown in Fig. 3.

Data of emergy attributes are from the *China Statistical Yearbook 2001–2011* (National Bureau of Statistics of China, 2001–2011), *Statistical Yearbook 2001–2011* (National Bureau of Statistics of China, 2001–2011), and *China Environmental Statistical Yearbook 2001–2011* (National Bureau of Statistics of China, 2001–2011). More detailed information on urban resources, energy as well as services are from the statistical yearbook of each city (2001–2011). Due to data inavailability, cities like Lhasa, Yinchuan, Taibei, Hong Kong, and Macao, *etc.*, are not included in the study.

3 Results

3.1 Storages of urban emergy metabolic system

Based on the emergy flow analysis of 31 sample cities' urban metabolisms, the total emergy without exports and wastes (U) and the total emergy with exports and wastes (Us) are shown in Fig. 4 and Fig. 5, respectively. The results reveal that the metropolises (including Beijing, Shanghai, Guangzhou, and Shenzhen) and cities along the Changjiang (Yangtze) River (e.g., Suzhou, Ningbo) have significant emergy storage. The emergy values of the inland cities (such as Xi'an and Lanzhou) are small due to the low nonrenewable resource and energy products and consumptions, which suggests that

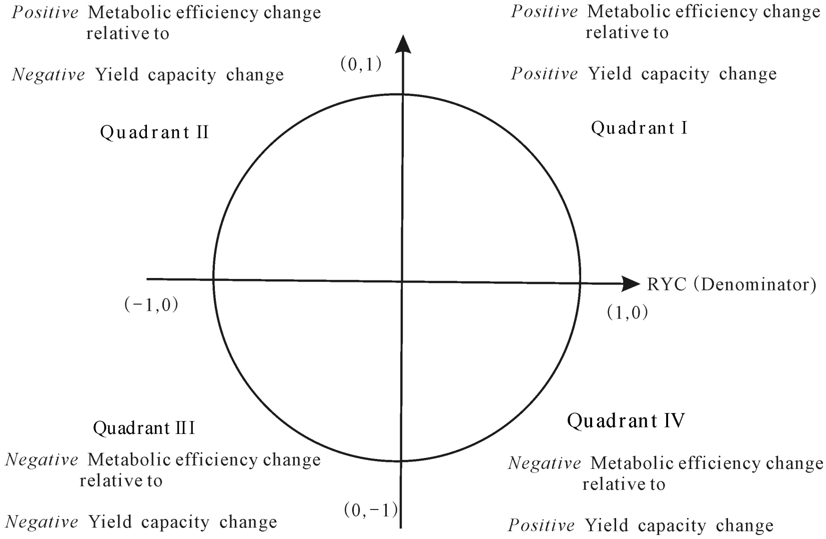

Fig. 2 Map of urban metabolic elasticity

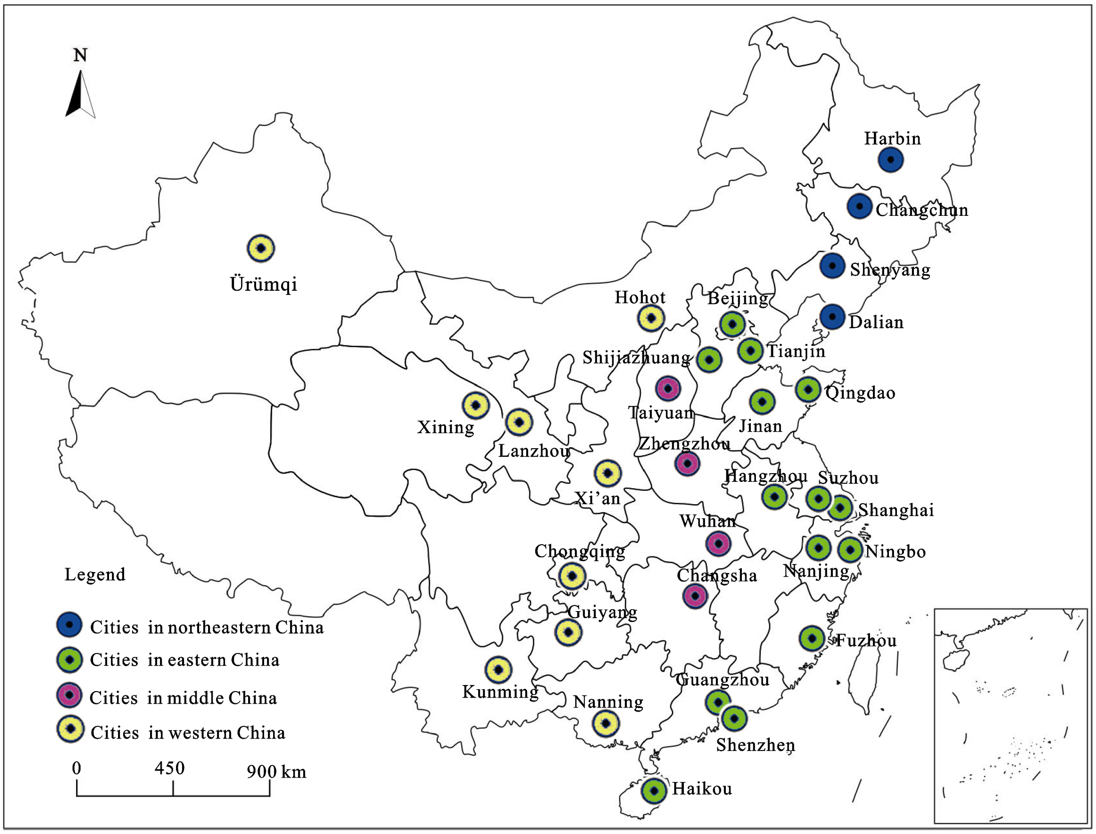

Fig. 3 Locations of sample cities in China

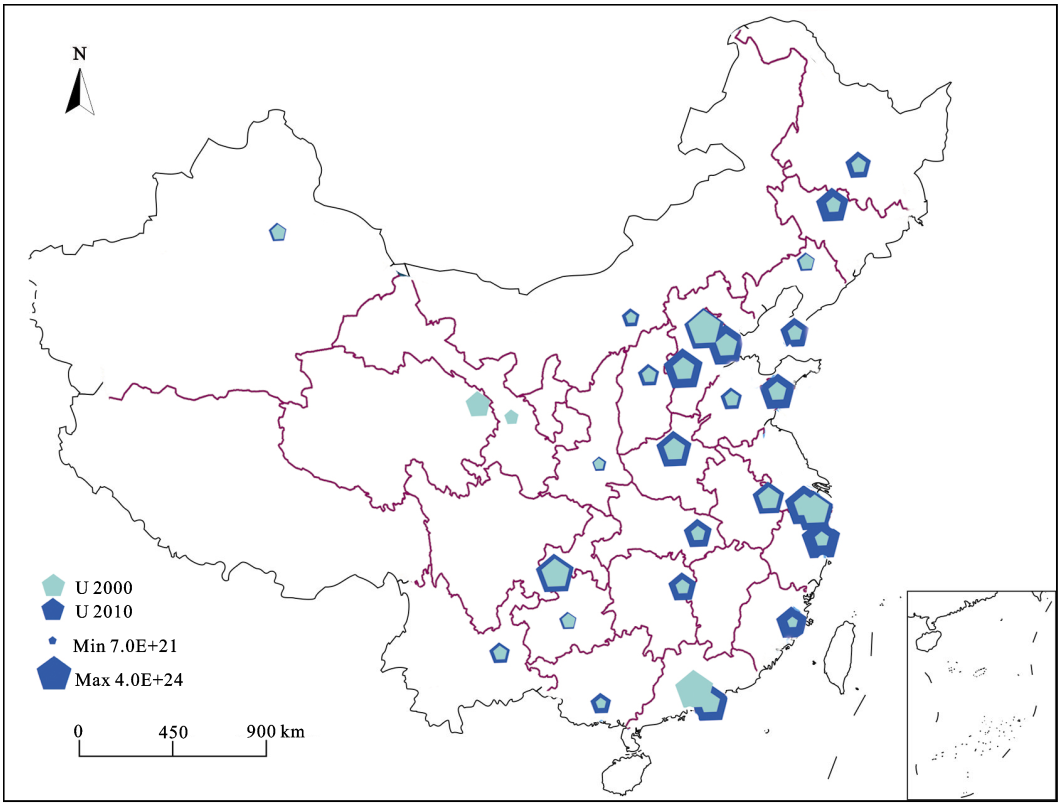

Fig. 4 Emergy performances of total emergy without exports and wastes (U) in 2000 and 2010

