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Emergy-based Ecological Economic Evaluation of Beijing Urban Ecosystem

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Abstract

This emergy-based urban economic account provided a historical portrait of the urban economy and its structures to understand the overload of the biosphere`s assimilative capacity. The basic situation of the urban economy, involving the indigenous resources base, emergy consumption patterns, emergy exports and imports, was investigated, accounted and discussed. Using a series of ratios and indices arising from emergy analysis, including emergy intensity, environmental load ratio and environmental sustainability, this paper analyzed the economic development in Beijing during the years of 1999 to 2006 and the heavy pressure it has put on the environment. Results showed that the development of economy in Beijing was closely correlated with the consumption of the non-renewable resources and it was exerting rising loads on the environment. Of the total emergy use by the economic system, the imported non-renewable resources from other provinces contributed most with increasing use from imported nonrenewable resources. Emergy intensity kept rising during the periods, with the increase of the environmental loads. The pressure of environmental protection, which was caused by the over-heated investments in Beijing, could be released after the completion of the infrastructure construction. On the whole, the results of this paper outlined a frame of reference towards how the urban metabolic analysis could drive the economic policies and sustainability.

Keywords: Urban metabolism; Emergy evaluation; Economy; Indicators

1. Introduction

As a city is one of the heterotrophic and self-regulating ecosystems in the biosphere, it is therefore important to understand the trends in its metabolism, where energy and materials are used as input and waste as output [1]. The metabolism approach is a powerful metaphor for the illustration of the processes in order to rebalance the social and environmental dimensions of sustainability. The knowledge of urban energy and material flows in comparison with those of natural flows is a major step towards the design of sustainable development schemes [2]. As a consequence,

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there is an urgent need to develop a quantitative evaluation methodology that can evaluate the adverse environmental effects of the urban metabolism and can also take into account how they affect the urban system's dynamics and sustainability.

Odum *et al*., [3,4] and his colleagues [5-7] developed emergy-based models for the quantification of socio-economic metabolism as an ecological system based on the analysis of resource inputs and waste release. Emergy synthesis provides a holistic alternative to many existing methods for urban study and environmentally conscious decision making and has been widely used in a series of combined systems of humanity and nature [8]. Till now, a large number of systems have been evaluated by means of the emergy method on regional and national scales [9-14]. Notwithstanding the advantages of emergy synthesis [15], it has also undergone many criticisms as any newly developed ideas. One major opposing point of view is if it is possible to "forecast" the future evolution of urban systems based on their interaction with surrounding environment, competition for available resources, and the mix and the quality of resources attracted from outside [16]. Therefore, the purpose of this study was to employ the Emergy Synthesis where empirical data from government sources and the latest information on transformities were used to update the emergy inputs supporting the economic activities in Beijing from 1999 to 2006, related to the city´s structure, function and organization during its development phases responding to human activities and environmental changes associated.

2. Emergy-based urban metabolic model

A typical diagram describing an urban system is shown in Figure 1, where the energy system symbols are used [17]. At the planetary level of organization, there are no substantial exchanges with the larger system except for solar and gravitational energy entering the system from external sources. Figure 1 shows the inputs and internal structures of Beijing that were quantified in this study. We evaluated the emergy inputs supporting the economic activities of urban system and compared the emergy inflows to measures of economic activity in Beijing. The following eight major classes of emergy inputs supporting Beijing urban system from 1999 to 2006 were documented: (1) renewable energy sources, (2) soil erosion, (3) energy consumption, (4) minerals consumed, (5) imported goods other than fuels and minerals, (6) imported services in goods, fuels and minerals, (7) imported services, and (8) immigrants. Here, imported fuels, minerals, goods and services are divided into two parts, which respectively refer to the ones imported from other provinces and those from other countries. The emergy of any product or service can be quantified by obtaining data on the available energy or mass of the product or service and then multiplying this value by the appropriate emergy per unit value, i.e., the transformities (seJ/J) for energy or the specific emergy (seJ/g) for mass. Emergy analyses are carried out using transformities, specific emergies and other factors that are determined relative to a particular planetary baseline [18]. In this study, transformities were converted from global emergy baseline of 9.44E+24 to 15.83E+24 seJ/yr recommended by Ulgiati and Brown [18].

