Emergy-based Urban Ecosystem Health Assessment for Typical Cities along the Belt and Road

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Abstract. In order to promote construction of a green Belt and Road, it is necessary to evaluate the status of Chinese cities along the Belt and Road, amongst which urban ecosystem health is a useful indicator. Based on re-understanding of urban ecosystem health, we first proposed a new assessment framework composed of structure, function, process, and system. Subsequently, we applied the systems-oriented tool-emergy analysis-to simulate the urban ecosystem and establish the concrete assessment indicators of urban ecosystem health associated with the framework. Finally, we calculated the comprehensive urban ecosystem health index and compared the health status of 14 typical cities using the set pair analysis. The results indicated relatively high levels of urban ecosystem health in the cities of Kunming and Xi'an in 2015. Levels of urban ecosystem health in Shenzhen, Shanghai, Zhengzhou, and Beijing were relatively low, while these levels were moderate in other cities. We also proposed suggestions of improving urban health states according to the results of limiting factor analysis for different cities.

1. Introduction

The Silk Road Economic Belt and the 21st Century Maritime Silk Road (hereinafter referred to in combination as the "Belt and Road" Initiative) were proposed by the Chinese government as strategies for effectively aligning changes in its domestic and international situations. In the new era of globalization, this long-term strategy will have significant and far-reaching impacts for both China and other countries. A basic principle of the "Belt and Road" Initiative is green development, which requires enabling eco-environmental protection to serve, support and guarantee the Belt and Road construction towards environment-friendly routes [1]. As the key node and executive unit of green development, the healthy development of cities is essential for the construction of the Belt and Road [2]. It is necessary to first evaluate the health states of cities along the Belt and Road, especially when considering the fact that there is still a lack of ecological assessment for cities although a number of studies related to the "Belt and Road" have been conducted from aspects of economics, international issues, and ethnic issues [3].

In this study, we conducted a systematic assessment of the health status of representative urban ecosystems located along the Belt and Road routes, by combining emergy analysis, a useful method

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of systems ecology, with set pair analysis, a method of uncertainty analysis. In doing so, we identified limiting factors and proposed regulatory suggestions that could provide a scientific basis for the advancement of the Belt and Road initiative.

2. Urban ecosystem health assessment methods

2.1. Feature of urban ecosystem health

There is not a well-acknowledged concept of urban ecosystem health due to the complexity of urban ecosystem. Based on our re-understanding of urban ecosystem health and its existent concepts [4], we identified the following four interactive features of a healthy urban ecosystem: (1) rational structure which emphasizes the diversity of components and balance amongst them, (2) optimal function which emphasizes both the urban ecosystem's ability of maintaining its own structure and providing services for human beings, (3) smooth process which emphasizes the efficiency of interaction between urban ecosystems and their external environment, and (4) sustainable system which emphasizes the ability of supporting urban development in the future.

2.2. Emergy-based urban ecosystem health indices

In order to comprehensively measure the above-proposed four interactive features of urban ecosystems, we applied a useful systems-oriented method, named as emergy analysis, for urban ecosystem health assessment in this paper. With the merit of quantifying different sorts of energy and materials in a common unit, emergy analysis connects different subsystems and factors together through various flows among them and also provides a unified analysis platform for different urban ecosystems [5-6]. It enables the systematic evaluation of different features of urban ecosystems and scientific comparison of ecosystem health among different cities.

According to their specific meanings, 17 emergy-based indices were selected to reflect the health status of urban ecosystems from the four aspects of structure, function, process, and system. The concrete structure of these indices and their expressions are given in Table 1. More details of the indices can be found in the related references [7-8].

Table 1. The emergy-based index system.