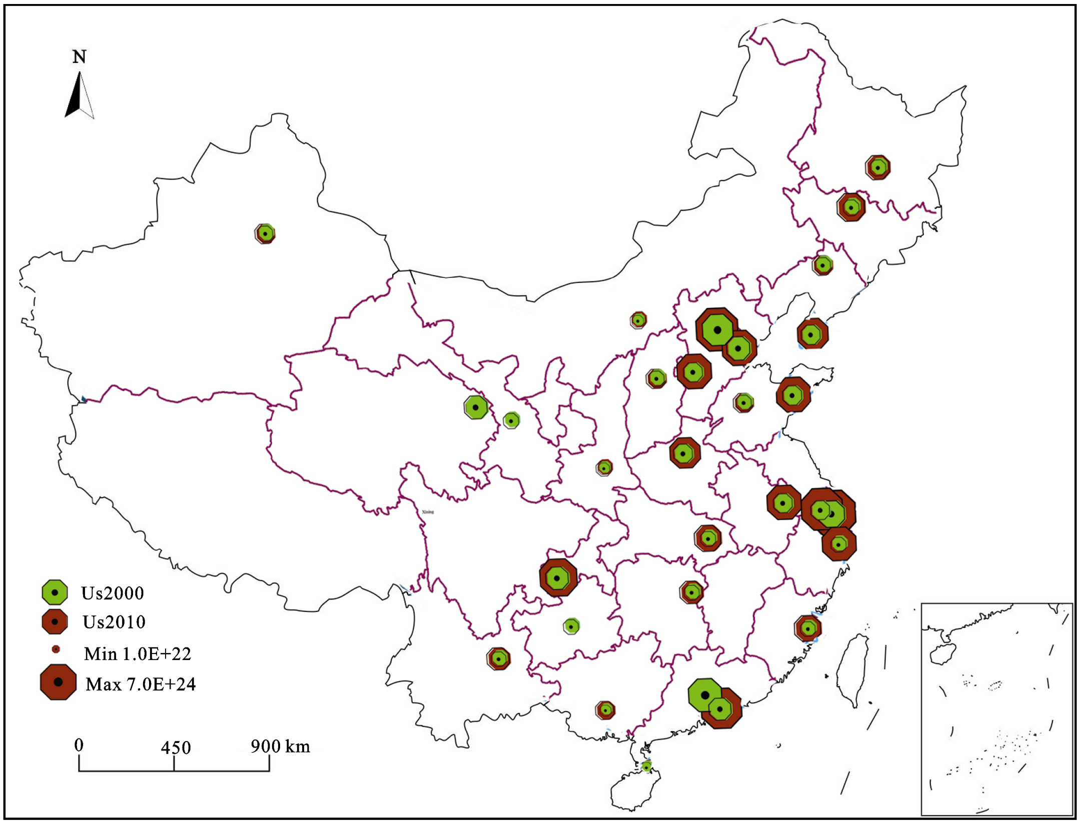

Fig. 5 Emergy performances of total emergy without exports and wastes (Us) in 2000 and 2010

urban energy and materials consumptions are related to the urban size and comprehensive development level. Comparing the emergy performances of 2000 with 2010, the emergy flows in metropolises, such as Shanghai and Beijing, had experienced a massive growth during the past decade due to the substantial increase of imports and exports, as well as the increased provision of nonrenewable resources, such as steel and coal. In sum, most cities have exhibited an overall increasing trend of emergy, whatever U or Us, representing its increasing contribution to urban economic activities.

From Fig. 6 it can be seen that hinterland cities, such as Chongqing, Shijiazhuang, Zhengzhou, Hohhot, had more resource emergy than other cities in 2000 and 2010, which aligns fairly well with their resource-oriented industrial structure, especially known for metal, mineral and material industries. The resource emergy values of most cities experienced a steady growth during the past decade, except Fuzhou, Dalian, Xining, and Changchun. The resource emergy values of the four cities all increased by more than 3 times, which may be caused by the more intense industrialization in these cities compared with others. In general, regarding to RYR (Fig. 7), the emergy yield rates of export-oriented cities, such as Shenzhen, Suzhou, Qingdao and Ningbo, are lower than others. A direct cause of these low values is that large amounts of export increase the endogenous emergy (Us), resulting in the low RYR rates. The emergy yield rate growth will be discussed in section of 3.3.

3.2 Urban metabolic performances based on SBM

The overall technical efficiency scores (ρ) and urban metabolic efficiencies (UM) of 31 cities with the inclusion of undesirable outputs have been shown in Fig. 8 and Fig. 9, respectively. The results illustrate that urban metabolic efficiencies are highly related to the overall technical efficiency scores. The 31 cities are roughly divided into three groups. The first group includes Shanghai, Shenzhen, Suzhou, Haikou, whose ρ and UM are 1 in 2000 (except Suzhou) and 2010, without any slack of input and output (Values of inputs and outputs' Slacks equal to zero). It means that metropolises like Shanghai, coastal open cities, Suzhou, *etc.*, and specialization cities that specialize in certain industries like Haikou (for its tourism), are more efficient in urban

