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Limiting Factor Analysis of Urban Ecosystems based on Emergy—A Case Study of three cities in the Pearl River Delta in China

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Abstract: The development of urban ecosystems is usually restricted by a few key limiting factors, including both the natural resource condition and the socioeconomic performance. To link the natural, economic and social subsystems together and uniformly measure the multiple ecological flows within and amongst these subsystems, emergy analysis was applied in this paper to describe the status quo of urban ecosystems in terms of energy and materials metabolism. Three typical cities, namely Guangzhou, Shenzhen and Zhuhai all in the Pearl River Delta urban cluster in China, are chosen as the cases, regarding the urban cluster as an important developmental pattern and trend of urban ecosystems. Using the data in 2005, an emergy-based analysis was conducted for the three cities from aspects of emergy structure, emergy intensity, emergy welfare, environmental pressure and ecologic economic interface. Based on the comparative results, the limiting factors of these urban ecosystems were further analyzed. This paper presents a meaningful comparison among different urban ecosystems in the same region, and provides a useful framework for urban ecological management based on limiting factors analysis of urban ecosystems.

Keywords: urban ecosystem; limiting factor; emergy; the Pearl River Delta

1 INTRODUCTION

Facing with more and more huge systems and emerging complicated problems, that sort of method in systematic view is required, so as to understand the systems' performance, diagnose their status quo, find out the key points and give suggestion to optimize the systems' structure and function. Composed of multiple interactive factors and plays various roles in socio-economic development, urban ecosystem is known as a typical complex system, for which the systematic analysis method is indeed necessary. Based on this consideration as well as the focus on the energy and climate change issues, the emergy synthesis, a well-suited integrated ecological economic evaluation method grounded in energetics and systems ecology which can measure different energy and materials flows on the same criteria (Odum, 1996; Ulgiati et al., 1998), is applied in this paper to assess urban ecosystems systematically, like a comprehensive physical examination for human beings. Based on the systematic evaluation, the limiting factors of urban healthy development can be revealed and corresponding regulation scheme can be put forward. As a useful tool for ecosystem accounting and evaluation, except for the theoretical discussion (Brown et al., 2002; Huang et al., 2005; Li et al., 2010; Lu et al., 2003; Odum, 1988; Ulgiati et al., 2009), emery synthesis has also been introduced into case studies on socio-economic metabolism of many urban ecosystems in different countries (Ascione et al., 2009; Huang et al., 2007; Jiang et al., 2009; Lan et al., 1994; Lei et al., 2008; Liu et al., 2009; Su et al., 2009; Whitfield, 1994; Zhang et al., 2009), which is of great value for urban ecosystem assessment and diagnosis.

As an important trend of urban ecosystems' developmental pattern, urban clusters (also named urban agglomerations) becomes more and more attractive around the world, which link many cities in a certain natural geographical area by societal, economic and cultural

communication. Emergy analysis has also been conducted on urban clusters and other closely-related regions, e.g., the Oak Openings region in USA (Higgins, 2003), the Jing-Jin-Tang urban clusters (Cai et al., 2009) and the Yellow River basin (Chen et al., 2009) in China, and a coastal resort region in Italy (Vassallo et al., 2009). The Pearl River Delta urban cluster is regarded as an important pioneer for the national economic development in the past several decades. In this paper, this urban cluster located in the southeast of China is chosen as the study site. Since it is difficult to collect the emergy data on the whole urban cluster scale, three cities namely Guangzhou, Shenzhen and Zhuhai within the urban cluster, are selected as the concrete cases to represent the biophysical situations of the Pearl River Delta urban cluster. Through a comparison analysis amongst cities within the same urban cluster, which share similar local resources, it may be hopeful to discover the limiting factors of different urban ecosystems more easily.