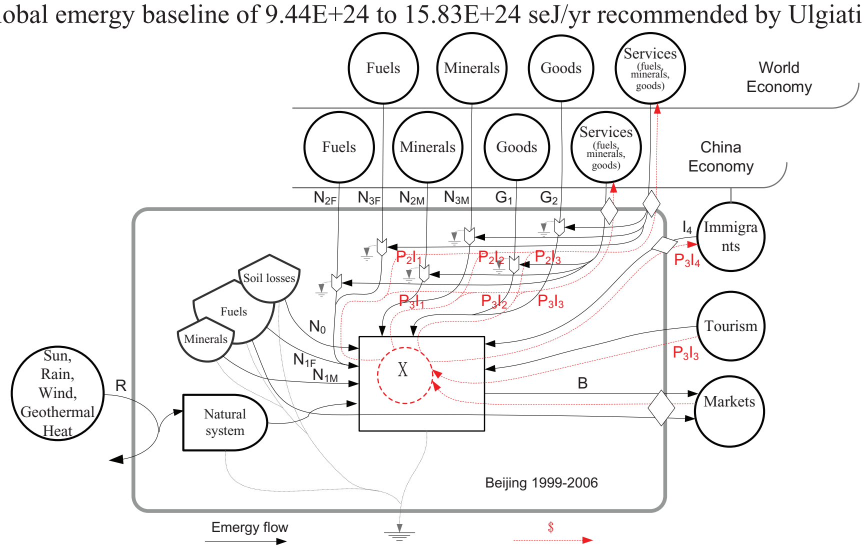

Fig. 1. Summary flow diagram for the main emergy flows in Beijing

3. Ecological economic account of Beijing urban ecosystem

3.1. Characteristics of the environment and economy in Beijing

Beijing, capital of China, is located in the northern part of the North China Plain. It lies at longitudes between 115º25´E and 117º30´E and latitudes between 39º26´N and 41º03´N, covering an area of 16,807 square kilometers Situated at the eastern edge of the Eurasian continent and belonging to the Bohai sea rim economic circle, the city has small plain in the south and mountains in the west and north. Characterized by its long history and central political and cultural position, Beijing is amongst the most developed cities in China with a fully integrated industrial structure, including electronics, machinery, chemicals, light industry, textile and automobile manufacturing. Like other metropolises in developing countries, Beijing faces the dilemma of urban economic development versus social and ecological problems comprising the large floating population, high-yield agricultural land lost, resources shortage, high levels of pollution, ecological deterioration, and increasing disaster risk. The evolution of the Beijing urban system can be treated as a history of resource consumption and accumulation, which in turn bring about the changes in the urban structure and organization. As mentioned above, most of these intensive resources consumed in Beijing are purchased from outside with the exception of a small proportion of fuels and minerals. Also, all the flows of resources are accompanied with human services and money flows.

3.2. Ecological economic analysis of Beijing ecosystem

In accordance with the system picture of Beijing and the consequent calculations, main flows introduced to the Beijing urban metabolic system for the studied years are summarized in Table 1.

Table 1. Comparison of main emergy indexes and flows

Variable	Item	Unit	1999	2000	2001	2002	2003	2004	2005	2006
sic flow										
R	Renewable sources	seJ/yr	1.05E+21	1.05E+21	1.05E+21	1.05E+21	1.03E+21	1.03E+21	1.03E+21	1.03E+21
$_{0}+N_{1F}+N_{1M}$	Locally nonrenewable resources	seJ/yr	6.25E+22	5.65E+22	5.66E+22	6.48E+22	6.91E+22	8.34E+22	8.60E+22	8.04E+22
$N_{2F}+N_{2M}$	Imported fuels and minerals (from other provinces)	seJ/yr	9.58E+22	1.04E+23	1.07E+23	1.07E+23	1.13E+23	1.25E+23	1.38E+23	1.45E+23
$N_{3F}+N_{3M}$	Imported fuels and minerals (from other countries)	seJ/yr	3.82E+20	0.00E+00	0.00E+00	2.28E+20	1.60E+21	5.95E+21	6.30E+21	7.19E+21
G_1	Imported goods (from other provinces)	seJ/yr	3.30E+22	4.69E+22	5.63E+22	6.71E+22	7.66E+22	9.54E+22	1.09E+23	1.19E+23
G_2	Imported goods (from other countries)	seJ/yr	1.90E+22	2.76E+22	3.05E+22	3.39E+22	4.44E+22	5.56E+22	6.37E+22	6.95E+22
$_{11}+I_{12}+I_{13}$	Dollars paid for imports goods (from other provinces)	$/yr	8.94E+09	1.28E+10	1.36E+10	1.50E+10	2.00E+10	2.44E+10	3.01E+10	3.61E+10
$_{21}+I_{22}+I_{23}$	Dollars paid for imports goods (from other countries)	seJ/yr	5.15E+09	7.55E+09	7.37E+09	7.60E+09	1.16E+10	1.42E+10	1.75E+10	2.10E+10
I_3	Dollars for tourism	$/yr	8.91E+09	1.10E+10	1.37E+10	1.43E+10	1.04E+10	1.70E+10	1.95E+10	2.30E+10
I_4	Dollars paid for imported labor	$/yr	1.32E+08	1.89E+08	2.58E+08	2.88E+08	3.74E+08	4.67E+08	7.30E+08	7.30E+08

