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Research on Sustainable Development Capacity for the Urban Ecosystem—A Case Study

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Based on the evolution analysis of urban ecosystem and its dissipative structure, this paper established an evaluation index system of urban ecosystem sustainable development capacity. The sustainable development capacity evaluation model of urban ecosystem was built based on the entropy change equation in the second law of thermodynamics and information entropy theory; taking Nanjing city as an example, this paper empirically studies the Nanjing's urban ecosystem sustainable development capacity. The results showed that: between 2005 and 2013, Nanjing's urban environmental pollution has been effectively eliminated; Nanjing's urban ecosystem has developed in an orderly and healthy direction; the carrying capacity of Nanjing's urban ecosystem has been showing an upward trend. The quality of Ecological environment has been improved and the ability of the urban ecosystem to support the urban socioeconomic ecosystem increased continuously.

1. Introduction

Urban sustainable development theory plays an important role in ecosystem sustainable development strategy and has indispensable influences on socioeconomic development. Therefore, how to scientifically judge whether urban ecological environment is well-developed or not becomes a hot issue that is highly related to the aim of achieving ecosystem sustainable development. Meanwhile, the scientific evaluation of urban ecological environment is the basis of judging whether urban ecological environment has a sound development. There are some researches about urban sustainable development. And the main research methods of urban sustainable development can be summarized as follows: first, use comprehensive evaluate on methods, the theory of ecological footprint and the method of artificial neural network to study the issues concerning urban sustainable development (Li et al., 2005; Su and Lin, 2006; Zhou and Guan, 2012); second, draw on the urban ecological theory and the information entropy theory to analyze urban ecosystem sustainable development capacity (Li et al., 2002; Tong et al., 2010); third, employ ecological theories and GIS technology to figure out urban environmental carrying capacity (Xu et al., 2012; Zhou et al., 2002).
However, previous scholars failed to, from the perspective of urban compound ecosystem, carry out an overall analysis of the structure, functions and evolution mode of cities. Given the analysis above and based on the relevant former research, this paper applied the theory of dissipative structure, information entropy theory, to research the structure, function and evolution mode of urban, and combine entropy change analysis and information entropy to establish a coordination degree quantification model of urban ecological environment. Then takes Nanjing as an example, and performs an empirical analysis of Nanjing urban ecological environment sustainable development capacity. This paper tries to offer a new way of systematically studying urban ecological environment sustainable development.

2. Study area

Nanjing (31°14´-32°37´N, 118°22´-119°14´E) is a center for modern services base and also a very important comprehensive industrial production base in Jiangsu China. Since the reform and opening-up, Nanjing's economy has been developing rapidly. Nanjing has achieved extraordinary success in economic and social

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development. Meanwhile, Nanjing faces more and more serious ecological problems, which put much pressure on the city's environmental carrying capacity.

Table1.Index system of sustainable development ability evaluation for the urban ecosystem in Nanjing

Objective	Criterion	Indicators	Unit
Evaluation of the sustainable development evaluation of urban ecosystem	The input supportive type of entropy(A)	Total output of Grain(A_1)	10^4t
		Total output of oil plants(A_2)	10^4t
		Total output of fruits(A_3)	10^4t
		Area of forestation (A_4)	10^3ha
		Output of meat(A_5)	10^4t
		Total aquatic products(A_6)	10^4t
		Output of iron ore(A_7)	10^4t
		Amount of crude oil processing(A_8)	10^4t
		Output of steel(A_9)	10^4t
		Total Exports and Imports in Nanjing(A_{10})	$10^8$$
	The output pressure type of entropy (B)	Permanent population density(B_1)	person/km^2
		Growth rate of population(B_2)	‰
		Per capita annual expenditure for consumption by urban residents family(B_3)	RMB
		Per capita annual expenditure for consumption by rural residents family(B_4)	RMB
		electricity consumption(B_5)	10^8kwh
		Pesticide use(B_6)	10^4t
		fertilizer input level(B_7)	10^4t
		energy consumption of industry(B_8)	10^4tSCE
		Car ownership per 100 urban households by urban residents' family(B_9)	Unit
	The consumption metabolic type of entropy (C)	Industrial wastewater discharged(C_1)	10^8t
		COD in industrial wastewater discharged(C_2)	10^4t
		Emissions of industrial waste gases(C_3)	$10^8/m^3$
		SO_2 in industrial waste gases(C_4)	10^4t
		Emissions of industrial soot(C_5)	10^4t
		Emissions of industrial solid waste(C_6)	10^4t
		Annual average concentration of inspirable particle (C_7)	mg/m^3
		Annual average concentration of NO_2(C_8)	mg/m^3
		Annual average concentration of SO_2 (C_9)	mg/m^3
		number of days of good air quality(C_{10})	day
	The regeneration metabolic type of entropy (D)	Rate of industrial wastewater that meets the discharge standards(D_1)	%
		Rate of Industrial water reuse(D_2)	%
		Rate of industrial solid waste treated and utilized (D_3)	%
		Treatment rate of city sewage(D_4)	%
		Green coverage rate in built-up areas(D_5)	%
		Rate of harmless garbage disposal(D_6)	%
		Water quality of surface water function area compliance rate(D_7)	%
		Environmental protection investment accounted for the proportion of GDP(D_8)	%