In this paper, emergy analysis is used to integrate various energy and materials flows in the urban ecosystem and organize suitable indicators to assess the urban ecosystem, followed by the ecologic economic analysis of three urban ecosystems in the Pearl River Delta urban cluster from aspects of emergy structure, emergy intensity, emergy welfare, environmental pressure and ecologic economic interface. According to the basic results, the limiting factors of these urban ecosystems are further discussed, from which some regulatory measures for advancing urban ecosystem development are suggested.

2 METHODOLOGY

2.1 Study Site

Located at Guangdong Province in southeast of China, the Pearl River Delta urban cluster covers nine cities in Guangdong and the two adjacent special administrative regions namely Hong Kong and Macao, with a total area of more than 40 000 km². Attributing to the national policy of reform and opening, the Pearl River Delta urban cluster developed relatively early and fast in China, so that the regional GDP increased from eight billion dollars in 1980 to 232 billion dollars in 2005. It has grown as the economic and financial center of south of China, and will continuously play important roles in the future economic development in China¹. In this paper, three famous and typical cities including Guangzhou, Shenzhen and Zhuhai are chosen as the cases to represent the situation of the Pearl River Delta urban cluster in terms of energy and materials metabolism, based on which the urban ecosystem development can be evaluated and diagnosed comprehensively in view of systems ecology perspective. The general introduction of three cities is shown in Table 1.

Table 1. General situations of Guangzhou, Shenzhen and Zhuhai in 2005

Items	Guangzhou	Shenzhen	Zhuhai
Area (km ²)	7434	1953	1688
Population density (pop/km ²)	1010	931	531
Per capita GDP (\$)	6562	7415	5522
Proportion of information industry to GDP (%)	57.8	46.6	43.5
Per capita water resource (m ³)	1139	313	811
Green coverage in built-up area (%)	36.2	33.6	45
Energy consumption per unit GDP (tce/10 ⁴ \$)	6.4	7.3	7.0

2.2 Emergy Synthesis

With the great effort of researchers like Odum, emergy synthesis has developed into a

¹ <http://business.sohu.com/47/79/article206657947.shtml>.

mature theoretical system in the past several decades. According to the basic procedure of emergy synthesis, the systematic emergy analysis for three urban ecosystems can be generalized into five steps as follows: (1) Confirming the urban ecosystem boundary and collecting related data of three cities, e.g., the natural resources condition, economic flows, the basic information of agriculture, industry, import, export, energy and materials consumption, and waste emission; (2) Drawing the emergy system diagram to describe the energy and materials flows within and amongst each subsystem, based on the collected data; (3) Establishing the emergy accounting table to summarize major resources and economic flows in each urban ecosystem; (4) Setting up suitable emergy-based indicators (see Table 2) and calculating their values in each urban ecosystem; and (5) Result analysis for three urban ecosystems.

Table 2. Emergy-based indicators for urban ecosystem evaluation

Factors	Indicator	Expression
Emergy source	Emergy self-sufficiency	$(R+N_0+N_1)/U$
	Fraction of locally renewable emergy used	R/U
	Fraction of locally non-renewable emergy used	$(N_0+N_1)/U$
	Fraction of purchased emergy used	$(F+G+P_2I_3)/U$
	Ratio of import to indigenous emergy	$(F+G+P_2I_3)/(R+N_0+N_1)$
	Emergy diversity index	$-\sum(\frac{U_i}{U}) \times \ln(\frac{U_i}{U})$
Emergy intensity	Emergy density	U/area
	Ratio of concentrated to rural use	$(F+G+P_2I_3+N_1)/(R+N_0)$
Emergy welfare	Per capita emergy used	U/Pop
	Per capita fuel emergy used	Fuel/Pop
	Ratio of electricity emergy used	e/U
	Carrying capacity density based on renewable emergy	$(R \times \text{Pop})/(U \times \text{area})$
Environmental load	Ratio of waste to renewable emergy	W/R
	Ratio of waste to total emergy used	W/U
Ecological economic interface	Emdollar ratio	U/GDP
	Emergy investment ratio	$(F+G+P_2I_3+N_0+N_1)/R$
	Ratio of export to import	$(N_2+B+P_1E_3)/(F+G+P_2I_3)$

