Evaluation of the Sustainable Development Ability of the Urban Ecosystem in Jiangsu Province Based on the Information Entropy

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Abstract. Urban ecosystem (UE) is a typical “natural-social-economic system”. In the process of a new round of urbanization, urban ecosystems are facing challenges on ecological land reduction and environmental degradation. Better understanding and optimizing the evolutionary directions of UE are of great significance for both urban sustainable development and eco-civilization construction. In this study, based on dissipative structure theory and urban nature-economy-society complex ecosystem theory, the indicator system of evaluating UE developing direction was set up through information entropy method. This indicator system was made up by four types of information entropy including backup inflow entropy, imposed output entropy, destructive metabolism entropy, and regenerative metabolism entropy. Then, Jiangsu province were selected as the study area. Year-based information entropy model together with UE evolution index system were applied to analyse the order and complexity of UE during 2005-2015; The weights of indicators evaluating UE were calculated. Furthermore, the index scores of UE were calculated by combing with standardization values of indicators. And urban ecosystem sustainable development level was evaluated based on integrated development degree and coordinated development degree models. This study aims to provide a theoretical reference for the sustainable development and optimization of UE health in the Jiangsu province.

1. Introduction

We are living in an era of rapid economic development, people are enjoying great achievements of economy development as well as facing with many ecological environment problems. Such as environmental pollution, lack of energy, loss of biodiversity and so on, which are destroying the health of UE [1]. Compared with other ecosystems, UE has high vulnerability and human dependence, how to correctly evaluate the sustainable development of urban ecosystem process has been a hotspot in the research of the sustainable development of ecosystem. UE is a typical social - economic - natural compound ecosystem and a people-centric ecosystem. This system generally includes three parts of economic, social and natural systems, they have an impact on the health of urban ecosystems together [2].

A healthy urban ecosystem should be stable and sustainable. It is the integration of society, economy and natural system [3]. In recent years, some scholars imported the concept of entropy into the evaluation of the sustainable development of ecosystem. They studied the evolution of UE from the perspective of "information entropy". For example, Wu et al. [4] analyzed the evolution of UE of
Wuhan based on information entropy and found the driving factors. Wang et al. [5] analyzed the evolution of ecological system in Shanghai from 2003 to 2013 by using the information entropy theory and made a prediction of the sustainable development ability of 2014-2020 with grey model. These studies enrich the methods of urban ecological environmental assessment and prove the feasibility of information entropy method in UE evolution and sustainable development.

2. Study area
Jiangsu province is located in the east coast of China, and the level of economic and social development is at the forefront of the country. However, behind the rapid development of economic is the challenge of ecological environment. With high resource consumption and serious environmental damage, the environmental situation is increasingly serious. Therefore, it is of great significance to analyze the evolution trend of human settlements ecosystem of Jiangsu province so as to ensure the sustainable development of social and economic development in the region and to advise on regional development patterns in other areas.

3. Method

3.1 Information entropy theory of urban ecosystem
"Entropy" was originally a state parameter elicited by the second law of thermodynamics reflecting the irreversibility of the spontaneous process. The larger the entropy is, the more chaotic the system is, and if the entropy of the system is neutralized by some means, the system can be re-formed into a new ordered structure. The entropy change of UE is divided into two parts: first is the "input-output entropy" of material exchange between natural ecological environment and social and economic system, which reflects the support of natural system to urban system. The second is the entropy produced in human habitation, which is referred to as "metabolism entropy production", which reflects the ability to recover and metabolism of UE [6]. The "input-output entropy" and "metabolism entropy production" can be further divided into four parts, namely backup inflow entropy, imposed output entropy, destructive metabolism entropy, and regenerative metabolism entropy. According to "input-output entropy" and "metabolism entropy production", the "total entropy" of the UE can be obtained to quantify the orderness of the system. The specific index system is shown in table 1.

| Target hierarchy | Rule hierarchy | Index hierarchy | Units |
|------------------|----------------|-----------------|-------|
| UE               | Input-output entropy | Backup inflow entropy | Per capita GDP |
|                  |                |                 | Local financial revenue |
|                  |                |                 | Total volume of foreign trade $\times 10^8$ US $ |
|                  |                |                 | Grain output $\times 10^4$ t |
|                  |                |                 | Total vegetable production $\times 10^4$ t |
|                  |                |                 | Total output of meat $\times 10^4$ t |
|                  |                |                 | Total fruit production $\times 10^4$ t |
|                  |                |                 | Total aquatic product $\times 10^4$ t |
|                  |                |                 | Steel product quantity $\times 10^4$ t |
|                  |                |                 | Cement output $\times 10^4$ t |
|                  |                |                 | Electric energy production $\times 10^4$ kw· h |
|                  |                |                 | Urban residents’ education cultural entertainment expenses Yuan per person |

