Emergy-based Ecological Economic Evaluation of Beijing Urban Ecosystem

Geng-Yuan Liu, Zhi-Feng Yang*, Bin Chen

State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China

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, were 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 explained the level of economic development and environmental pressure of the Beijing economy during 1999 to 2006. Results showed that the development of economy in Beijing was closely correlated with the consumption of the nonrenewable resources and exerting rising load on environment. Of the total emergy use by the economic system, the imported nonrenewable resources from other province contribute most with increasing use from imported nonrenewable resources. Emergy intensity kept rising during the periods, with the increasing of environmental load. The pressure of environmental protect which was caused by over-heated investment in Beijing could be released after finishing the infrastructure construction. The results offer a reference towards the urban metabolic analysis driving economic policy 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 trends in its metabolism, where energy and materials are used as input and waste as output (Odum, 1989). 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 with comparison to those of natural flows is a major step towards the design of sustainable development schemes (Sachs, 2005). As a consequence, there is an urgent need to develop a quantitative methodology that can evaluate the adverse environmental effects of urban metabolism and taking into account how they affect the urban system's dynamics and sustainability.

* Corresponding author: Tel.:+86 10 58807951; fax: +86 10 58800397.
E-mail address: zfyang@bnu.edu.cn (Zhi-Feng Yang).

Odum et al., (1983, 1995) and his colleagues (Brown and Ulgiati, 2001; Campbell et al., 2005; Huang and Chen, 2005) developed emergy-based models for the quantification of socio-economical 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 (Brown and Ulgiati, 2004). Till now, a large number of systems have been evaluated by means of the emergy method on regional and national scales (Brown and Odum, 1992; Yan and Odum, 1998; Lan and Odum, 2004; Jiang et al., 2007; Ulgiati et al., 2007; Chen et al., 2009; Liu et al., 2010). Notwithstanding the advantages of emergy synthesis (Herendeen, 2004), it has also undergone many critics as any newly developed ideas. One point of discussions 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 (Bastianoni et al., 2004). One purpose of this study was to employ the Emergy Synthesis where empirical data from government sources and the latest information on trasnformities where used to update the emergy inputs supporting 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 (Odum, 1996). 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 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 imported from other provinces and 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 (Ulgiati and Brown, 1998). 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 (2002).

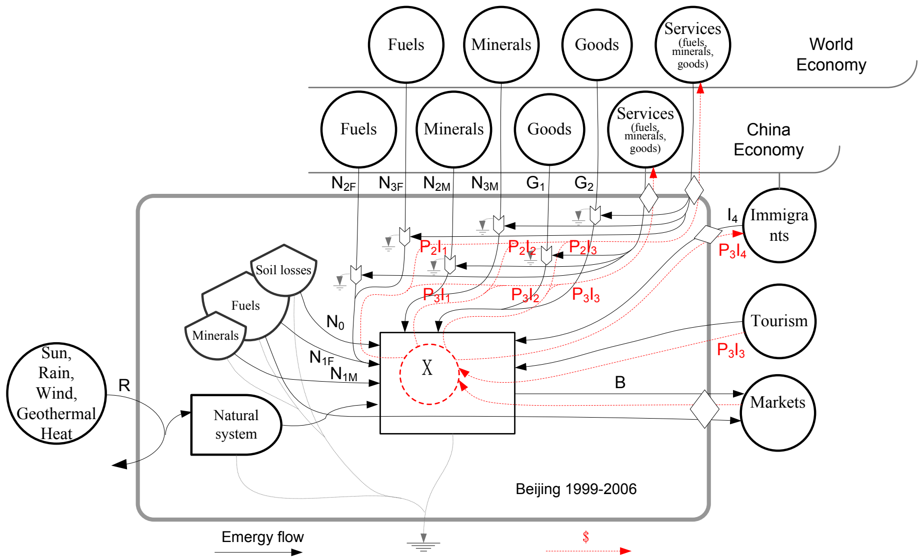

Figure 1 Summary flow diagram for the main emergy flows in Beijing

3. Ecological economic account of Beijing urban ecosystem

3.1 Characteristics of the environment and economy in Beijing

Beijing, which is located in North China, lies between longitudes 115º25´E and 117º30´E and between latitudes 39º26´N and 41º03´N. Beijing is located at the eastern edge of the Eurasian continent and belongs to the Bohai sea rim economic circle, with small plain in the south and mountains in the west and north, covering an area of 16807.8 km2. 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 brought 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
Basic 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
$N_0+N_{1F}+N_{1M}$	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
$I_{11}+I_{12}+I_{13}$	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
$I_{21}+I_{22}+I_{23}$	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
$P_3(I_{11}+I_{12}+I_{13})$	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
$P_2(I_{21}+I_{22}+I_{23})$	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
Products 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
Performance 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

3.2.2.1 Emergy inflows in Beijing metabolic system

Since 1999, Beijing as the capital of China has adhered to the policy of reform and opening-up, with the focus on economic construction, and has gradually stepped onto the road of establishing a market-oriented economy system with the rapid development of processing, manufacture and trade. As a result, the consumption of energy, material and labors has increased correspondingly. Total emergy actually used (U), as potential investment in emergy yield of the city, has increased with an average of 19.88% annually 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 that from abroad, indicating that the imports of Beijing were still upward dependence upon the transmission of domestic market. And it's worth to mention 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.