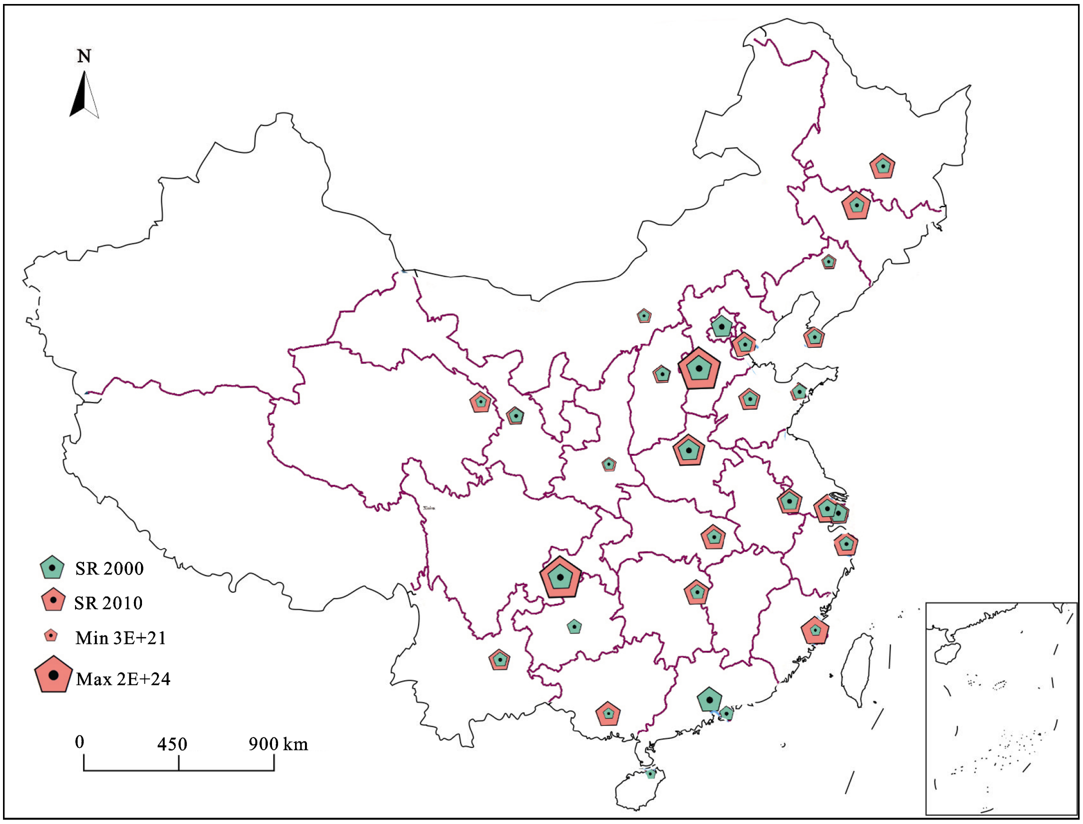

Fig. 6 Emergy of resources (SR) of 31cities in 2000 and 2010

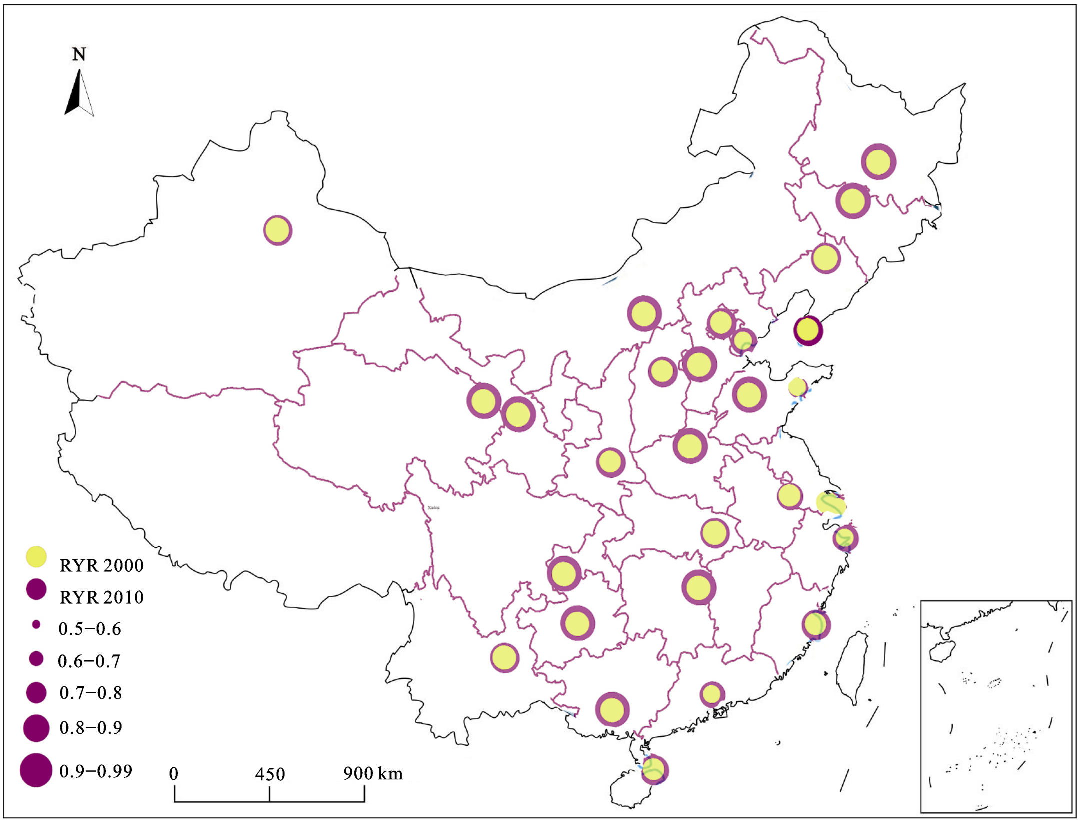

Fig. 7 Emergy yield rate (RYR) of 31 sample cities in 2000 and 2010

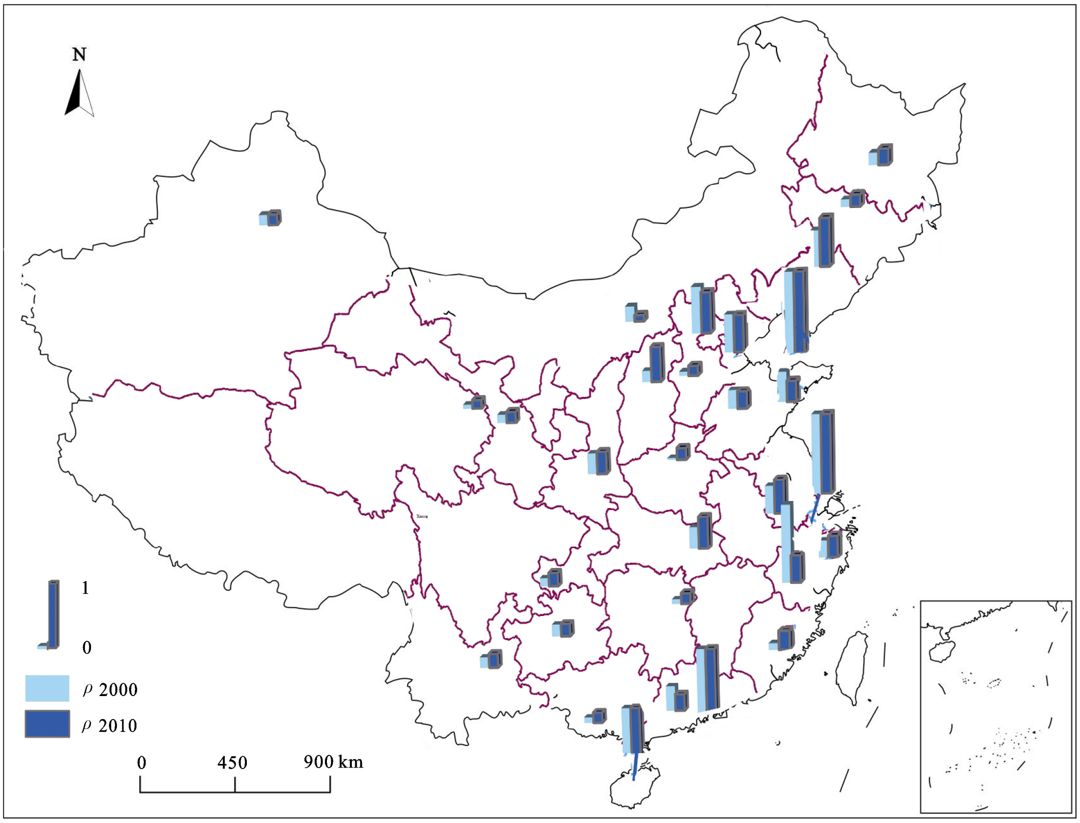

Fig. 8 Overall technical efficiency score ρ of 31 cities based on SBM

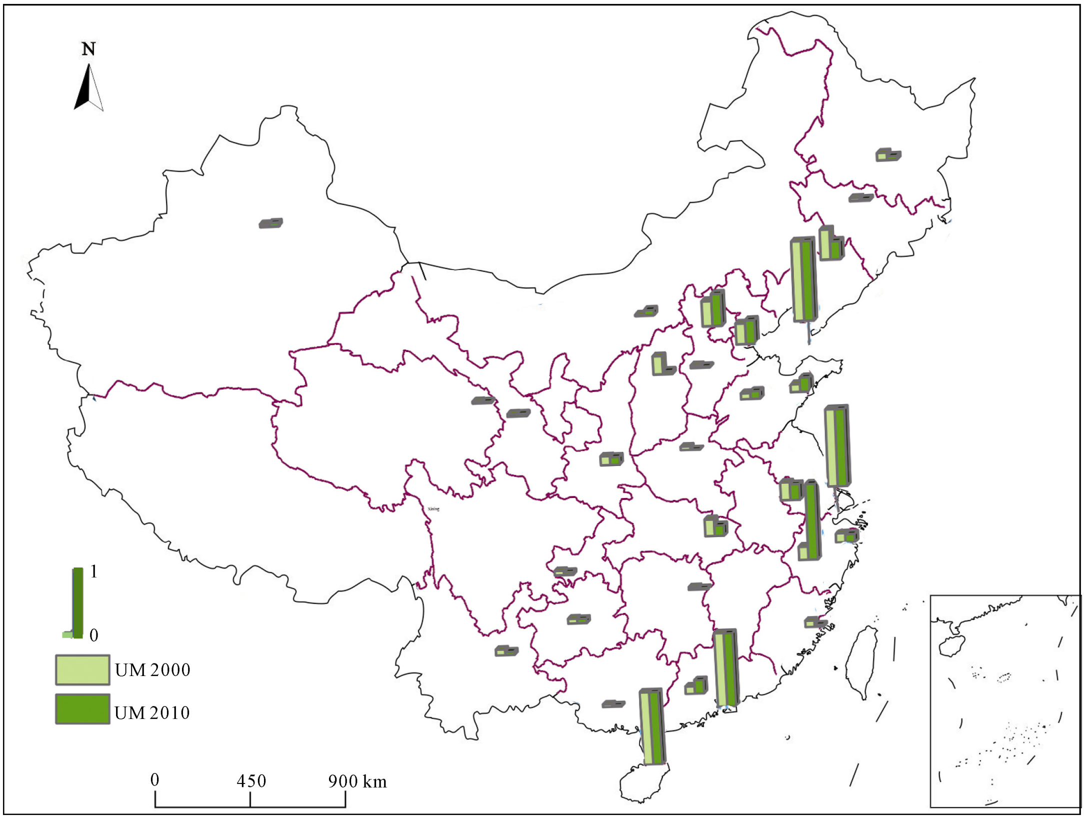

Fig. 9 Urban metabolic efficiencies (UM) of 31 sample cities in 2000 and 2010

metabolisms. Beijing, Tianjin, Shenyang, Nanjing, Guangzhou, Qingdao are in the second group, whose UM values vary from 0.1 to 0.5, implying that metropolises and coastal open cities play a key role in urban metabolic systems. It is also clear from our data that other cities, classified as the third group, have lower metabolic efficiencies in 2000 and 2010, in both ρ and UM. Most of them are China′s middle and western cities which are highly dependent on resource-energy oriented industries.

Urban metabolic efficiencies of 31 cities have also been classified by GDP and population, as shown in Table 3. Our results show that a city can be more metaboliccally efficient when its scale has been growing to some extent. Cities were also able to achieve material and energy flows′ efficiency with different economic outputs. Bigger cities showed more efficient results than smaller ones. As indicated by Table 6, 33% of metropolitans with more than 1×10^{12} yuan (RMB) output were efficient, with their average efficiency reaching 0.57, while 27%, 0% cities with 5×10^{11}–9.99×10^{11}, 1×10^{11}–4.99×10^{11} yuan (RMB) output were efficient, respectively. Similar situations were also observed at the population scale. The average metabolic efficiency also increased as population continuously grew. Cities, such as Shanghai, Shenzhen and Suzhou with the size of more than 1×10^7 inhabitants arrived at 44% in urban metabolic efficiency in 2010. By contrast, the average efficiencies were only 0.16 in both these cities that the size of 5×10^6–9.9×10^6 inhabitants and those having less than 5×10^6 inhabitants. This illustrates that cities become more competitive through shared services and infrastructure by less cost of energy, resources and land when cities are larger.

