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Ecosystem Health Assessment and Regulation for Urban Ecosystems: A Case Study of the Yangtze River Delta Urban Cluster, China

M. R. Su, Z. F. Yang*, G. Y. Liu, and B. Chen

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

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ABSTRACT. Methods and indicators need to be developed to investigate urban ecosystem health to mitigate eco-environmental problems and develop holistic policies for integrated urban ecosystem management. Considering the importance of energy and materials flows in urban ecosystems, the emergy synthesis model was applied to organize the urban ecosystem health indicators from the biophysical perspective in this paper, through which a better understanding of urban ecological patterns and processes can be obtained. Set pair analysis was combined to conduct the data processing of health indicators and promote objectivity of ecosystem health criteria. Set pair analysis defines the approximate degree of a real index set relative to an optimal one, which is evaluated to describe the relative urban ecosystem health levels in view of the emergy-based health indicators. Six cities in the Yangtze River Delta urban cluster in China (Shanghai, Suzhou, Wuxi, Changzhou, Nanjing and Hangzhou) were selected as case studies using 2005 data. The evaluation showed that the urban ecosystem health states of Shanghai and Hangzhou are relatively good, while the health states of Wuxi and Suzhou are relatively poor. The health states of the cities based on the factors (vigor, structure, resilience, ecosystem service maintenance and environmental impact) and individual indicators were also analyzed to identify regulatory directions and measures for improving the health status of those cities with relatively poor ecosystem health. This paper presents a meaningful comparison between different urban ecosystems at different indicator levels and provides a useful framework for urban ecological management with respect to urban ecosystem health status.

Keywords: ecosystem health assessment, emergy synthesis, set pair analysis, urban cluster, urban ecosystem regulation, Yangtze River Delta

1. Introduction

Because of the significant impacts of cities on regional, national and even international socioeconomic development (Huang, 1998), the state of urban ecosystem health is important. Urban ecosystem health is particularly relevant when the viability of the urban ecosystem and the living standards of urban residents are jeopardized by various emerging eco-environmental problems, such as air pollution, water quality degradation, resource shortages and energy scarcity. These problems make the comprehensive diagnosis of the urban ecosystem health state, using suitable indicators and methods, an urgent matter. After the urban ecosystem health state has been investigated from a systems ecology perspective, the critical factors of urban ecosystem health may be defined to inform suitable urban ecological restoration, management and regulation practices to reduce the effects of eco-environmental damage and degradation on sustainable urban development.

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

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Although there is no robust and acknowledged definition, urban ecosystem health has been recognized as both the ability to satisfy reasonable human demands and the ability to renew and maintain the ecosystem. Based on this understanding, scientists and organizations have developed appropriate urban ecosystem health indicators, considering different priorities and objectives (Su et al., 2010). Focusing on a comparison between urban and rural health in Gambia, Harpham (1996) developed urban health indicators by considering the urban economy, environment, public health statistics, health-seeking behavior, health expenditure, and nutrition. The World Health Organization (WHO) has proposed hundreds of indicators for healthy cities including: human health, urban infrastructure, environmental quality, living surroundings, and community function and action (Takano and Nakamura, 1998). Guo et al. (2002) defined urban ecosystem health using vigor, organizational structure, resilience, and maintenance of ecosystem services, and human health as key factors. Similarly, Hu et al. (2005) presented the distance index and the coordination index to describe spatial differences in urban ecosystem health. Among the present indicators, most are focused on the external performance of the urban ecosystem. However, internal biophysical drivers such as flows of energy and materials, should also be integrated into ecosystem health indicators to enhance the understanding of urban ecological patterns and processes. This would allow for better analysis of the complex structure and functions of the urban ecosystem represented by natural-social-economic factors and their interactive relationships. To measure the various flows among the social, economic and ecological subsystems, an ecological evaluation model based on emergy, grounded in energetics and systems ecology (Odum, 1983; Ulgiati and Brown, 1998), is introduced in this paper to understand urban ecosystem health and organize corresponding health indicators.

Emergy synthesis is an effective tool for ecosystem accounting and evaluation, and it has been successfully applied to study the socio-economic metabolism of many cities in recent years; for example in Miami by Zucchetto and Jansson (1985), Jacksonville by Whitfield (1994), Hong Kong by Lan and Odum (1994), Taipei by Huang (1998, 2004) and Huang et al. (2007), Zhongshan by Lu et al. (2003), Shanghai by Zhang (2007), Lanzhou by Liu (2008), Macao by Lei and Wang (2008), Baotou by Liu et al. (2009), and Beijing by Jiang et al. (2009) and Zhang et al. (2009). These studies are valuable references for integrating urban ecosystem health assessment with emergy synthesis.