3. Research methods

3.1 Establish the evaluation index system

Scientific evaluation indicators are the necessary premise of further researches. Based on the structure, functions, characteristics and the process of metabolism, entropy flow and entropy production of urban socioeconomic ecosystem, this paper divides the evaluation indicators of urban ecosystem into four categories: input supportive type of entropy, output pressure type of entropy, consumption metabolic type of entropy and regeneration metabolic type of entropy.

Input supportive type of entropy mainly refers to the carrying capacity of urban ecosystem. On one hand, the necessities of people's daily life, like grain, meat and edible oil and so on are chosen as the evaluation indicators; on the other hand, the natural ecosystem provides human beings with natural resources to carry out economic activities, so it is necessary to take natural resources, such as iron ore and petroleum, as the evaluation indicators to show the current condition of exploiting and utilizing natural resources.

Output pressure type of entropy refers to the pressure that human economic activities bring to the urban ecosystem. Nowadays, in the process of rapid urbanization, the rate of population growth of cities is still in a high level as more and more people move to cities. It results in the increase of population density and more demand for resources. Meanwhile, with the improvement of people's income, people's consumption capacity also increases, which has brought more pressure to urban ecosystem.

Consumption metabolic type of entropy is about the influences of the wastes and pollution on urban ecosystem. The wastes and pollution are produced in the process of developing urban economy; this also reflects the increase of entropy in the urban ecosystem. Regeneration metabolic type of entropy mainly refers to the condition of controlling pollution. Since the emissions have already been beyond the carrying capacity of the urban ecosystem, people needs to establish policies and apply technologies to tackle the pollution issues and improve the carrying capacity of the urban ecosystem. Given to these four categories, this paper makes an evaluation index system of urban ecosystem sustainable development, as shown in Table 1.

3.2 Building evaluation models based on information entropy

According to the theory of entropy, if a random variable $X=\{x_1, x_2, \ldots, x_n\}$ ($n \geq 2$) and is used to describe the characteristics of a certain system; the corresponding probability of each value of X is $P=\{P_1, P_2, \ldots, P_n\}$ ($0 \leq p_i \leq 1$; i =1, 2, ……n), and $\sum$=1, then the information entropy of the system can be formulated as given by Eq. (1), where S represents the information entropy of an uncertain system, pi refers to the probability of random variable X.

$$S = -\sum P_i \ln(P_i) \tag{1}$$

In the evaluation process of urban ecosystem sustainable development capacity, it is assumed that n indicators have been evaluated in m years, and so ΔS represents the four types of entropy based on information entropy, i.e., input supportive type of entropy ($\Delta S1$), output pressure type of entropy ($\Delta S2$), consumption metabolic type of entropy ($\triangle S_3$) and regeneration metabolic type of entropy ($\triangle S_4$) (Eq. 3).

$$\Delta S = -1/\ln(m)\sum_{i=1}^{n}\frac{q_{ij}}{q_j}\ln\left(\frac{q_{ij}}{q_j}\right) \quad (i=1, 2, \ldots\ldots, n;\ j=1, 2, \ldots\ldots, m) \tag{2}$$

In Eq. (2) the parameter irepresents an indicator, jrepresents an appraisal event, q_{ij} means the standardized value of initial data of the evaluation indicators i, q_j refers to the sum of standardized value of evaluation indicators in j year, and it is fixed that when $q_{ij} / q_j = 0$, $q_{ij} / q_j \ln(q_{ij} / q_j) = 0$, and in this way can $\Delta S \in [0, 1]$.