The slack analysis (Table 4) shows that renewable resource slacks (S_R) have been found in most cities like Harbin, Chongqing, Kunming, Shenyang, *etc*. It implies that there is a huge potential for most cities to apply emergy-saving technologies. As for nonrenewable resource slacks (S_N), results of 2000 and 2010 are totally different. Dalian, Zhengzhou, Xining, and Changchun in 2010 had nonrenewable input slacks, reflecting that the improvement of nonrenewable resource utilities is needed in those cities. However, nonrenewable input inefficiencies were found in Chongqing, Beijing, Nanjing, Guangzhou, Tianjin, Harbin, Kunming, Zhengzhou, Jinan, Wuhan, Guiyang, Hangzhou and Suzhou with substantial input slacks (S_N) in 2000. The differences of S_N between 2000 and 2010 may be due to the environmental techniques and investment growth in metropolises. In terms of desirable output slacks (S^g), most cities need to increase GDP in 2000 and 2010 considering the current inputs to the decision-making units (DMU_0) of production systems in the frontiers, especially such cities as Chongqing, Shijiazhuang, Zhengzhou, which are located in China′s middle and western regions and characterized by heavy industry oriented development. Moreover, undesirable output slacks (S^b) in 2000 and 2010 came from two sets of cities which are metropolises, such as Guangzhou, Shenzhen, and industrial cities, such as Shijiazhuang and Changchun. The results enable to stimulate those inefficient cities in undesirable output performances to further improve their productivities and environmental influences.

3.3 Urban metabolic types

Four scenarios of urban metabolic elasticity (ME) are shown in Fig.10 and Tables 5, 6. Vertical and horizontal axes are aggregate urban metabolic efficiency rate changes (UMc) and aggregate urban metabolic yield

Table 3 Urban metabolic efficiencies of sample cities at various scales in China

Scale		2010				2000			
		Number of cities	Number of efficient cities	%	Average	Number of cities	Number of efficient cities	%	Average
Classified by GDP (1×10^9 yuan)	>1000	3	1	33	0.53	No data	No data	No data	No data
	500–999	11	3	27	0.39	No data	No data	No data	No data
	100–499	14	0	0	0.05	17	3	18	0.31
	<100	3	1	33	0.34	14	1	7	0.13
Classified by Population (1×10^6)	>10	9	3	33	0.44	3	1	33	0.46
	5–9.9	14	1	7	0.16	21	2	10	0.21
	<5	8	1	13	0.16	7	1	14	0.20

Table 4 Slacks of inputs and outputs of 31 cities in 2000, 2010

City	Slacks in renewable emergy input S_R (seJ)		Slacks in unrenewable input S_N (seJ)		Slacks in desirable output S^g (10^4 yuan)		Slacks in undesirable output S^b (seJ)	
	2000	2010	2000	2010	2000	2010	2000	2010
Beijing	1.31E+21	3.19E+20	1.78E+23	0	557.0	4048.9	0	1.93E+22
Shanghai	0	0	0	0	0	0	0	0
Chongqing	6.66E+21	3.25E+21	3.85E+23	0	1920.8	105245.5	0	0
Tianjin	1.69E+21	7.21E+20	6.05E+22	0	298.7	15802.6	0	0
Harbin	0	6.34E+21	2.78E+22	0	7444.4	22455.2	0	0
Changchun	2.11E+21	0	0	1.57E+22	1700.4	29611.8	9.8E+21	6.39E+22
Shenyang	1.78E+21	2.35E+21	0	0	296.1	2401.2	0	5.20E+21
Shijiazhuang	8.29E+20	9.36E+20	0	0	7598.6	110262.3	3.34E+22	3.92E+21
Lanzhou	2.24E+20	9.04E+20	0	0	2070.4	13380.0	9.12E+21	0
Kunming	0	2.47E+21	3.77E+22	0	4827.2	18229.9	0	0
Xining	3.79E+20	0	0	4.23E+22	1001.5	22419.4	4.35E+21	0
Xi'an	1.26E+21	1.63E+21	0	0	365.1	1958.4	3.3E+21	7.68E+21
Zhengzhou	0	0	5.81E+22	1.13E+23	5006.7	42898.6	2.04E+22	0
Jinan	2.29E+21	1.92E+21	1.41E+23	0	62.8	15674.8	0	0
Taiyuan	1.40E+21	0	0	1.02E+23	377.9	13835.3	2.99E+21	3.58E+22
Wuhan	1.56E+21	1.14E+21	4.89E+22	0	508.7	20528.3	0	0
Changsha	1.69E+21	1.14E+21	0	0	1840.2	0	9.81E+21	4.79E+22
Nanjing	0	0	1.89E+23	0	1222.7	18500.9	0	0
Guiyang	0	5.09E+20	4.05E+22	0	2078.0	9973.5	0	0
Nanning	4.99E+20	3.53E+21	0	0	1440.6	26788.4	6.77E+21	5.63E+20
Hangzhou	0	1.60E+21	5.10E+22	0	4193.9	43928.7	2.01E+22	0
Guangzhou	0	3.89E+20	1.88E+23	0	0	0	2.61E+22	3.22E+22
Fuzhou	2.82E+21	1.29E+21	0	0	0	42121.8	3.38E+21	7.17E+20
Haikou	0	0	0	0	0	0	0	0
Hohhot	1.22E+21	1.58E+21	0	0	965.3	9796.3	4.83E+21	0
Ürümqi	7.49E+20	5.32E+20	0	0	2019.8	14438.9	8.27E+21	0
Dalian	0	0	0	0	0	0	0	0
Qingdao	2.24E+21	2.34E+21	0	0	1679.4	4112.0	8.6E+21	9.87E+21
Ningbo	1.18E+21	6.65E+20	0	0	1155.8	29642.8	7.67E+21	0
Shenzhen	0	0	0	0	0	0	0	1.93E+22
Suzhou	0	0	4.21E+22	0	2349.3	0	1.13E+22	0