$(I_{11}+I_{12}+I_{13})$	Emergy value of imported services (from other provinces)	seJ/yr	3.20E+22	4.59E+22	4.95E+22	5.56E+22	7.16E+22	8.72E+22	1.07E+23	1.29E+23
$(I_{21}+I_{22}+I_{23})$	Emergy value of imported services (from other countries)	seJ/yr	1.85E+22	2.69E+22	2.68E+22	2.81E+22	4.14E+22	5.08E+22	6.25E+22	7.51E+22
P_3I_2	Emergy value for tourism	seJ/yr	4.46E+22	5.52E+22	6.85E+22	7.17E+22	5.21E+22	8.50E+22	9.74E+22	1.15E+23
P_3I_3	Emergy paid for imported labor	seJ/yr	6.62E+20	9.43E+20	1.29E+21	1.44E+21	1.87E+21	2.33E+21	3.65E+21	3.65E+21
oducts considered										
POP	People supported	Unit	1.26E+07	1.36E+07	1.38E+07	1.42E+07	1.46E+07	1.49E+07	1.54E+07	1.58E+07
GDP	Gross domestic product	\$/yr	2.63E+10	3.00E+10	3.45E+10	3.88E+10	4.43E+10	5.17E+10	8.41E+10	1.01E+11
rformance indicators										
U	Total emergy used $U=R+N_{2F}+N_{2M}+N_{3F}+N_{3M}+G_1+G_2+P_3(I_{11}+I_{12}+I_{13})+P_2(I_{21}+I_{22}+I_{23})+P_3I_2+P_3I_3+N_0+N_{1F}+N_{1M}$	seJ/yr	3.11E+23	3.68E+23	4.01E+23	4.30E+23	4.77E+23	5.96E+23	6.81E+23	7.53E+23
ED	Empower density ED=U/area	seJ/m^2	1.85E+13	2.19E+13	2.39E+13	2.56E+13	2.91E+13	3.63E+13	4.15E+13	4.59E+13
U/POP	Use per person	seJ/ population	2.47E+16	2.71E+16	2.90E+16	3.02E+16	3.27E+16	4.00E+16	4.43E+16	4.76E+16
ELR	Environmental loading ratio $ELR=(N_{2F}+N_{2M}+N_{3F}+N_{3M}+G_1+G_2+P_3(I_{11}+I_{12}+I_{13})+P_2(I_{21}+I_{22}+I_{23})+P_3I_2+P_3I_3+N_0+N_{1F}+N_{1M})/R$		2.94E+02	3.48E+02	3.79E+02	4.07E+02	4.62E+02	5.78E+02	6.61E+02	7.31E+02
EYR	Net emergy yield ratio $EYR=U/(N_{2F}+N_{2M}+N_{3F}+N_{3M}+G_1+G_2+P_3(I_{11}+I_{12}+I_{13})+P_2(I_{21}+I_{22}+I_{23})+P_3I_2+P_3I_3)$		1.26E+00	1.19E+00	1.17E+00	1.18E+00	1.17E+00	1.16E+00	1.15E+00	1.12E+00
ESI	Environmental sustainability index ESI=EYR/ELR		4.28E-03	3.40E-03	3.08E-03	2.90E-03	2.54E-03	2.01E-03	1.73E-03	1.53E-03

3.2.1 Basic flow analysis of Beijing ecosystem

(1) Emergy inflows in Beijing metabolic system

Since 1999, Beijing has adhered to the policy of reform and opening-up, with the focus on economic construction. With the rapid development of processing, manufacture and trade, it has gradually stepped onto the road of establishing a market-oriented economy system. As a result, the consumption of energy, material and labor has increased correspondingly. The total emergy actually used (U), as potential investment in emergy yield of the city, has increased at an annual average rate of 19.88% with a peak in 2004 (25.11%).

Table 1 lists the main imported inputs in terms of emergy flows for 2006 in Beijing. The total imports increased from 1.51E+23 to 3.49E+23 seJ/yr. Of the total imported resources, fuels grew by 1.52 times with emergy rising from 8.84E+22 to 1.35E+23 seJ/yr, while the total imported building materials (including iron ores, sand and gravel, iron and steel) increased by 3.92 times from 4.32E+22 to 1.70E+23 seJ/yr. This indicates that the development of Beijing's economy is increasingly dependent on the infrastructure construction, which even replaced fuel-consuming industry for nearly a decade. In emergy to money terms, imported goods have become the most important item in this category. Among the export emergy flows could be highlighted petroleum derived products, minerals and mechanical and transport equipment. As shown in the table, the services associated to imports in Beijing were 2.04E+23 seJ/yr in 2006, 4.04 times of that in 1999. This increase in import results in decreased self-sufficiency, so the purchased component of the total economy was more important, supporting the growth of the economy. The services imported from other provinces were 7.6 times of those from abroad, indicating that the imports of Beijing were still increasingly dependent upon the transmission of domestic market. And it's worth mentioning that, in emergy to money terms, the tourism and emergy paid for imported labor are increasing strongly, more than 2.58 and 5.52 times respectively.