Table 1. Evaluation index system of sustainable development ability
| Imposed output entropy | Population density | Person/km² |
|------------------------|--------------------|------------|
|                        | Population growth  |            |
|                        | Residential electricity consumption | \( \times 10^6 \) kw·h |
|                        | Daily water consumption per capita | Litre |
|                        | The per capita consumption expenditure of urban residents | Yuan |
|                        | The per capita living consumption expenditure of rural residents | Yuan |
|                        | Energy consumption | \( \times 10^4 \) t standard coal |
|                        | Industrial energy consumption | \( \times 10^4 \) t standard coal |
|                        | Consumption of chemical fertilizers | \( \times 10^4 \) t |
|                        | Car ownership per 100 households | - |
| Metabolism entropy production | Destructive metabolism entropy | |
|                        | Total industrial wastewater discharge | \( \times 10^4 \) t |
|                        | Urban sewage discharge | \( \times 10^8 \) m³ |
|                        | Total industrial emissions | \( \times 10^4 \) t |
|                        | Total dust emission of smoke | \( \times 10^4 \) t |
|                        | Total sulfur dioxide emissions | \( \times 10^4 \) t |
|                        | PM concentrations | \( \mu g/m³ \) |
|                        | SO₂ concentration | \( \mu g/m³ \) |
|                        | NO₂ concentration | \( \mu g/m³ \) |
|                        | Industrial solid waste production | \( \times 10^4 \) t |
|                        | Life garbage clearance volume | \( \times 10^4 \) t |
| Regenerative metabolism entropy | Treatment rate of domestic sewage | % |
|                        | Life garbage treatment rate | % |
|                        | The percentage of industrial solid wastes that are comprehensively utilized | % |
|                        | Water grades better than III | % |
|                        | Green coverage of built-up area | % |
|                        | Nature reserve area ratio | m² |
|                        | Per capita park green area | m² |
|                        | Water-saving irrigation area | \( \times 10^3 \) hm² |
|                        | Length of drainage pipes | km |
|                        | The proportion of environmental protection input | % |
3.2. Quantitative model of information entropy

According to the information entropy theory of Shannon C. E., for an uncertain system such as the UE, if the random variable \( X \) is used to represent its state characteristics: for discrete random variables, assume the value of \( X \) is \( X = \{x_1, x_2, ..., x_n\} (n \geq 2) \), each value corresponds to probability \( P = \{p_1, p_2, ..., p_n\} \) \((0 \leq p_i \leq 1, i = 1, 2, ..., n)\), and \( \sum_{i=1}^{n} p_i = 1 \), then the information entropy of the system can be calculated by following formula[7]:

\[
S = - \sum_{i=1}^{n} p_i \cdot \ln(p_i) \tag{1}
\]

Where \( S \) is the information entropy of the uncertain system, and \( p_i \) represents the probability of each discrete random variable \( X \).

Based on the above theories, this model is divided into two parts: the year information entropy and the index information entropy. The evolution direction and complexity of the system are analyzed by year information entropy. The index information entropy is combined with the analytic hierarchy process to determine the index weight, which can calculate the comprehensive score of the system and the comprehensive development degree and the coordinated development degree. Thus, the health and coordination degree of UE are judged.

3.2.1. Year information entropy

Year information entropy \( \Delta S \) system can be expressed as follows:

\[
\Delta S = - \frac{1}{\ln m} \sum_{i=1}^{n} \frac{q_{ij}}{q_j} \ln \frac{q_{ij}}{q_j}, q_j = \sum_{i=1}^{n} q_{ij} \quad (i = 1, 2, ..., n; j = 1, 2, ..., m) \tag{2}
\]

Where \( m \) is the year, \( n \) is the index, and the \( \Delta S \) is the year information entropy of the UE. \( q_{ij} \) is the standardized value of each index and \( q_j \) is the sum of the normalized values of the \( j \) year.

3.2.2. Index information entropy

The multi-dimensional information in the system is comprehensively quantified, and the score of UE in this study adopted the comprehensive weighted index model:

\[
G = \sum W_i \cdot X_{ij} \tag{3}
\]

Where \( G \) is the total score of the sustainable development ability of UE in a certain year, and \( X_{ij} \) is the standardized value of each index. \( W_i \) is the weight of each index, which can be calculated by the following formulas:

\[
W_i = (w_{i1} + w_{i2})/2, w_{i1} = (1 - e_i)/(n - \sum_{i=1}^{n} e_i) \tag{4}
\]

\[
e_i = - \frac{1}{\ln m} \sum_{j=1}^{m} \frac{x_{ij}}{x_i} \ln \frac{x_{ij}}{x_i}, X_i = \sum_{i=1}^{n} X_{ij} \quad (i = 1, 2, ..., n; j = 1, 2, ..., m) \tag{5}
\]

Where \( w_{i1} \) is the weight of entropy weight calculation, and \( w_{i2} \) is the weight of analytic hierarchy process, \( e_i \) is the index information entropy.

