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Urban ecological regulation based on information entropy at the town scale

A case study on Tongzhou district, Beijing City

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Abstract

Based on dissipative structure theory and ecological cybernetics, an ecological regulation approach at the town scale was developed, which was aimed at increasing system order and maintaining a healthy system by reducing the entropy of the urban ecosystem. First, considering the characteristics of the urban nature-economy-society complex ecosystem and entropy theory, the entropy of the urban ecosystem was defined as a state parameter indicating system disorder, and it could be divided into entropy flow and entropy production. Second, an entropy evaluation indicator system for the urban ecosystem was constructed by associating ecosystem characteristics at the town scale. Then, using Tongzhou district of Beijing City as an example and future city development planning objects and policies about national environmental protection and energy-saving and emission-reduction, adjustable indicators were selected, and a system entropy regulation approach was established. These indicators were easy to obtain and regulate with the purpose of reducing system entropy. Finally, via quantitative model of computing information entropy, we analyzed the entropy change of the urban ecosystem, as well as the harmonious degree and developmental degree in Tongzhou district for both the evaluation time period (2000-2007) and the planning year (2020). Our results indicated that after the regulation approach was brought into effect, the entropy flow, entropy production and total entropy substantially would reduce compared with the same variable during the evaluation period. Thus, system order can be significantly enhanced, and the regulation approach was proven to be effective. This study provides a new regulation approach to solve complex eco-environmental problems during the urbanization process.

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1. Introduction

The occurrence and development of urban disease is an unbalanced and inharmonious phenomenon that is caused by the interaction of complex ecosystems, including nature, the economy, and society. It is also a process characterized by dissipativity and disorderliness, in which the degree of system disorder increases [1]. In recent years, as a tool to measure disorderliness, entropy (a thermodynamic concept) was introduced into research of ecological and environmental systems, such as aquatic environments [2, 3], land use [4], transportation systems [5], ecological economies, and cyclic economy systems [6]. In research that uses entropy to analyze the urban nature-economy-society complex ecosystem, Miyano [7] analyzed the evolution of the urban ecosystem by introducing entropy analysis into the dynamical model. He used metabolic processes to describe the evolution of the urban ecosystem and found that using physical and chemical concepts (e.g., oxidation and reduction) could clearly describe the timeline dynamics characteristics of an urban ecosystem. Zhang et al. [8] analyzed the harmonious degree, system order, and sustainable developmental degree of an urban ecosystem (Ningbo City in China) by using information entropy theory from 1996 to 2003 and developed four types of calculation and evaluation methods for entropy indicators. Qiu and Wang [9] analyzed the operation of complex ecosystems with entropy theory, which provided the research basis for flow analysis and harmony control of urban ecosystem entropy. Currently, most concepts and methods about entropy are applied in the evaluation and evolution analysis of various systems based on information entropy theory, but little has been written about entropy theory for ecological regulation.

At present, both domestic and foreign conventional urban ecological regulation approaches generally summarize urban problems with subjective thought and judgment and then develop regulatory measures. Thus, these approaches do not focus on system integrity and cannot quantitatively inspect the effects of regulation. Moreover, domestic cases are concentrated in Beijing, Shanghai, Guangzhou, and other large central cities. With the urbanization of rural districts, many urbanization problems have become barriers to sustainable development construction processes in rural areas. Considering that urban ecosystems always develop in the direction where entropy has continuously increased (i.e., increasing disorder), this study extends the quantitative assessment model of urban ecosystem evolution proposed in reference [8] to the research of urban ecosystem regulation based on system theory and the second law of thermodynamics. Taking Tongzhou district of Beijing City as an example, an urban ecological regulation method at the town scale is developed with the aim of reducing entropy. This method provides a scientific decision basis for the harmonious development of urban ecosystems.