In the evaluation of urban ecosystem health, scholars have developed mathematical methods to conduct data processing and reduce uncertainty in the urban ecosystem health assessment, such as the fuzzy synthetic assessment method (e.g., Zhou and Wang, 2005; Tao, 2008), the relative vector comprehensive assessment method (Sang et al., 2006) and the attribute theory method (Wen and Xiong, 2008). However, few models have been established based on descriptions of the intrinsic relativity of urban ecosystem health induced by the complexity, openness and human-dominance of the urban ecosystem (Su et al., 2010). Thus, set pair analysis, which considers symmetrical information from three aspects embracing identity, discrepancy and opposition (Jiang et al., 2004), is applied here and combined with emergy-based indicators to quantify the relative urban ecosystem health status.

Additionally, urban clusters, which connect a number of cities in a certain natural geographical area through economic and cultural linkages, have become an important pattern and trend in urban long-term development in both developed and developing countries. This was initially recognized by Howard (1985) who first identified the urban developmental pattern in garden cities. Within the cluster developmental trend, developing with a higher health level is an important topic for each city. Therefore, a comparison analysis between cities in the same region, which share and compete for local resources and undoubtedly create environmental pressures for each other with respect to local sustainability (Cai et al., 2009b), will help better understand urban ecosystem performance and efforts based on integrated regional development.

In this paper, the emergy synthesis model is used to organize the urban ecosystem health indicators considering the energy and materials flow, following which, set pair analysis is applied to assess the relative health levels of different urban ecosystems. Finally, the results of the emergy-based indicators for six cities in the Yangtze River Delta urban cluster are described and discussed, which provide suggestions for regulatory direction and measures for improving urban ecosystem health status.

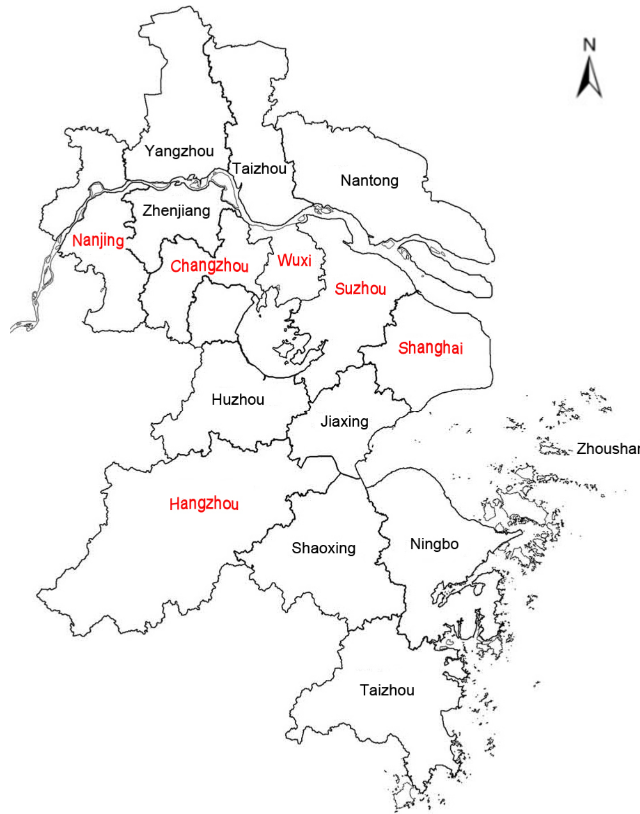

Figure 1. Cities in the Yangtze River Delta urban cluster.

2. Methodology

2.1. Study Area

Generating about one fifth of China's GDP, the Yangtze River Delta urban cluster is one of the most well-known urban clusters in China because of its rapid socioeconomic growth rate. Located on the southeast coast of China, the Yangtze River Delta urban cluster includes Shanghai, eight cities in southern Jiangsu Province and seven cities in the north of Zhejiang Province (see Figure 1), covering an area of 110,821 km^2. In 2005, the region had a total population of 82.7 million and a population density of 746 persons/km^2, which was much higher than the average population density in China (133 persons/km^2). In terms of natural resources, there are many river and lake networks and ample plant and animal resources, but scarce mineral and energy resources in the Yangtze River Delta area (Zhang, 2007).

Six cities were chosen for this study (Shanghai, Suzhou, Wuxi, Changzhou, Nanjing and Hangzhou, labeled in red on Figure 1), considering the condition of natural resources, level of economic development, social civilization progress and data availability.

Table 1. Emergy Synthesis Table of Resources and Economic Flows for Shanghai in 2005