Number	Item	Expression	Weight
Structure			0.25
1	Non-renewable resource emergy ratio	N/U	0.2
2	Renewable resource emergy ratio	R/U	0.2
3	Purchased emergy ratio	$(F+G+P_2I_3)/U$	0.2
4	Electricity in energy consumption ratio	ELE/EC	0.1
5	Emergy diversity index	$-\sum\left(\frac{U_i}{U}\right)*\ln(\frac{U_i}{U})$	0.3
Function			0.25
6	Power emergy usage ratio	ELE/U	0.2
7	Emergy dollar ratio	U/GDP	0.2
8	Emergy yield ratio	$(N+R+R_1+F)/(F+R_1)$	0.2
9	Emergy self-support ratio	(R+N)/U	0.2
10	Emergy per area	U/Area	0.1
11	Emergy per person	U/POP	0.1
Process			0.25
12	Emergy exchange ratio	$(F+G+P_2I_3)/P_1E$	0.25
13	Environment load ratio	$(F+N)/(R+R_1)$	0.25
14	Emergy waste ratio	W/R	0.25
15	Emergy input and self-emergy ratio	$(F+G+P_2I_3)/(R+N)$	0.25
System			0.25
16	Emergy sustainable indices	EYR/ELR	0.4
17	Emergy index for sustainable development	EYR*EER/(ELR+EWI)	0.6

2.3. Mathematical model

Considering the intrinsic uncertainty of urban ecosystem health, we applied a useful uncertainty method, set pair analysis, to process the emergy-based index data and relatively evaluate the health status of different cities. It enables maintenance and integration of various information embodied in the assessed cities and multi-layer analysis of urban ecosystem health characteristics, contributed by its respect of uncertainty information.

The detailed calculation based on set pair analysis can be found in the literature [9-10]. Briefly speaking, in the space of comparison [*U*, *V*] of the assessed city s_k (the set composed of the emergy-based indices data), we combined the weight of each index in Table 1 (obtained based on analytic hierarchy process [11] and the Delphi method) to calculate the average identity degree (marked as a_k) and the average contrary degree (marked as c_k). Finally, we calculated the relative proximity degree of s_k and *U* (marked as r_k), which determines the ranking of the assessed city s_k in relation to urban ecosystem health status. A higher value of r_k indicates a higher level of urban ecosystem health.

$$a_k = \sum_{r=1}^{n} w_r a_{kr} \tag{1}$$

$$c_k = \sum_{r=1}^{n} w_r c_{kr} \tag{2}$$

$$r_k = \frac{a_k}{a_k + c_k} \tag{3}$$

2.4. Study area

Considering the representativeness of typical cities and the availability and limitations of urban data, we finally selected 14 typical cities located along the Belt and Road routes, including Guangzhou, Shenzhen, Shanghai, Qingdao, Fuzhou, Urumqi, Changchun, Kunming, Beijing, Zhengzhou, Wuhan, Chongqing, Hefei, and Xi'an.

3. Results and discussion

3.1. Urban ecosystem health states in 2015

As Figure 1 shows, Kunming and Xi'an evidenced relatively high levels of ecosystem health in 2015, whereas the urban ecosystem health of Shenzhen, Shanghai, Zhengzhou, and Beijing were relatively low. The health of other investigated cities remained at a medium level. To conduct a more detailed and comprehensive diagnosis of the health status of each city's ecosystem and to identify limiting factors, set pair analysis was performed on the four ecosystem health subindices relating to structure, function, process, and system. Levels of the structural sub-index of ecosystem health for Kunming, Hefei, Shenzhen, and Fuzhou were higher than those of other cities, whereas these levels were relatively low in Urumqi and Zhengzhou. Kunming, Urumqi, Hefei, and Xi'an evidenced a relatively high health status relating to the functional sub-index, whereas Zhengzhou, Shanghai, and Beijing evidenced a relatively poor health status. Levels of the process sub-index of urban ecosystem health were relatively high for Chongqing, Hefei, Changchun, and Fuzhou, whereas these levels were relatively low for Shenzhen, Shanghai, and Zhengzhou. Finally, a trend of polarization was found for the system sub-index of urban ecosystem health. Whereas levels of this sub-index were relatively high for Kunming, Changchun, Wuhan, Chongqing, and Xi'an, they were relatively low for Shenzhen, Shanghai, Zhengzhou, and Beijing.