R: renewable energy flow; N: indigenous non-renewable flows; N_0 : dispersal rural (e.g. soil loss); N_1 : concentrated use (e.g. hydroelectricity); N_2 : exported of raw materials; F: imported fuel; G: imported goods; I_3 : dollars paid for imported service; B: exported products; E_3 : dollars received for exported service; P_2 : world emdollar ratio; P_1 : emdollar ratio; U: total emergy used ($U=R+N_0+N_1+F+G+P_2I_3$, U_i respectively denotes each component of U); W: waste; Fuel: fuel used; e: electricity used; GDP: gross domestic products; Pop: population.

3 RESULTLS

After collecting data and implementing the emergy synthesis procedure, the final results of urban ecosystem evaluation are obtained, which is described from five basic aspects of emergy analysis, i.e., emergy source, emergy intensity, emergy welfare, environmental load, and ecological economic interface.

3.1 Emergy Source

The emergy source situations of the three cities are analyzed from three aspects based on six indicators, including accounting the emergy source from two kinds of inputs, i.e., self-sufficiency (renewable energy, dispersal rural non-renewable energy, and

concentrated used non-renewable energy) and purchase (imported fuel, imported goods, and imported service) (see Figure 1a), further dividing the indigenous resources into two parts, i.e., locally renewable and non-renewable energy (see Figure 1b), and measuring the energy source structure by the indicator ‘Ratio of import to indigenous energy’ and calculating the emergy diversity index (see Figure 1c).

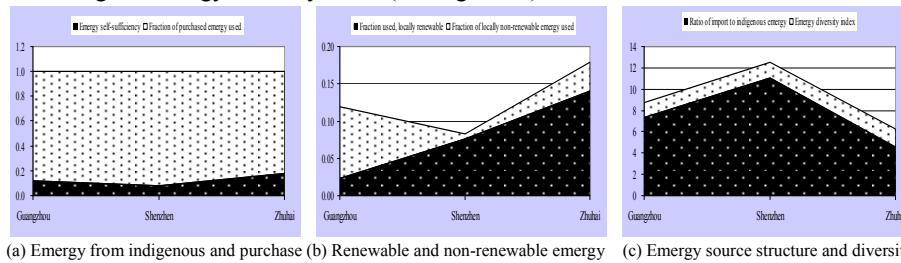


Figure 1. Situations of emergy source indicators for three urban ecosystems

It is indicated in Figure 1 that, the emergy self-sufficiency of the three cities ranges from 0.08 to 0.18, amongst which Zhuhai is on the highest self-sufficiency level while Shenzhen on the lowest level. Correspondingly, fraction of purchased emergy accounts for the biggest portion for Shenzhen and smallest for Zhuhai city. As for the self-sufficient emergy, the ratios of renewable part to the non-renewable part are about eight and four in Shenzhen and Zhuhai respectively, while the non-renewable part is three times more than the renewable part in Guangzhou. In view of the indicator ‘Ratio of import to indigenous emergy’, Zhuhai has the lowest value of 4.6 while Shenzhen has the highest value of 11.1. Regarding the emergy diversity index, the situations of the three cities are similar with each other when their values fluctuate between 1.39 and 1.65.

3.2 Emergy Intensity

The situations of emergy intensity for the three cities are described from two aspects, through indicators of ‘Ratio of concentrated to rural use’ and ‘Emergy density’. As shown in Figure 2, Guangzhou uses the resources with the most concentrated degree while Zhuhai uses the resources with the least concentrated degree, while Shenzhen has the highest emergy density which is nearly three times of that of Zhuhai city.