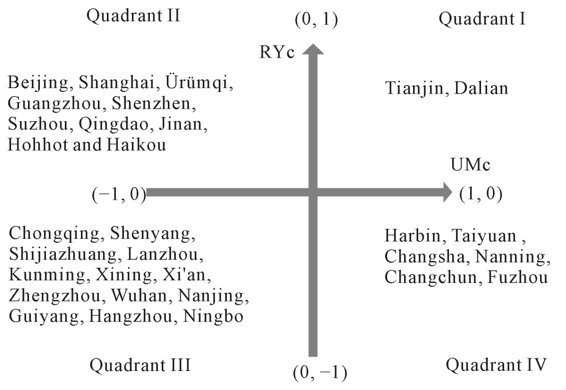

Fig. 10 Urban metabolic types of 31 sample cities. UMc: urban metabolic efficiency rate changes; RYc: aggregate urban metabolic yield rate changes

rate changes (RYc) from 2000 to 2010, respectively. The results of the ME model show that Tianjin and Dalian are located in Quadrant I with both positive urban metabolic efficiency rate changes and urban metabolic yield rate changes. It reflects that both cities were experiencing good growth trends in urban metabolism systems, which are preferred by urban regulators and managers. The level of waste emergy and energy consumption in cities of Quadrant I is the lowest in all kinds of urban metabolic cities, with better economic and social performances in GDP, GDP per capita, urbanization as well as acceleration of service sectors.

Beijing, Shanghai, Guangzhou, Shenzhen, Suzhou, Qingdao, Jinan, Hohhot and Haikou are in Quadrant II,

Table 5 Urban metabolic elasticities of 31 sample cities

Quadrant	City name	Aggregate UM change (Umc)	Aggregate RYR change (Ryc)	Quadrant	City name	Aggregate UM change (Umc)	Aggregate RYR change (Ryc)
I	Tianjin	0.183	0.930	III	Xining	–0.904	–0.318
I	Dalian	0.126	0.653	III	Xi'an	–0.859	–0.434
II	Beijing	0.206	–0.320	III	Zhengzhou	–1.000	–0.300
II	Shanghai	0.158	–1.000	III	Wuhan	0.907	–0.397
II	Guangzhou	0.311	–0.339	III	Nanjing	–0.861	–0.533
II	Shenzhen	0.158	–0.70	III	Guiyang	–0.853	–0.335
II	Suzhou	1.000	–0.90	III	Hangzhou	–0.860	–0.520
II	Qingdao	0.304	–0.452	III	Ningbo	–0.860	–0.583
II	Jinan	0.215	–0.436	III	Chongqing	–0.901	–0.297
II	Hohhot	0.955	–0.392	IV	Harbin	–0.930	0.765
II	Haikou	0.158	–0.437	IV	Taiyuan	–0.960	0.852
III	Ürümqi	0.236	–0.465	IV	Changsha	–0.934	0.804
III	Shenyang	–0.912	–0.450	IV	Nanning	–0.928	0.782
III	Shijiazhuang	–0.937	–0.30	IV	Changchun	–0.938	0.831
III	Lanzhou	–0.847	–0.332	IV	Fuzhou	–0.961	1.000
III	Kunming	–0.912	–0.453				

whose urban metabolic efficiencies have been improved since 2000, but with negative metabolic yield rate changes, indicating a substantial increase of exported and wasted emergy. Many metropolitan cities are in Quadrant II, including Beijing, Shanghai, Guangzhou, which are already moving into a postindustrial phase of development, characterized by service-oriented industry, most prominent economic outputs, high population density, as well as most waste emergy. A range of rapidly growing and highly specialized cities in ICT, tourism, manufacturing, trade, or transport logistics, like Haikou, Shenzhen, Suzhou, are also emerging in this type. It may be a better choice for these cities to assign more weight to endogenous economic development (more rely on resource and energy saving model) than exogenous economic development (more rely on exports and resource-consumption model).

Most of the cities, such as Chongqing, Nanjing, Shijiazhuang, Hangzhou, are currently located in Quadrant III, which were experiencing drastic urban metabolic efficiency decline accompanied with a moderate decrease of industrial outputs. A common feature of cities in Quadrant III is the lowest economic performance at the highest cost of energy consumptions. The average GDP in Quadrant III was only 3.31×10^{10} yuan in 2010. In contrast, energy consumption in ten thousand GDP of Quadrant III is 1.29 t/10^4 yuan. Cities in Quadrant III featured by resource-based industry are even less productive.