3.2.2.2 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 was decrease 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 increase along with coal consumption in these ten years. Imported electricity is 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 becomes the fourth largest energy source. The consumption of natural gas showed a similar trend that imported electricity, but with a damped response to fluctuations.

3.2.2.3 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 position of the 3th largest emergy input after consider 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 characters of the Beijing economy.

3.2.3.1 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 1.85×1013 seJ/m2 in 1999 to 4.59×1013 seJ/m2 in 2006, revealing that during the past years, Beijing maintained a rapid economic growth and scored a new high in economic aggregates. Accounting shows that this growth mainly caused by the input from goods and services which hold 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 depend completely on the purchase of resources from outside.

3.2.3.2 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 resource. However, table 2 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.

3.2.3.3 Environmental sustainability index

This index is an aggregate measure of the economic benefit (EYR) per unit of environmental loading (ELR). It shows that the longterm 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 (Odum 1996). 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 in a historical perspective for the contemporary Beijing urban system from 1999 to 2006. Conclusion shows that there is 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 brought the growth of living standard in many aspects, but also resulted in the increase of environmental load. 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 is a hidden peril for the sustainable development of Beijing. Furthermore, the pressure of environmental protect which was caused by over-heated investment in Beijing could be released after finishing the infrastructure construction. The results offer a reference towards the urban metabolic analysis driving economic policy and sustainability.

ACKNOWLEDGE

This work is supported by the National Natural Science Foundation of China (Grant No. 40871056), National Basic Research Program of China (973 Program, Grant No. 2005CB724204 and 2006CB403303) and National Science Foundation for Distinguished Young Scholars (Grant No. 50625926).

REFERENCES

Bastianoni, S., Nielsen, S.N., Marchettini, N., Jøgensen S.E., Use of thermodynamic functions for expressing some relevant aspects of sustainability. *International Journal of Energy Resource*. 29, 53-64, 2004.

Brown, M.T., Odum, H.T., *Emergy synthesis perspectives, sustainable development and public policy options for Papua New Guinea*. In: A Research Report to the Cousteau Society. Gainsville, FL: Center for wetlands, University of Florida, pp. 111–124, 1992.

Brown, M., Ulgiati, S., Emergy measures of carrying capacity to evaluate economic investment. *Population and Environment*. 22, 471-501, 2001.

Brown, M., Ulgiati, S., Emergy analysis and environmental accounting. *Encyclopedia of Energy*. 2, 1-25, 2004.

Campbell, D.E., Brandt-Williams, S.L., Meisch, M.E.A., Environmental Accounting Using Emergy: Evaluation of the State of West Virginia. *USEPA*, Narragansett, RI, 2005.

Herendeen, R., Energy analysis and EMERGY analysis - a comparison. *Ecological Modelling*. 178, 227-237, 2004.

Huang, S.L., Chen, C.W., Theory of urban energetics and mechanisms of urban development. *Ecological Modelling*. 189, 49-71, 2005.

Jiang, M.M., Chen, B., Zhou, J.B., Tao, F.R., Li, R., Yang, Z.F., Chen, G.Q., Emergy account for biomass resource exploitation by agriculture in China. *Energy Policy*. 35(9), 4704-4719, 2007.

Lan, S.F., Odum, H.T., Emergy evaluation of the environment and economy of Hong Kong. *Journal of Environmental Science*. 6(4), 432-439, 2004.

Liu, G.Y., Yang, Z.F., Chen, B., Ulgiati, S., Emergy-based urban health evaluation and development pattern analysis. *Ecological Modelling*. 220(18), 2291–2301, 2009.

Odum, H.T., *Systems ecology*. New York: John Wiley and Sons, 1983.

Odum, H.T., *Ecological engineering and self-organization*. In: Mitsch and Jorgensen. (eds). Ecological engineering - An introduction to ecotechnology, John Wiley & Sons, 1989.

Odum, H.T., *Self-organization and maximum power*. In: Hall, C. (ed) Maximum Power. The ideas and applications of H.T. Odum. University Press, 1995.

Odum, H.T., *Environmental accounting: EMERGY and environmental decision making*. John Wiley & Sons, New York, pp. 370, 1996.

Sachs J. *Investing in development: a practical plan to achieve the Millennium Development Goals*. UN Millennium Project. London, UK: Earthscan, 2005.

Ulgiati, S., Brown, M., Assessing resource quality by means of emergy accounting techniques: Transformities as quality indicators. *Emergy Policy*, 1998.

Ulgiati, S., Brown, M.T. Quantifying the environmental support for dilution and abatement of process emissions: The case of electricity production. *Journal of Clean Production*. 10, 335–348, 2002.

Ulgiati, S., Bargigli, S., Raugei, M., An emergy evaluation of complexity, information and technology, towards maximum power and zero emissions. *Journal of Clean Production*. 15(13-14), 1354-1372, 2007.

Yan, M.C., Odum, H.T., A study on emergy evaluation and sustainable development of Tibet eco-economic system. *Journal of Natural Resources*. 13(2), 116-125, 1998 (in Chinese).