No.	Item	Raw data	Solar transformity (sej/unit)	Refs.	Solar emergy (sej)	Emdollar values (US$)
Renewable sources						
1	Sunlight (J)	1.99E+19	1	Odum, 1996	1.99E+19	2.86E+06
2	Wind, kinetic (J)	6.64E+15	2.45E+03	Odum et al., 2000, Folio #1	1.63E+19	2.35E+06
3	Rain, geopotential (J)	2.81E+14	4.70E+04	Odum et al., 2000, Folio #1	1.32E+19	1.90E+06
4	Rain, chemical (J)	3.93E+16	3.05E+04	Odum et al., 2000, Folio #1	1.20E+21	1.73E+08
5	Tide (J)	8.77E+16	7.39E+04	Odum et al., 2000, Folio #1	6.48E+21	9.32E+08
6	Wave (J)	8.71E+17	5.10E+04	Odum et al., 2000, Folio #1	4.44E+22	6.39E+09
7	Earth cycle (J)	9.19E+15	5.80E+04	Odum, 2000, Folio #2	5.33E+20	7.67E+07
8	Typhoon (J)	3.86E+16	6.89E+04	Huang, 2004	2.66E+21	3.83E+08
Indigenous Renewable Energy						
9	Agriculture Production (J)	3.73E+16	3.36E+05	Brown & McClanahan,1996	1.25E+22	1.80E+09
10	Livestock Production (J)	1.08E+16	3.36E+06	Brown & McClanahan,1996	3.62E+22	5.21E+09
11	Fisheries Production (J)	1.48E+15	3.36E+06	Brown & McClanahan,1996	4.98E+21	7.17E+08
12	Wood (J)	6.20E+13	2.21E+04	Romitelli,2000	1.37E+18	1.97E+05
Non-renewable sources from within Shanghai						
13	Natural gas (J)	2.35E+16	5.88E+04	Romitelli,2000	1.38E+21	1.99E+08
14	Oil (J)	1.52E+16	8.90E+04	Odum, 1996	1.35E+21	1.94E+08
15	Soil losses (g)	1.01E+21	1.68E+09	Odum, 1996	1.70E+21	2.45E+08
16	Net top soil losses (J)	3.44E+14	7.40E+04	Brown & Bardi, 2001, Folio#3	2.54E+19	3.65E+06
Imports and outside sources						
17	Goods (US$)	9.56E+10	1.06E+12	Jiang et al., 2009	1.01E+23	1.45E+10
18	Services (US$)	8.04E+10	1.06E+12	Jiang et al., 2009	8.49E+22	1.22E+10
19	Tour (US$)	1.64E+10	6.95E+12	This work	1.14E+23	1.64E+10
20	Fuels (J)	5.22E+18	8.32E+04	This work	4.34E+23	6.24E+10
Exports						
21	Goods (US$)	9.07E+10	6.95E+12	Jiang et al., 2009	6.30E+23	9.06E+10
22	Services (US$)	7.63E+10	6.95E+12	Jiang et al., 2009	5.30E+23	7.63E+10
Resource consumed						
23	Fuels (J)	2.79E+18	7.57E+04	This work	2.11E+23	3.04E+10
24	Electricity (J)	3.32E+17	2.69E+05	Odum, 1996	8.93E+22	1.28E+10
Waste produced						
25	Solid waste (J)	8.27E+16	3.02E+06	Huang et al., 1995	2.50E+23	3.60E+10
26	Waste water (J)	2.56E+15	1.12E+06	Huang et al., 1995	2.86E+21	4.12E+08
Dollar flow						
27	GDP (US$)	1.14E+11	6.95E+12	Jiang et al., 2009	7.92E+23	1.14E+11

2.2. Emergy-based Urban Ecosystem Health Representation Model

In this paper, emergy synthesis is used to comprehensively understand the urban ecosystem and measure urban ecosystem health status by integrating and abstracting the information on biophysical metabolism.

The emergy synthesis model was first applied to six urban ecosystems. The steps involved in emergy synthesis for urban ecosystems are: 1) confirming the system boundary and collecting data such as natural conditions, agriculture and industry production, energy consumption and import and export trade, through field investigations and standard yearbooks complied by local government; 2) drawing the emergy system diagram, through which the urban emergy flows can be delineated, which involves renewable resources (sunlight, rain, wind, earth cycle and the inflow rivers), non-renewable resources (mineral, nutrients both from the natural topsoil losses and the soil degradation), locally renewable resources (hydroelectricity, agricultural production, forestry production and fish), resources and services to and from the outside of the system boundaries, and corresponding money flows; 3) preparing the emergy synthesis table to summarize the major energy, materials, goods and services flows (the major emergy flows for Shanghai in 2005 are listed in Table 1 as an example); 4) establishing the emergy-based indicators and calculating their values; and 5) analyzing the results for the urban ecosystem.

Through emergy synthesis, various energy and material flows are accounted for and simulated to connect the socio-economic subsystem with the natural subsystem. The emergy synthesis also depicts biophysical characteristics of the urban ecosystem including: energy hierarchy, environmental capacity, ecological economic efficiency and interaction mode with the surrounding environment.

Following the emergy synthesis, the concept of urban ecosystem health was reviewed to confirm the main evaluation factors. Ecosystem health is defined as a field which integrates ecological, socio-economic and human health aspects, in which both the ability to satisfy reasonable human demands and ecosystem renewal and maintenance are emphasized (Rapport et al., 1999). Based on this description, five factors of urban ecosystem health – vigor, structure, resilience, ecosystem service maintenance and environmental impact – were selected as the main evaluation concerns (see Figure 2) using the eight classic factors of natural ecosystem health (Mageau et al., 1995; Rapport et al., 1998) and a similar broadly-used framework of urban ecosystem health assessment (Guo et al., 2002) as references.