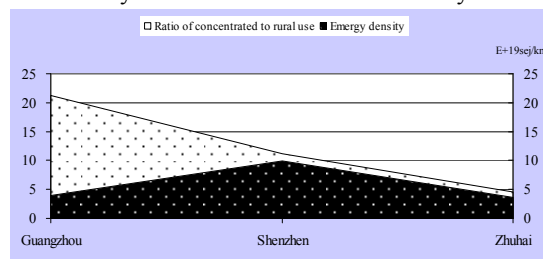


Figure 2. Situations of emergy intensity indicators for three urban ecosystems

3.3 Emergy Welfare

The emergy welfare is represented by four indicators, including ‘Per capita emergy used’, ‘Per capita fuel emergy used’, ‘Carrying capacity density based on renewable emergy’, and ‘Ratio of electricity emergy used’. The former two indicators can denote the welfare with respect to the per capita emergy quantity (Figure 3a), while the latter twos with respect to the economic development level and the sustainable carrying capacity based on local resources (Figure 3b).

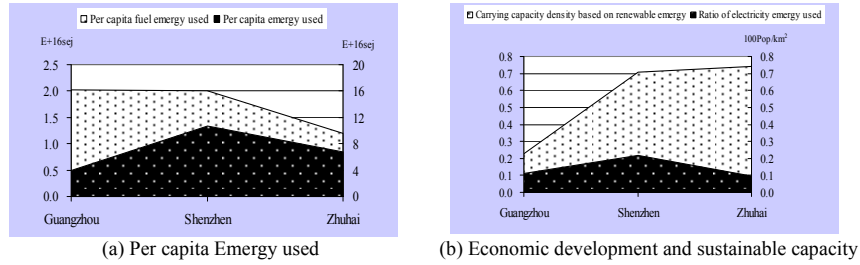


Figure 3. Situations of energy welfare indicators for three urban ecosystems

For per capita total energy used, the value of Shenzhen city is on the top while that of Guangzhou city is at the bottom. But in terms of per capita fuel energy used, the value of Guangzhou city reaches the highest level while that of Zhuhai city is the lowest. Based on the local renewable resources, the carrying capacity of Guangzhou city is the smallest, which only accounts for one third of that of the other cities. When it comes to the indicator ‘Ratio of electricity energy used’, the value of Shenzhen city is the largest.

3.4 Environmental Load

Ratio of waste to energy is used to express the situations of environmental load in the three cities. As for the ratio of waste to the total energy used, Guangzhou accounts for 24 percent while Zhuhai and Shenzhen account for 12 and 6 percent respectively. As for the ratio of waste to the renewable energy, the value of Guangzhou city is more than ten while that of the other two cities is less than one (see Figure 4).

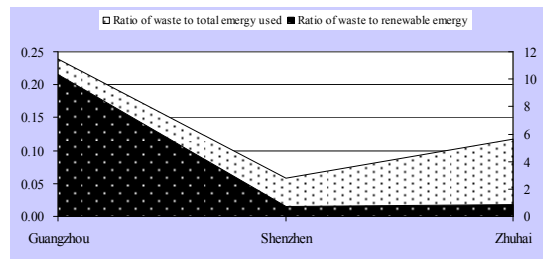


Figure 4. Situations of environmental load indicators for three urban ecosystems

3.5 Ecological Economic Interface

The situations of ecological economic interface are denoted through three indicators, namely ‘Emergy investment ratio’, ‘Ratio of export to import’, and ‘Emdollar ratio’. As indicated in Figure 5, Guangzhou’s emergy investment ratio is much bigger than that of Shenzhen and Zhuhai, while its exchange efficiency based on ‘Ratio of export to import’ is lower than the other two’. And Zhuhai possesses the biggest emdollar ratio among the three cities.

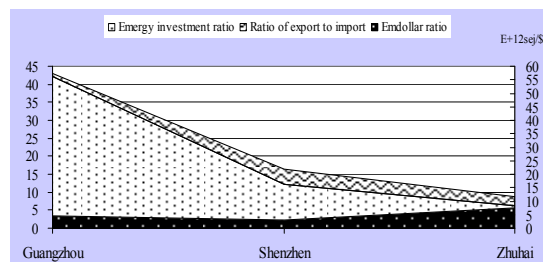


Figure 5. Situations of ecological economic interface indicators for three urban ecosystems

4 DISCUSSION AND CONCLUSION

Based on the above basic results, the characteristics of the three cities can be summarized (Table 3). Subsequently, the limiting factors of these three urban ecosystems can be further analyzed.