Thus, the entropy flow, the entropy production and the total entropy change of the urban ecosystem can be concluded as expressed by Eqs. (3-5), where $\Delta S'$ is the entropy flow of the urban socioeconomic ecosystem in each year of the study period, $\Delta S''$ refers to the entropy production of the urban socioeconomic ecosystem in each year of the study period, $\Delta S'''$ means the total entropy change of the urban socioeconomic ecosystem in each year of the study period.

$$\Delta S' = \Delta S_2 - \Delta S_1 \tag{3}$$

$$\Delta S'' = \Delta S_3 - \Delta S_4 \tag{4}$$

$$\Delta S''' = \Delta S' + \Delta S'' \tag{5}$$

Based on the theory of entropy, the derivative of information entropy and multi-dimension information of the urban ecosystem can be quantified and synthesized systematically. When n indicators have been evaluated in m years, let E_i be the information entropy of evaluation indicatori, then it can be can be derived according to Eq. (6), where q_{ij} is the standardized value of initial data of the evaluation indicators i, q_{ij} refers to the sum of standardized value of evaluation indicators in *j* year, and it is fixed that when $q_{ij} / q_j = 0$, $q_{ij} / q_j \ln (q_{ij} / q_j) = 0$.

$$E_i = -1 / \ln(m) \sum_{i=1}^{n} \frac{q_{ij}}{q_j} \ln(\frac{q_{ij}}{q_j}) \quad (i=1, 2, \ldots\ldots, n;\ j=1, 2, \ldots\ldots, m) \tag{6}$$

According to the theory of entropy weight, after the information entropy E_i of evaluation indicator i is figured out, the entropy weight of i indicators can be defined as given by Eq. (7), where Q_i is the entropy weight of evaluation indicatori, E_i refers to the information entropy of evaluation indicator i, n is the number of evaluation indicators. It is also settled that $\sum Qi=1$, $Qi \in [0, 1]$.

$$Q_i = (1 - E_i) / (n - \sum_{i=1}^{n} E_i) \quad (i=1, 2, \ldots\ldots, n) \tag{7}$$

Based on the theory of information, entropy weight presents an evaluation indicator represents how much useful information an indicator can provide. Thus, in the evaluation indicator system of urban ecosystem sustainable development, the bigger entropy weight of an evaluation indicator is, the more useful information it offers, in other words, it has more effects on the evaluation system.

After calculating the entropy weight of all the evaluation indicators, the urban ecosystem sustainable development capacity G in m year can be derived, according to Eq. (8), where Q_i is the entropy weight of evaluation indicator i,X_i is the standardized value of the evaluation indicators.

$$G = \sum Q_i X_j \quad (i=1, 2, \ldots\ldots, n;\ j=1, 2, \ldots\ldots, m) \tag{8}$$

The larger G is, the safer the urban ecosystem is and the stronger the urban sustainable development capacity is. Otherwise, the urban sustainable development capacity is weak and may limit the development of the city in the future.

3.3 Data sources and method

All the data used in the research is from Statistical Yearbook of Nanjing between 2006 and 2013. The method of standardizing data in this paper is shown as follows (Eq. 9).

$$X' = X_{ij} / \sum X_{ij} \quad (i=1, 2, \ldots\ldots, n;\ j=1, 2, \ldots\ldots, m) \tag{9}$$

In Eq. (9), X' is the standardized value of evaluation indicators, X_{ij} is the initial data of evaluation indicators.

4. Results and analysis

4.1 Analysis of the sustainable development ability of Nanjing's urban ecosystem

According to the models (1)-(9) and the theory of information entropy, the entropy values of Nanjing's urban ecosystem and the evolution process of entropy change was shown in Table 2.

From Table 2, it can be seen that even though Nanjing's input supportive type of entropy reached the minimum 0.09576 in 2010, Nanjing's input supportive type of entropy has been increasing rapidly in the research period and it reached the maximum in 2012. With 2007 as the cut-off point, the development of the output pressure type of entropy can be divided into two stages. The first stage is from 2005 to 2007, when Nanjing's output pressure type of entropy gradually decreased; the second stage is from 2008 to 2012, when Nanjing's output pressure type of entropy increased speedily. The increase of output pressure type of entropy shows that Nanjing's economy developed very swiftly, the population grew at a high speed and the adjustment of industrial structure went on slowly. All these made Nanjing's urban ecosystem under great pressure.