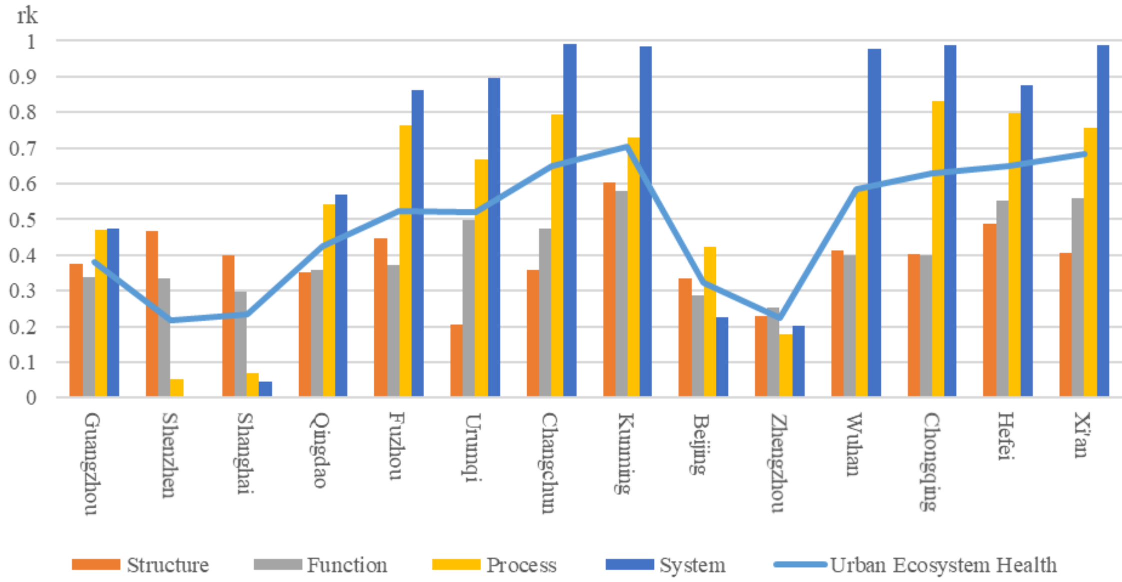

Figure 1. Urban ecosystem health index and health subindices relating to structure, function, process, and system in 2015.

3.2. Concrete analysis of urban ecosystem health for Shenzhen

3.2.1. Multi-dimensional analysis of Shenzhen Ecosystem Health Subindices. To analyze the status of Shenzhen's ecosystem health in more detail and to identify key constraining factors, we performed a multidimensional analysis of this city's ecosystem health subindices (see Figure 2). Figure 1 shows that Shenzhen's ecosystem health subindices relating to structure and function were at medium levels, while those for process and system were at low levels. Therefore, attempts to, improve Shenzhen's ecosystem health should focus on the dimensions of process and system.

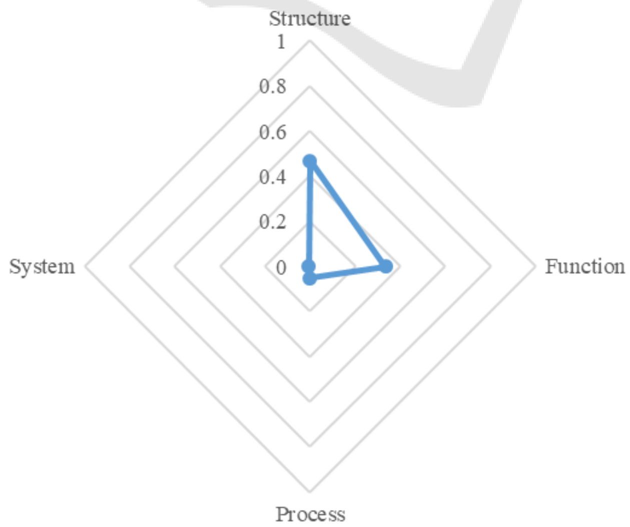

Figure 2. Multidimensional analysis of Shenzhen's ecosystem health subindices.