2. Connotation of urban ecosystem entropy and urban ecological regulation principles

An urban ecosystem is a typical dissipative structure deviating from equilibrium, so its entropy flow and entropy production have different meanings from the traditional ones. Urban ecosystem entropy is a state parameter indicating system disorder, and it can be divided into entropy flow and entropy production [8]. Urban ecosystem entropy flow refers to the entropy change resulting from the exchange of material flow and energy flow between the urban socio-economic system and the natural support system. Urban ecosystem entropy production refers to pollutants and energy loss generated in the inner operation of socio-economic systems, as well as the entropy change resulting from the construction of the ecological environment and infrastructure. Urban ecosystem entropy flow includes sustaining input entropy from natural ecological subsystems to socio-economic subsystems and imposed output entropy, which is

caused by the cost of natural resources for the socio-economic subsystems' development. Entropy production includes destructive metabolism entropy, which is caused by environmental pollutants with socio-economic activities, and regenerative metabolism entropy, which indicates material energy stored in the urban environmental protection and infrastructure in the urban metabolism process. Urban ecosystem entropy flow can represent the harmonious capacity of system. Entropy production reflects the capacity for system reduction and reproduction in metabolism processes, so it can indicate the vigor of the system. Entropy change, which refers to the overall development of an urban ecosystem, can indicate system order and fitness.

Under practical economic and technical conditions, urban ecological regulation based on entropy is used to analyze and control entropy flow of the system by means of regulating system structure to reduce the system's internal friction and increasing infrastructure construction and environmental protection. The object is to decrease the total entropy of an urban ecosystem and enhance system order. As a result, sustainable development of the ecosystem will be accelerated.

3. Urban ecological regulation methods at the town scale

3.1. Construction of an entropy assessment indicator system for an urban ecosystem

According to dissipative structure theory, considering eco-environmental pressures from anthropic production and socio-economic activities, support from the existence of natural resources to socio-economic activities, pollutants production in socio-economic systems, and an ecological environment's purification ability, we construct an entropy assessment indicator system with a multi-hierarchy and multi-indicators for an urban ecosystem, as shown in Table 1. Sustaining type indicators and imposed type indicators are used to calculate the entropy flow of the urban ecosystem, while oxidative type indicators and reductive type indicators are used to calculate the entropy production of the urban ecosystem. Because urban ecosystems are complicated by their own characteristics and urban issues, indicator selection should be adjusted based on local conditions. For example, the socio-economic development and ecological environmental conditions of Tongzhou district are considered in this case study. Undergoing a rapid urbanization process, all villages and towns of this area are dominated by typical rural areas, except for streets that are subordinate to municipal administration. Thus, when we select urban ecosystem entropy indicators for this district, its urban-rural characteristics are emphasized.

3.2. Quantitative method for urban ecosystem entropy

This paper applies the urban ecosystem evolution model established in reference [8] to quantify entropy flow and entropy production. Based on the calculation principle of information entropy and the nonlinear characteristics of an urban system, we can use equation (1) with the normalization value of the original value of the urban ecosystem entropy assessment to evaluate an urban ecosystem entropy with n indicators and m years, and four types of entropy are obtained [8]:

$$\Delta S = -\frac{1}{\ln n} \sum_{i=1}^n \frac{q_{ij}}{q_j} \ln \frac{q_{ij}}{q_j} \quad (1)$$

where q_{ij} is the normalization value of the i th indicator in year j , and q_j is the sum of normalization

values of n indicators in the j th year, i.e., $q_j = \sum_{i=1}^n q_{ij} (i = 1, 2, \dots, n; j = 1, 2, \dots, m)$.

Then, based on the difference between positive and negative values of entropy production and entropy flow, we apply equation (2) to obtain the total entropy of the system:

$$S = (\Delta_i S_2 - \Delta_i S_1) + (\Delta_e S_2 - \Delta_e S_1) \quad (2)$$

where S is the total entropy, $\Delta_e S_1$ is sustaining input entropy, $\Delta_e S_2$ is imposed output entropy, $\Delta_i S_1$ is regenerative metabolism entropy, and $\Delta_i S_2$ is destructive metabolism entropy. $\Delta_e S_2 - \Delta_e S_1$ indicates entropy flow, and $\Delta_i S_2 - \Delta_i S_1$ indicates entropy production.