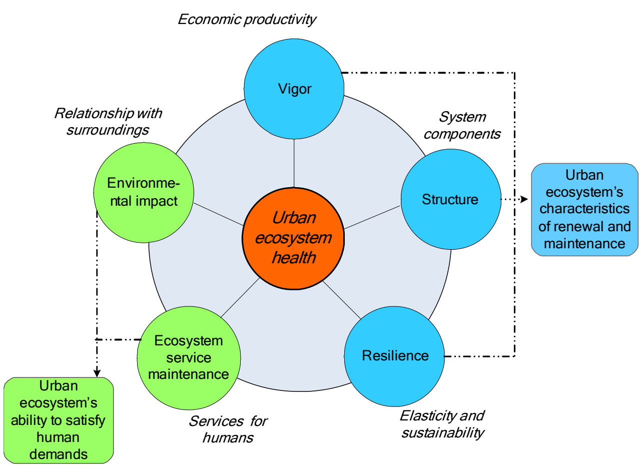

Figure 2. Evaluation framework for urban ecosystem health.

Table 2. Emergy-based urban ecosystem health indicators and their values for Shanghai in 2005

Factor layer (F)	Index layer (I)	Value
F_1 Vigor	I_1 Emergy density	1.25
	I_2 Emdollar ratio	6.94
F_2 Structure	I_3 Emergy self-sufficiency	0.08
	I_4 Ratio of concentrated to rural use	12.78
	I_5 Emergy diversity index	1.35
F_3 Resilience	I_6 Carrying capacity density based on renewable emergy	137.53
	I_7 Fraction of locally non-renewable emergy used	0.01
	I_8 Ratio of waste to renewable emergy	4.96
F_4 Ecosystem service maintenance	I_9 Per capita emergy used	5.84
	I_{10} Per capita fuel emergy used	1.55
	I_{11} Ratio of electricity emergy used	0.11
F_5 Environmental impact	I_{12} Environmental loading ratio	14.60
	I_{13} Ratio of export to import	1.58
	I_{14} Ratio of import to indigenous emergy	12.16

Finally, related emergy-based indicators were selected to embed the analysis into the evaluation framework for urban ecosystem health. As shown in Table 2, the emergy-based urban ecosystem health indicators were established to represent the health status in view of the biophysical foundation of urban ecosystems.

2.3. Data Processing and Analysis

2.3.1. Relative Urban Ecosystem Health Assessment based on Set Pair Analysis

Set pair analysis, which was initially developed as an attempt to understand and describe the uncertainty of large, complex systems (Zhao, 1989), has been successfully applied in many fields including artificial intelligence (Jiang et al., 2004), forecasting (Wang et al., 2004) and multi-attribute assessment (Jiang et al., 2005). Set pair analysis can be used to conduct the data processing of the emery-based health indicators when dealing with the uncertainty and relativity of urban ecosystem health.

A set pair is formed by putting two interrelated sets together regarding a given problem. The features of the set pair are analyzed, and a connection degree formula for the two sets, including the identity degree, discrepancy degree and opposition degree, can be set up to understand the relationships between the various objects.

Considering the emergy-based urban ecosystem health assessment, the problem space based on set pair analysis can be defined as:

$$Q = \{S, M, H\} \tag{1}$$

$$S = \{s_k\} \ (k = 1, 2, ..., p) \tag{2}$$

$$M = \{m_r\} \ (r = 1, 2, ..., n) \tag{3}$$

$$H = (h_{kr})_{p \times n} \tag{4}$$

where S is the assessed interval set composed of six selected cities within the Yangtze River Delta urban cluster, and s_k denotes the kth city. M is the emergy-based indices set, and m_r represents the rth index. H denotes the decision-making matrix for problem Q based on set pair analysis, and h_{kr} refers to the attribute value of index m_r in the interval s_k.

By collecting the best values for each index, the optimal evaluation set can be generated, identified as $U = \{u_1, u_2, \ldots, u_n\}$, while the worst evaluation set is generated in a similar way and identified as $V = \{v_1, v_2, \ldots, v_n\}$. u_r and v_r respectively denote the best and worst values of the index m_r. Based on the fixed procedure of set pair analysis (more details are provided in Su et al., 2009), a relative urban ecosystem health parameter, marked as r_k, can finally be obtained by integrating multiple indices:

$$r_k = \frac{a_k}{a_k + c_k} \tag{5}$$

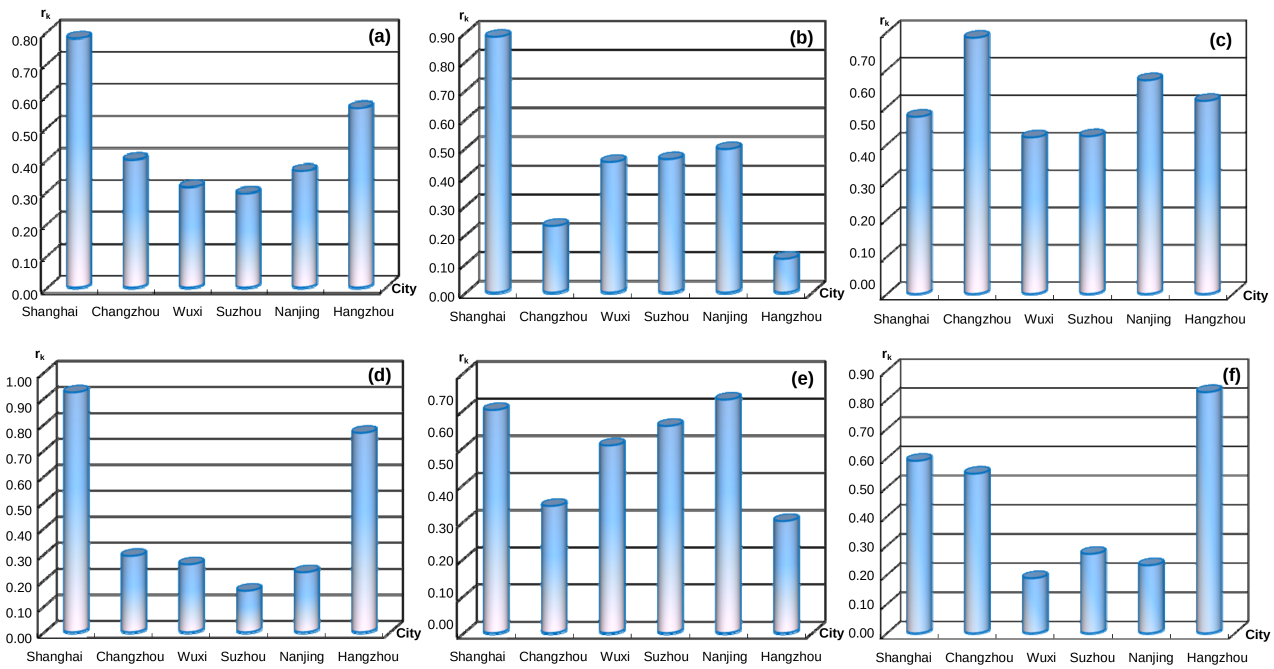

Figure 3. Relative health states of six cities in the Yangtze River Delta urban cluster in view of the emergy-based health indicators and each factor: (a) Overall emergy-based health indicators; (b) Vigor; (c) Structure; (d) Resilience; (e) Ecosystem service maintenance; (f) Environmental impact.

where r_k expresses the distance between the ecosystem health status of the concerned *k*th city and the optimal evaluation set *U*, with larger values of r_k related to a better ecosystem health state in the *k*th city. a_k and c_k denote the approaching degrees between s_k and *U*, and s_k and *V* respectively.

2.3.2. Multi-level Analysis based on Urban Ecosystem Health States

In addition to analyzing the full set of emergy-based health indicators to reflect the integrated health states of different urban ecosystems in the urban cluster, set pair analysis can be used on dimensions of the five factors or on each index individually to further analyze the performance of each urban ecosystem, in which the set pair analysis procedure is similar to that for integrated health states evaluation but with different assessed indices sets. Based on comparison among different urban ecosystems, the characteristics of each urban ecosystem within the urban cluster can be summarized.

2.3.3. Regulation Suggestion for Urban Ecosystems

According to the health assessment results on levels of the integrated emergy-based health indicators, the five factors and certain individual index, the limiting factors for the urban cluster and concerned urban ecosystems can be found, following which a corresponding regulation can be suggested. Concretely speaking, the regulatory direction for an urban ecosystem can be determined from the relative health state of those five factors. The concrete measures for improving the health state of an individual urban ecosystem with a relatively low level of health can be acquired by analyzing the situations of individual indicators of confirmed limiting factors. The regulations suggestion for the urban cluster can then be proposed after integrating the holistic health states of assessed urban ecosystems in the urban cluster and the situations of five factors.

3. Results

3.1. Relative Health States in view of the Emergy-based Health Indicators

The final results for the ecosystem health states of the six cities in the Yangtze River Delta urban cluster were obtained based on the emergy health indicators by calculating the approximate degree of urban ecosystem health relative to the optimal evaluation set using set pair analysis. The results are shown in Figure 3(a) and indicate that the urban ecosystem health levels in Shanghai and Hangzhou are relatively good, while the health levels of Wuxi and Suzhou are relatively poor, and Changzhou and Nanjing have an intermediate level of relative health.

3.2. Relative Health States Considering Each Factor of the Emergy-based Health Indicators

To better understand which factors induce the respective health levels of these cities, set pair analysis was also conducted for the five factors of the emergy-based health indicators (vigor, structure, resilience, ecosystem service maintenance and environmental impact). The relative health state of each factor for six cities in the Yangtze River Delta urban cluster are shown in Figure 3(b) to 3(f).