Cites in Quadrant IV (positive RYc change but negative UMc change) are also characterized by lagging behind in economic and urbanization growth. The urban metabolic improvement can only be achieved and sustained with a certain level of endogenous economic development as a foundation. Thus most cites currently located in this quadrant , such as Changsha, Changchun, Fuzhou, are more likely to move into I (positive UMc and RYc changes) after a prolonged period of endogenous economic development, rather than into II (positive UMc change but negative RYc change) (Rogers *et al.*,1997).

4 Discussion and Conclusions

The aim of this paper is to show a new methodology for assessing urban metabolic performances and identifying types based on emergy theory and SBM model by taking into account the undesirable outputs. Several key conclusions can be drawn from the model and its application in the case study: 1) metropolises and coastal cities have more emergy storage than inland cities, indicating that urban energy and materials consumptions are proportional to the urban development level. 2) Metropolises and special types of cities have better urban meta

Table 6 Development performances of different urban metabolic types of sample cities in 2010

Indicators (Average of sample cities)	Units	Quadrant I	Quadrant II	Quadrant III	Quadrant IV
Total renewable emergy (R′)	seJ	2.61E+21	2.07E+21	3.17E+21	3.94E+21
Total non-renewable emergy (N)	seJ	4.59E+23	2.89E+23	5.77E+23	5.2E+23
Waste emergy (W)	seJ	1.31E+22	1.39E+22	1.38E+22	8.81E+21
Gross domestic product (GDP)	10^8 yuan	7191.28	8261.75	3310.88	3719.16
Population	10^4	942.845	949.80	791.91	757.95
GDP per capita	Yuan per cap	79479.15	87168.42	44935.80	50824.78
Percentage of tertiary industry to GDP	%	58.10	57.24	54.18	45.64
Urbanization	%	58.28	55.45	42.86	35.08
Proportion of construction land to total land	%	4.63	12.88	2.84	2.99
Population density	persons/km^2	778.00	1654.11	543.84	534.42
Energy consumption in ten thousand GDP	t/per 10^4 yuan	0.77	0.78	1.29	0.82
Proportion of investments in industrial pollution control to GDP	%	0.14	0.18	0.65	0.23

bolic performances than other cities. The overall urban metabolic efficiencies of metropolises, such as Beijing, Shanghai, Guangzhou, Shenzhen, Suzhou, *etc*., have been improved since 2000, but also coming with a substantial increase of exported and wasted emergy. 3) Renewable resource slacks (S_R) have been found in most cities, while nonrenewable resource slacks (S_N) gathered in China′s middle and western cities, such as Chongqing, Xining, Zhengzhou, with substantial input slacks. Most cities need to increase desirable output values (S^g): GDP in 2000 and 2010. Undesirable output slacks (S^b) come from both China′s eastern metropolises and western industrial cities. 4) Most of China′s middle and western cities, such as Chongqing, were experiencing drastic urban metabolic efficiency decline, due to the high-speed industrial-oriented development. In contrast, China′s eastern metropolises witnessed a growth in urban metabolic efficiencies.

It is important that policy makers and stakeholders are given the urban metabolic models and indicators that could help to better design and manage the urban metabolisms of their cities (Kennedy *et al.*, 2007). Such an urban metabolic approach emphasizes the importance of the balance between the urban desirable outputs and inputs at the minimal costs of undesirable outputs. Thus such knowledge would stimulate related policies that enable to diversify the renewable supplies and boost urban emergy development while mitigating the undesirable output problems (Stratton *et al.*, 2011). To be specific, the first strategy that we recommend from this approach is to stimulate the industrial development of urban metabolisms in the renewable energy and resources by means of promoting and implementing new technologies and innovative products, considering the renewable input slacks in most sample cities. Second, since China′s middle and western inland cities (such as Xi′an, Chongqing and Xining) have lower metabolic efficiencies, characterized by resource-energy-oriented industrial development, widespread use of nonrenewable resource emergy in these cities will threaten climate and health because of dangerous emissions, leading to high social and economic costs. This will be the case if these cities simply continue with conventional approaches. Rather, these inland metabolisms should actively seek urban industrial restructuring path by diversifying the renewable industries and gradually phasing out polluting industries. Third, desirable and undesirable output slacks were found in both metropolises and industrial cities. It illustrates that improved technologies and management in clean production should be integrated in aiming for sustainable urban metabolic systems by minimizing waste and emissions and maximizing products. In particular, those middle and western cities with traditional industries should stimulate more clean production policies in mitigating the undesirable output treatment problems. Fourth, different types of urban metabolic policies need to be explicitly considered in urban programs for urban metabolic improvement. For example, metropolises with positive metabolic efficiency change but negative yield capacity change, should switch to renewable energy sources, instead of over reliance on the nonrenewable, imported and exported resources.

The urban metabolism model provides useful information for local urban management. However, such estimates do not consider spatial differences in urban metabolism systems as a result of differences in local land conditions. It is apparent that ecological footprints of different urban metabolisms are different from cities′ administrative areas. Thus more work needs to focus on the interpretation of ecological footprints of various urban metabolisms. Due to its significance to human beings, the research on the urban emergy flux of water and food should be a top priority for further research in a more specified and detailed way. Mechanisms of urban metabolic systems, and environmental feedback loops should also be investigated for governments and public to identify the prioritized actions that will make the urban metabolic systems more sustainable (Decker *et al*., 2000). The explicit results from this paper should also be used for further analysis of urban metabolic driving processes and assessment of the urban metabolic effects for different development scenarios.

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