4. Case study

This paper study urban ecological regulation with entropy decrease as an object by using Tongzhou district (Beijing) as an example. Tongzhou district is located southeast of Beijing, to the northern end of the Grant Canal from Beijing to Hangzhou. As an eastern development belt in the urban spatial structure of “two axes — two bands — multiple centers” proposed in the Beijing Urban Master Plan (2004-2020), Tongzhou district is Beijing city's comprehensive service center in the future and is also an important base where Beijing takes part in the cooperative development of districts surrounding Bohai Sea. It will develop into an important region by leading the economy in the capital's main city zone, dividing the population in the urban area, promoting eastern industrial belt development, and supplying new economic development for the capital. The boundaries of the research system are determined according to Tongzhou District's administrative region, which includes 11 towns (Yongshun, Liyuan, Songzhuang, Lucheng, Xiji, Huoxian, Yongledian, Zhangjiawan, Majuqiao, Taihu, and Yujiawu Hui Nationality Autonomous Town). In recent years, both the society and economy have rapidly developed in Tongzhou, and industries responsible for a large quantity of pollutants are concentrated in the chemical, paper, brewing, and machinery manufacture industries.

4.1. Establishment of regulation indicators

To provide evidence to develop a regulation program, equations (1) and (2) are applied to preliminarily analyze the developmental degree and harmonious degree of the urban ecosystem in the research area from 2000 to 2007. Our results demonstrate that entropy flow changes are the dominant factor affecting system entropy changes. This region is at the beginning of the urbanization construction stage, with economic development causing great pressure on the environment, so the harmonious development capacity of the system should be further strengthened.

Next, factors that greatly contribute to entropy flow and entropy production are chosen. According to the characteristics of specific indicators and difficulties in actual regulation, quantitative indicators of the system state can be divided into the following three types: 1) Adjustable indicators. These indicators can be adjusted through specific economic methods, technical methods, and policies to adjust them into the best range in which society, economy, and the environment can develop in harmony. Generally speaking, for single factor assessment, the larger that adjustable indicators are, the better they will be, such as

sustaining-type indicators of the natural socio-economic system (e.g., grain and vegetable yields), economic growth indicators (e.g., urbanization rate, rural per capita net income, and urban per capita disposable income), and reductive-type indicators of natural systems (e.g., the proportion of environmental protection investment in GDP and the forest coverage rate). 2) Controllable indicators. These indicators can mainly be controlled by administrative and economic means, as well as by auxiliary control from engineering technical means. Controllable indicators are generally negative factors in a system state assessment, i.e., the lower the value, the better the result. Such indicators include population density, application rates of pesticides and fertilizers, and pollutant yield indicators (e.g., industrial exhaust emission and SO₂ emission). 3) Indicators which are not easily regulated but relatively stable. These indicators cannot be easily adjusted by means of economy and technique, such as total annual electricity consumption of the entire region, the industrial solid waste treatment rate, and the urban garbage treatment rate.

According to the future development direction proposed in the Tongzhou New Town Planning (2005-2020), combined with the Tongzhou district environmental quality report and information about related industries and environmental policies, the predictive results of regulation indicators in the planning year (2020) are shown in last column of Table 1.

Table 1. Indicator system of entropy analysis and sample values in Tongzhou district, Beijing.

Indicator type	Indicator	Unit	Evaluation time frame								Planning year
			2000	2001	2002	2003	2004	2005	2006	2007	2020
Sustaining type indicator (A)	A ₁	×10 ⁴ t	22.4	16.5	13.5	12.3	14.3	18.4	21.5	22.7	23
	A ₂	×10 ⁴ t	85.9	93.4	99	91.4	87.9	73.5	72.4	65.6	70
	A ₃	t	42441	43329	48705.9	54648	57047	58875	55979	52049.3	50000
	A ₄	ha	1386.03	2646.67	4113.33	4793.33	466.67	718.47	324.53	377.78	350
	A ₅	million RMB	1378.38	4072.09	5349.77	8907.27	9698.75	10171.98	11855.87	13260.00	71460.00
	A ₆	billion RMB	6.07	7.34	9.13	10.76	12.99	14.298	16.305	18.68	95.28
	A ₇	t	3680	9828	12173.7	18331.2	19674.2	18897.4	17468.8	27885	55770
	A ₈	t	56202.3	67209.1	67924.6	97402.6	94762.8	97226.6	71714.8	64240.6	70000
	A ₉	thousands yuan/person	0.31	0.39	0.49	0.66	0.7	0.83	0.99	1.44	8
Imposed type indicator (B)	B ₁	person/km ²	658.6	666.7	669.3	673	683.8	693.6	702.5	708.9	1313
	B ₂	10 ⁴ kwh	87392.2	90374.2	112359.8	158596.9	202327.4	233493	268784	301947	777983.4
	B ₃	%	32	33.5	36	39	41	43	45	46.3	75.6
	B ₄	yuan	4903	5269.6	5835	6445	7092.4	7661.1	8348.9	9114.5	31423
	B ₅	yuan	7135	8505.5	10081	11969	13673	15604	17070	18887	65114
	B ₆	Kg/ha	677.55	677.55	569.25	569.25	569.25	465.75	465.75	378.25	250
	B ₇	Kg/ha	7.24	6.14	6.25	5.97	6.12	5.35	4.35	4.89	2.0
	B ₈	×10 ⁴ t standard coal	72.6	77.5	73.2	70.9	77.6	72.2	71.5	70.6	24
Oxidative type indicator	C ₁	×10 ⁴ standard m ³	665489	572831	688530	591137	579332	815515	608145	561102	417544
	C ₂	t	3612.5	3252.1	2811.3	3003.3	1799.8	1748	1688	1702.6	1415.8