(2) The components of the energy consumed in Beijing metabolic system

From 1999 to 2006, coal was still the most important energy source for Beijing as measured by both heat content and emergy. The coal input decreased in 2000, but this was followed by a rapid rebound over the next three years when Beijing won the bid to stage the 2008 Olympiad. Meanwhile, the consumption of petroleum from other province steadily decreased; however, the imported oil increased along with the coal consumption in these ten years. Imported electricity constitutes a large fraction of the total emergy use (11% to 13%) that grew fast from 1999 to 2006. During the decade, exported electricity in these years remained low. Natural gas also became the fourth largest energy source. The consumption of natural gas showed a similar trend to the imported electricity, but with a damped response to fluctuations.

(3) Mineral use in Beijing metabolic system

The emergy of iron and steel made the largest contribution to the emergy of minerals consumed followed by the emergy of lead up to 1999, when it was overtaken by the emergy of sand and gravel for construction. When we make a comparison between sand and gravel, Hi-tech products, machinery and electrical equipment, we note that they have increased largely from 1999 to 2006 and it consistently occupied the 3rd position in terms of emergy input after the labour and service.

3.2.2 Analysis of the emergy indicators for Beijing

In this section, a series of emergy indicators based on the emergy accounting for Beijing economy are analyzed, which lends insight to the emergy support basis, the environmental impacts and the characteristics of the Beijing economy.

(1) Emergy intensity

Empower density or the emergy flow per unit area is a related measure that indicates the spatial concentration of economic activity or the intensity of development in a city. As shown in Table 1, the empower density of the Beijing economy developed from 1.85E+13 seJ/m^2 in 1999 to 4.59E+13 seJ/m^2 in 2006, revealing that during the past few years, Beijing has maintained a rapid economic growth and scored a new high in economic aggregates. Accounting shows that this growth is mainly caused by the input from goods and services, which holds relatively high emergy transformity. Combined with the emergy use structure and the value of emergy use per person in Beijing, we will find that of the total resource consumed in Beijing, most are correlated with goods and services purchased from outside, with little from free natural input. It also means that the development both in living standard of local residents and in urban economy depends completely on the purchase of resources from outside.

(2) Environmental impacts

The Environmental Loading Ratio (ELR) is the ratio of the sum of local nonrenewable emergy and purchased emergy (including services) to the locally renewable emergy. A system with a higher ratio depends more heavily on indirect resources, compared to a fully natural system that only depends on locally renewables R. This ratio increased rapidly from 294 in 1999 to 731 in 2006. The higher the ratio, the greater the stress on the local environmental resources. However, Table 1 also shows there appeared a steady state after the year 2001. The small decline in 2006 might be attributed to an oscillation of the growth trend and cannot be interpreted until new data for the following years are available.

(3) Environmental sustainability index

This index is an aggregate measure of the economic benefit (EYR) per unit of environmental loading (ELR). It shows that the long-term capacity of the renewable emergy sources to support life is being degraded. A quick estimate of the renewable carrying capacity of a state at the current standard of living is obtained by multiplying the fraction of use that is renewable by the present population of the state [17]. As a consequence of EYR and ELR trends, the sustainability index ESI dropped significantly, thus suggesting that emissions greatly reduced the sustainability of the urban metabolic system by pulling resources for damage repair and for replacement of lost natural and human-made capital.

4. Conclusion

This research investigated the Beijing urban ecosystem based on an Emergy synthesis. Detailed structure of the resource base and system indicators are examined from a historical perspective for the contemporary Beijing urban system from 1999 to 2006. Our results showed that there was an intimate relationship between the resource base and economic structure. During the eight years, the emergy intensity in Beijing kept rising for the sustained investment of real wealth, which not only brought about the growth of living standard in many aspects, but also resulted in the increase of the environmental loads. Also, the increase of emergy investment ratio implicated that Beijing was at the risk of resources shortage and increasingly relied on the resources from outside, which was a hidden peril for the sustainable development of Beijing. Furthermore, the pressure of environmental protection, which was caused by over-heated investment in Beijing, could be released after the completion of the infrastructure construction. In conclusion, the results offered a reference towards the urban metabolic analysis driving economic policy and sustainability.

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