The relationship between urban ecological environment and socio-economic development can be analyzed by "comprehensive development degree" and "coordinated development degree" model [8]. Among them, the overall benefit evaluation of ecological environment and economic development adopts "comprehensive development degree \( T \)":

\[
T = \alpha_1 G_1 + \alpha_2 G_2 + \alpha_3 G_3 + \alpha_4 G_4 \tag{6}
\]

Where the \( \alpha_i \) ( \( i = 1, 2, 3, 4 \) ) is the coefficient of bias, and \( \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 = 1 \). \( G_1, G_2, G_3 \) and \( G_4 \) are the information entropy scores of various indicators. The higher the score of \( T \), the higher
the comprehensive development of UE. The level of coordinated development of environment and economy adopts the "coordinated development degree D":

$$D = \sqrt{\left(\frac{G_1G_2G_3G_4}{(G_1+G_2+G_3+G_4)^2}\right)^k \cdot T}$$

(7)

Where T is the comprehensive development degree; K is a constant which is 8 in this study. Similarly, the higher the score of D, the better coordinated development of UE.

4. Results and analysis

4.1. Entropy movement analysis of UE evolution

It can be seen from Figure 1 that the backup inflow entropy of Jiangsu province generally showed a parabolic upstate during 2005 to 2015. With the rapid development of social economy, the demand of UE for natural resource system is increasing, but this state is slowing down and the system is stabilizing. The imposed output entropy showed a decline trend, indicating that the pressure of population and society on the UE is getting smaller. The destructive metabolism entropy showed a decreasing state of oscillation, indicating that the emission of various pollutants in human production and life has decreased. However, in individual years it has been a significant rise, the governance effect has been repeated, and needed to be intensified to prevent deterioration. The line of regenerative metabolism entropy was a parabola, and in 2010 it exceeded the destructive metabolism entropy, which indicating that the pollution control capacity of urban environment is increasing, and the municipal engineering is also being improved. At the same time, it is found that there was no significant change in entropy in recent years. In order to prevent the occurrence of deterioration, the governance should not be relaxed.

From 2005 to 2015, the input-output entropy, metabolism entropy production and total entropy of the UE in Jiangsu province showed a wavelike decrease change. Although there were slight fluctuations in the year, the overall downward trend was obvious. The input-output entropy is negative, and the decline trend has slowed down in recent years, indicating that the capacity of natural resource system to UE is increasing. Entropy production has experienced the change from positive to negative and the overall trend in declining, which showing that the metabolism capacity of UE in Jiangsu province is increasing, but the entropy production is the most volatile of all three kinds of entropy. How to stabilize the entropy will be the focus of future work. The total entropy value is negative and decreasing continuously, the UE is changing in a healthy and orderly direction, and its stability is continuously enhanced.

4.2. Index movement analysis of UE evolution

As can be seen from Figure 2, the comprehensive development degree of Jiangsu province was almost consistent with the comprehensive score, and there was an obvious process of going up at first and then going down. The development trend of coordinated development degree D was to go up and then down, just the opposite of T. During the period of 2005-2008, the coordinated development degree D was on the rise, and the development type was environmental lag type. At this time, the metabolic and reduction ability of the UE was still at a low level, its carrying capacity to population is still weak. Therefore, although the coordinated development D was on the rise, the comprehensive development degree T and the comprehensive score have declined. In 2008-2015, it showed a trend of rapid decline, the development type was the economic lag type. At this time, the focus of development is to develop economy and improve the coordinated development of environment and economy. Due to the economic level and environmental control level has reached a higher level, so comprehensive development degree T and comprehensive score began to rise, especially after 2011.
Figure 1. Entropy movement of UE in Jiangsu province

Figure 2. Index movement of UE in Jiangsu province

5. Conclusion
The results of the study preliminarily reveal the evolution of urban ecological system and the trend of sustainable development in the past period of Jiangsu province, which can provide some scientific reference for the sustainable development. However, constrained by data acquisition and modeling theory, the algorithm and conclusion have some room for improvement. The study of dynamic evolution of UE with higher "spatial resolution" is an important direction for further research.
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