For the process dimension, the health status of Shenzhen's urban ecosystem is relatively low, indicating that Shenzhen's ecosystem is not able to communicate smoothly with its external and internal subsystems. Moreover, the efficiency of this process is relatively low. Of the investigated cities, the environmental load ratio, emergy input and self-emergy ratio of Shenzhen were much higher than those of other cities, whereas its emergy exchange ratio was lower. The environment load ratio reflects the pressure exerted by a developing system on the natural environment. Our findings indicated that Shenzhen's natural environment is under great pressure. Consequently, there is a need to change the previous approach that prioritized economic benefits achieved through a reduction of environmental benefits and to strengthen environmental protection and resource conservation. The economic development of the urban system must demonstrate high levels of efficiency and competitiveness. It must also entail free renewable resources and a rational mix of purchased resources that are of high quality in terms of energy. A higher emergy input and self-emergy ratio will reduce the competitiveness of the urban ecosystem. The emergy exchange ratio reflects the benefits and losses of the system relating to foreign exchanges. In developed countries or regions of the world, this ratio is generally greater than 1. However, Shenzhen's emergy exchange ratio is 0.16, which means that emergy wealth lost in foreign trade is higher than the emergy wealth that is received. This indicates that the emergy wealth of the urban ecosystem is always flowing out. For the system dimension, the two index values for emergy sustainable indices and emergy index for sustainable development were very low, indicating that Shenzhen's overall system demonstrates a low level of sustainable development of the ecological-economic system that has remained under the shadow of economic prosperity as the key goal.

3.2.2. Suggestions aimed at enhancing Shenzhen's urban ecosystem health. In light of the above analysis focusing on Shenzhen's urban ecosystem health, we offer the following suggestions for improving the health of urban ecosystems in Shenzhen:

- The concept of green development should be established, which entails strengthening environmental protection, pollution control, ecological construction, and supervision of environmental protection. In addition, there is a need to improve the environmental infrastructure, and relieve pressure on the city's natural environment.
- Trade import and export projects need to be adjusted. Exports of raw resource products should be reduced, with export as much as possible to final products, input high-value technology, culture, and education.
- Independent innovations should be prioritized, and sustained efforts should focus on developing new energy sources along with energy-saving and environmental protection approaches. Further, efforts should be made to develop other strategic emerging industries and modern service industries and to improve the social and economic benefits exchanged under unit environmental pressure. Such initiatives would contribute to optimizing the system's performance in relation to sustainable development.

4. Conclusions

In order to promote the construction of Belt and Road, it is necessary to understand the strength and weakness of the Chinese cities along the Belt and Road, based on which reasonable planning can be determined to guide the long-term construction. Aiming at the status quo that there is a lack of comprehensive evaluation for cities along the Belt and Road, urban ecosystem health was selected as the unified media to diagnose the situation of different cities in this paper. According to our re-understanding of urban ecosystem health, we first proposed an original assessment framework of Structure-Function-Process-System, and then introduced emergy analysis to establish concrete indicators of urban ecosystem health assessment.

The results indicate that the health status of typical Chinese cities situated along the Belt and Road routes is at a medium level in general. Of these cities, those evidencing high economic levels, such as Shenzhen, performed poorly for the system dimension, indicating that the development of the ecological-economic system of these cities, under the shadow of economic prosperity as the key goal, demonstrated a low level of sustainability. More analysis was implemented for Shenzhen, and certain suggestions was given to improve the health state.

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