3.2.1. Vigor

For the vigor factor of the emergy-based health indicators, the state of Shanghai health is relatively good among the urban ecosystems assessed here because of a high emergy density and low emdollar ratio, while the health statuses of Hangzhou and Changzhou are relatively poor, and the situations of the other three cities are at intermediate levels. Among the 14 indices, the emergy density indicator has the greatest weight, and thus has a relatively large influence on the final result. Therefore, the relatively large difference in emergy density among the six cities is reflected in large differences in the overall urban ecosystem health for these cities.

3.2.2. Structure

Considering the structure factor, the order of the cities from best to worst is Changzhou, Nanjing, Hangzhou, Shanghai, Suzhou and Wuxi. Overall, the status of the structure factors for the six cities are relatively similar, partly because the structure indicators (emergy self-sufficiency, ratio of concentrated to rural use, and emergy diversity index) are more dependent on natural conditions than the other indicators. Hence, the health of the structure of the different cities in the same urban cluster is similar because of their similar natural conditions, which is reflected to some extent by the relatively low weights of the structure indices.

3.2.3. Resilience

For the resilience factor, the health states of Shanghai and Hangzhou are relatively good because of large carrying capacity density of renewable emergy and the low ratio of waste to renewable emergy, while the state of Suzhou is relatively weak, and the other cities have an intermediate level. It can be concluded from these results that urban ecosystems with more renewable energy and resources and less environmental pressure caused by waste discharge will be healthier with respect to resilience.

3.2.4. Ecosystem Service Maintenance

The health states for ecosystem service maintenance in the six cities from best to worst are Nanjing, Shanghai, Suzhou, Wuxi, Changzhou and Hangzhou, with the health states of the first four cities being very similar, and the states of the last two cities also comparable.

3.2.5. Environmental Impact

In terms of the environmental impact factor, the relative health state of Hangzhou is good, attributed to the relatively small environmental loading ratio and large ratio of export to import, while the health states of Wuxi, Nanjing and Suzhou are relatively poor, and the situations of Shanghai and Changzhou are at intermediate levels.

Figure 4 combines the relative health states for each factor and the overall emergy-based health indicators for six cities in the Yangtze River Delta region. There are no obvious correlations between each individual factor with the overall health indicators, and only the resilience factor has a roughly similar trend to the overall health indicators. This implies that the health status of an urban ecosystem may be influenced largely by its vitality and elasticity under various pressures, which are determined by both the condition of the innate natural resources and the acquired socioeconomic developmental pattern. Considering the correlations among the different factors, only the trends for vigor and ecosystem service maintenance were similar, which is explained by the fact that urban ecosystems with high economic development levels can provide sufficient services for human beings.

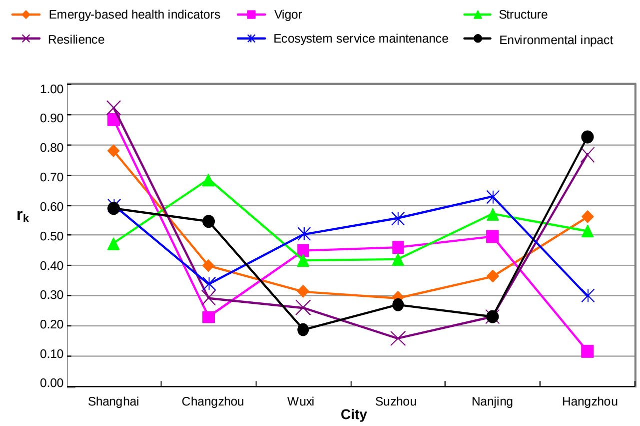

Figure 4. Combination of the relative health states of six cities in the Yangtze River Delta urban cluster in view of the overall emergy-based health indicators and each factor.

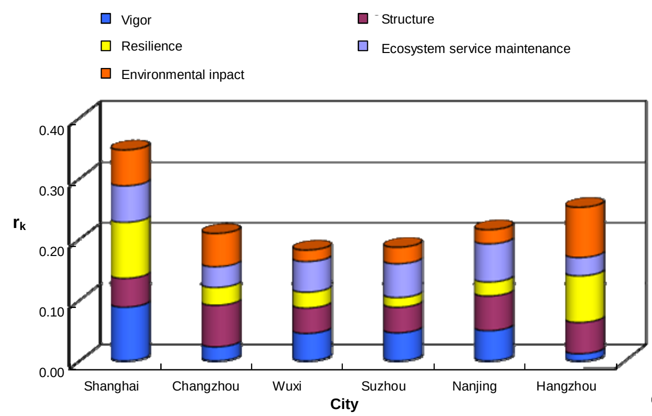

Figure 5. Relative health states among five factors of the emergy-based health indicators for the six cities in the Yangtze River Delta urban cluster.