The consumption metabolic type of entropy and the regeneration metabolic type of entropy of Nanjing's urban ecosystem did not great changes during the years from 2005 to 2012. However, generally speaking, the consumption metabolic type of entropy had been decreasing. With 2008 as the turning point, the development of the regeneration metabolic type of entropy can be divided into two stages. This former one is before 2008, when the regeneration metabolic type of entropy increased gradually; the later one is after 2008, when the regeneration metabolic type of entropy decreased gradually. And the regeneration metabolic type of entropy was still bigger than consumption metabolic type of entropy (Table 2). This change of the regeneration metabolic type of entropy indicates that pollution issues in Nanjing began to be under control, and Nanjing's urban ecosystem carrying capacity has been improved.

From Table 2 and Figure1, it can be seen that the entropy flow of Nanjing's urban ecosystem gradually improved from 2005 to 2012. The entropy production and total entropy change present a narrowly vibrating trend since it's sometimes increased and sometimes decreased and the tendency of the entropy production and total entropy change is to increase on the whole. This showed that the environmental pollution in Nanjing had been effectively controlled, Nanjing urban ecosystem was improved. Nanjing's urban ecosystem carrying capacity was gradually improved during the study period. However, Nanjing will still face many great environmental challenges in the coming years.

Table 2: Values of the entropy of the urban socioeconomic ecosystem in Nanjing during 2005–2012

Type of Entropy	2005	2006	2007	2008	2009	2010	2011	2012
Input supportive type of entropy	0.1088	0.1110	0.1162	0.1160	0.1180	0.0958	0.1623	0.1718
Output pressure type of entropy	0.1021	0.0946	0.0975	0.1160	0.1168	0.1172	0.1744	0.1813
Consumption metabolic type of entropy	0.1332	0.1369	0.1295	0.1250	0.1110	0.1169	0.1283	0.1192
Regeneration metabolic type of entropy	0.1192	0.1263	0.1307	0.1311	0.1245	0.1269	0.1168	0.1223
Entropy flow	-0.00671	-0.01643	-0.01872	0.00005	-0.00112	0.02143	0.0121	0.0095
Entropy production	0.0141	0.0106	-0.0012	-0.0060	-0.0135	-0.0099	0.01144	-0.00314
Total entropy change	0.0073	-0.0058	-0.0199	-0.0060	-0.0146	0.0115	0.0235	0.0063

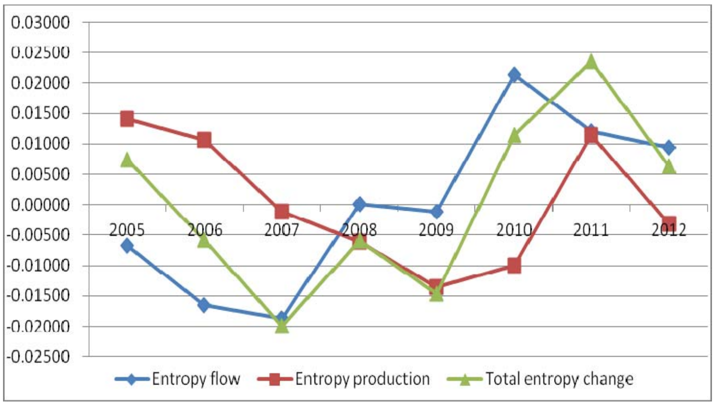

Figure 1: Values of entropy flow, entropy production and total entropy change of the urban socioeconomic ecosystem in Nanjing during 2005–2012

5. Conclusions

With the rapid development of Nanjing's economy and society, Nanjing demands more and more natural resources from the urban ecosystem; but the environmental pollution and the waste resources occurred in the development of economy and society, has brought tremendous pressure on Nanjing's urban ecosystem. While, Nanjing municipal government has taken effective policies to deal with pollution and other environmental problems. Now, the city's ecosystem and carrying capacity of urban ecosystem, as well as the urban ecosystem sustainable development capacity has been improved steadily. The urban ecosystem itself, on the whole, gradually developed towards being orderly and healthy during the study period.

This paper also finds that it is feasible to apply the theory of dissipative structure and information entropy theory to the evaluation of urban ecosystem sustainable development capacity. The research results not only correspond to reality, but also make up the insufficiency of the studies on urban ecosystem.

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