Table 3. Comparison of the key characteristics of Guangzhou, Shenzhen and Zhuhai

Items	Guangzhou	Shenzhen	Zhuhai
General situation	Relatively large area, population and GDP, and relatively high energy usage efficiency	Relatively small area and population but large GDP, and relatively low energy usage efficiency	Relatively small area, population and GDP, and relatively low energy usage efficiency
Emergy source	Relatively low energy self-sufficiency and locally renewable energy, relatively high dependence on import energy, and relatively few energy diversity	Medium energy self-sufficiency, relatively few locally non-renewable energy, relatively high dependence on import energy, and relatively few energy diversity	Relatively high energy self-sufficiency and locally renewable energy, relatively few dependence on import energy, and relatively large energy diversity
Emergy intensity	Relatively small energy density, and large degree of concentrated usage	Relatively large energy density, and medium degree of concentrated usage	Relatively small energy density and degree of concentrated usage
Emergy welfare	Relatively few energy amount per capita, and relatively small carrying capacity density based on renewable energy	Relatively large energy amount per capita and carrying capacity density based on renewable energy	Medium energy amount per capita, and relatively large carrying capacity density based on renewable energy
Environmental load	Relatively large ratios of waste to renewable energy and total energy used	Relatively small ratios of waste to renewable energy and total energy used	Relatively small ratio of waste to renewable energy and medium ratio of waste to total energy used
Ecological economic interface	Relatively low emdollar ratio, relatively big energy investment ratio, and relatively small ratio of export to import	Relatively low emdollar ratio, medium energy investment ratio, and relatively big ratio of export to import	Relatively high emdollar ratio, relatively small energy investment ratio, and medium ratio of export to import
Limiting factors	Large population, few renewable resources, high dependence on import from outside, and great amount of waste	Few non-renewable resources, high dependence on import from outside, and low energy usage efficiency	Low economic product, and low energy usage efficiency

According to the limiting factor analysis, three typical sorts of problems happened during urban ecosystem development are clearly revealed. Guangzhou is a representative of those mega cities without enough natural resources, in which economy develops fast on the basis of great amount of outside resources and energy, large population gather and thus huge pollution discharges to the environment, so that resident can't enjoy good-quality environment nor comfortable living standard. Shenzhen is a representative of middle cities without abundant resources during fast economic progress, in which the human living level improved fast in the past periods, but the resources and energy shortage is becoming more and more obvious. Zhuhai is a representative of middle cities with relatively good environment but without large population nor plentiful economic product, for which the problems like energy shortage and environmental pollution may emerge along with the economic development in the future. Corresponding regulation can be implemented for different urban ecosystems due to their limiting factors, e.g., population control, pollution treatment and ecological restoration should be emphasized for cities like Guangzhou, promoting the energy usage efficiency and decreasing dependence on outside import should be conducted for Shenzhen city, while developing economic pattern of high energy usage efficiency and low pollution emission should be performed for Zhuhai city.

Based on the emergy synthesis and related indicators, three urban ecosystems in the Pearl

River Delta urban cluster are systematically evaluated and diagnosed from perspective of systems ecology. The main characteristics of the three cities are summarized from aspect of energy source, energy intensity, energy welfare, environmental load, and ecological economic interface. Furthermore, the limiting factors of the three urban ecosystems are analyzed. A meaningful evaluation and comparison framework among different urban ecosystems is presented in this paper, which is helpful for providing reference for urban ecological management based on limiting factors analysis. With enough data, further study can be conducted by analyzing the change trend of urban ecosystems over time, which can provide more valuable support for optimization and regulation of urban ecosystems.

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