4. Discussion

4.1. Suggestions for Regulation to Improve the State of Urban Ecosystem Health

The above results for the urban ecosystem health status in view of the emergy-based health indicators and each factor point to areas of focus for regulation to improve urban ecosystem health states. By collecting data on vigor, structure,

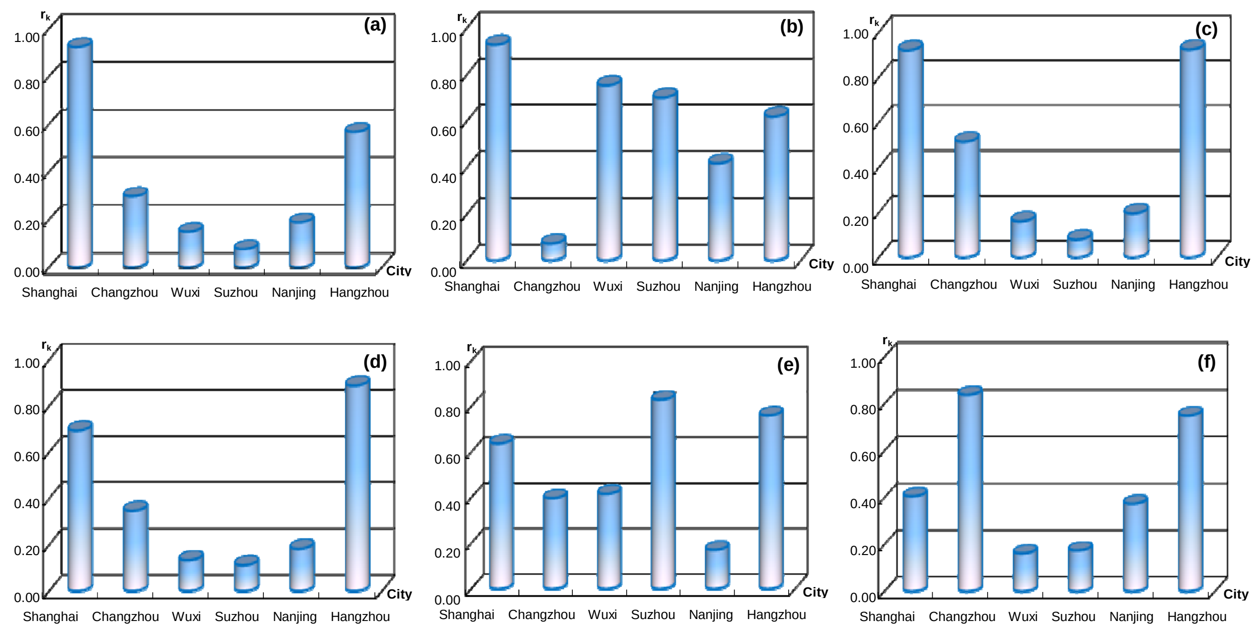

Figure 6. Relative health states of six cities in the Yangtze River Delta urban cluster for selected indicators: (a) Carrying capacity density based on renewable emergy; (b) Fraction of locally non-renewable emergy used; (c) Ratio of waste to renewable emergy; (d) Environmental loading ratio; (e) Ratio of export to import; (f) Ratio of import to indigenous emergy.

resilience, ecosystem service maintenance and environmental impact, corresponding regulatory directions can be determined by describing the relative health levels among the five factors of urban ecosystem health.

As indicated in Figure 5, the key regulatory points are unique for each urban ecosystem. For example, in Suzhou, regulation should be implemented to improve the health of resilience and environmental impact (i.e., raising the elasticity and maintenance under pressure and reducing environmental stress on surroundings), while measures aiming at improving the vigor and ecosystem services should be implemented for Hangzhou (i.e., increasing the economic production efficiency as well as transforming production into services for humans in terms of energy and materials flows). It can be further concluded that Changzhou should improve its vigor, resilience and ecosystem services, while Nanjing and Wuxi should improve their environmental impact and resilience, and Shanghai should improve its environmental impact and structure. In other words, more attention should be paid to the internal productivity of the urban ecosystems and functions for residents in Changzhou and Hangzhou, while emphasis should be focused on sustainability under stress and the impact on the surroundings in Suzhou, Nanjing, and Wuxi. Regulation should be implemented aimed at the internal ecosystem structure and potential influence on external surroundings for Shanghai.

4.2. Measures for Improving the State of Health of the Individual Urban Ecosystem

After determining the appropriate regulatory direction for improving urban ecosystem health status, the health situations can be further tracked based on indicators of limiting factors. Focusing on Suzhou, which has the relatively lowest health level among six cities in the Yangtze River Delta urban cluster, set pair analysis was conducted for the six indicators related to the factors of resilience and environmental impact, which revealed the indices that most significantly affect the integrated health status. As shown in Figure 6, for the resilience factor, the indicators; "carrying capacity density based on renewable emergy" and "ratio of waste to renewable emergy" are relatively weak. This implies that Suzhou, with few renewable resources, was pressured mostly by its increasing population and the correspondingly large amount of waste, which usually accompanies rapid economic development and high living standards. Consequently, a regulation scheme should be implemented to control the population increase, reduce the waste discharge, and improve waste reuse and recycling to in turn improve the urban health status with respect to resilience. When considering environmental impact, the health levels in Suzhou based on the "environmental loading ratio" and "ratio of import to indigenous emergy" indicators are relatively poor. It indicates that Suzhou, with few locally-derived resources, depends on external inputs and therefore has a large impact on its surroundings. Therefore, appropriate management measures should be constructed to exploit new energy and increase the usage efficiency of energy and materials, for improving the health status with regard to environmental impact.

4.3. Integrated Regional Development based on State of Ecosystem Health

According to the weights of the individual indicators, the factors of vigor, resilience and environmental impact have much more influence on the final urban ecosystem health status than other factors. However, in terms of correlations between each factor and the overall urban ecosystem health indicators, only resilience has a roughly similar trend to the overall health indicators (see Figure 4), which indicates the importance of an ecosystem's ability to remain vital and elastic under pressure. Based on these results, it is clear that the resilience factor, which is determined by both the condition of the innate natural resources and the acquired socioeconomic developmental pattern, is a key element of urban ecosystem health. To improve resilience, and therefore health level, based on the energy and materials metabolism, measures should be implemented to exploit new clean energy (such as wind, hydropower and biotic energy), improve the energy use efficiency (such as advancing economic production technology and developing ecological industrial parks in the urban cluster), reducing population and controlling and recycling waste. These measures can provide a reference for the urban cluster's integrated development from aspects of resource possession, use, distribution and environmental capacity with regard to stress.

5. Conclusions

At the center of human activities and social civilization, cities have developed as places for huge material wealth and psychological enjoyment. However, prosperous urban development is obtained at the cost of serious environmental degradation and huge eco-environmental pressure from air pollution, water resource scarcity and energy shortage, which can lower human living standards and impede the sustainable development of urban ecosystems. Thus, investigations into urban ecosystem health from the perspective of systems ecology are important to mitigate these serious eco-environmental problems and develop holistic policies for integrated urban ecosystem management. Ecosystem health assessment for urban clusters is especially essential because the urban cluster is an important pattern and trend in urban long-term development. Because different urban ecosystems located in the same urban cluster possess similar natural conditions and political and economic policies, the health assessment for these urban ecosystems is helpful to reveal the central factors that influence urban ecosystem health.

The emergy synthesis model, which links the natural, economic, and social systems in an overall assessment, was applied to organize the urban ecosystem health indicators in this paper to diagnose the health status of urban ecosystems from the perspective of energy and materials metabolism. Given the importance of a biophysical foundation for complex ecosystems, it is reasonable to assume that future studies will be further developed to analyze urban ecosystems in view of biophysical foundation.

This study demonstrates that a modified uncertainty theory, set pair analysis, can be applied to deal with the data of emergy-based health indicators and relatively assess the urban ecosystem health status. It can guarantee and promote the objectivity of the health criteria to derive an optimal assessment set from the concerned urban ecosystems and can be updated over time. The aim of this paper is to help formulate a framework from the biophysical perspective to assess urban ecosystem health status by integrating the information represented by the emergy synthesis model and extracted by set pair analysis. Certain suitable management and regulation measures for improving the health status of different urban ecosystems and an urban cluster can also be established based on the health assessment results.

This paper evaluated and compared the health status of different urban ecosystems of six cities in the Yangtze River Delta urban cluster which have certain similar natural characteristics (i.e., they are located in the same region and share similar geographical conditions and local resources). Based on the emergy synthesis model and set pair analysis, the relative health levels of the six urban ecosystems were evaluated so that the health situations of each urban ecosystem could be compared. A detailed analysis was also conducted by evaluating the individual factors or indices of the emergy-based health indicators, which is beneficial for identifying appropriate regulatory directions and concrete measures to improve the state of those urban ecosystems in relatively poor health. This approach may also help present a meaningful comparison for different urban ecosystems at different indicator scales, which will provide a useful framework for urban ecosystem management so that the situation can be viewed from multiple perspectives at the same time.

In this paper, set pair analysis has been applied to the urban ecosystem health assessment of six cities in the Yangtze River Delta urban cluster. In addition to analyzing cities within an urban cluster, set pair analysis can be employed on a wider scale, comparing cities in different urban clusters. Thus the health characteristics of different urban clusters from the perspective of energy and materials flows can be analyzed in more detail, and the essential factors that influence urban ecosystem health status can be identified. Regarding inherent uncertainties and various complexities within urban ecosystems, set pair analysis can be combined with other uncertainty methods like fuzzy-stochastic programming model (Li et al., 2009) and fuzzy-random interval programming model (Cai et al., 2009b) to quantify the uncertainty of urban ecosystem health more accurately.

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