Reductive type indicator (D)	(C)	C ₃	Mg/m ³	0.159	0.155	0.152	0.147	0.157	0.139	0.156	0.142	0.10
	C ₄	×10 ⁴ t	552.35	626.01	829.46	819	799.56	760.69	758.96	734.76	6290.8	
	C ₅	×10 ⁴ t	5.56	6.58	8.6	11.2	11	10.87	10.78	10.56	12	
	C ₆	×10 ⁴ t	13.5	13.7	13.7	13.8	14.0	14.2	14.4	14.6	26.9	
	C ₇	×10 ⁴ t	2595.35	3045.01	3237.46	3441	3799.56	3860.66	3885.11	3903	12154.5	
	D ₁	%	90	95.2	100	100	100	100	100	100	100	
	D ₂	%	45.5	43.2	50.6	45.7	71.1	72.3	87.5	99.8	100	
	D ₃	%	55	60	70	80	90	100	100	100	100	
	D ₄	%	55	63	68	70	75	80	85	90	100	
	D ₅	%	45	45	65	80	90	100	100	100	100	
	D ₆	%	3.15	3.84	3.95	3.75	2.94	4.49	5.64	6.33	6.5	
	D ₇	%	14.1	15.78	17.68	21.95	22.15	22.27	22.34	22.41	25	

Note: A₁, total grain yield; A₂, total vegetable yield; A₃, nut and fruit yield; A₄, afforestation area; A₅, total investment in fixed assets; A₆, GDP; A₇, finished construction materials; A₈, total meat yield; A₉, culture, education, and health investment; B₁, population density; B₂, total electricity consumption of the whole district; B₃, urbanization rate; B₄, per capita annual net income of rural residents; B₅, per capita annual disposable income of rural residents; B₆, consumption of fertilizers; B₇, consumption of pesticides; B₈, consumption of coal; C₁, industrial exhaust emissions; C₂, SO₂ emission; C₃, annual daily average of inhalable particles; C₄, total industrial wastewater emission; C₅, industrial solid waste production; C₆, household garbage production; C₇, total wastewater emission; D₁, rate of industrial wastewater that meets the discharge standards; D₂, utilization rate of straw; D₃, treatment rate of industrial solid waste; D₄, resourcing rate of animal manure; D₅, treatment rate of hazardous urban household garbage disposal; D₆, proportion of environmental protection investment in GDP; and D₇, forest coverage rate.

4.2. Entropy analysis of the regulation program for the urban ecosystem

Next, we combine the regulation indicators values of the urban ecosystem entropy for the planning year 2020 with those of the evaluation time period (2000-2007) in Tongzhou district. After normalization, we apply equations (1) and (2) to calculate information entropy of the indicators, and the results are shown in Fig. 1 and Fig. 2. In Fig. 1, compared with 2000-2007, we find that sustaining input entropy (i.e., negative entropy) has increased significantly, destructive metabolism entropy (i.e., positive entropy production) has decreased substantially, and imposed output entropy and regenerative metabolism entropy has trended stably after regulation. The main reason for these effects is that aside from speeding the development of the social economy and technology, this program also pays attention to energy saving and emission reduction, pollution control, and management. This enables the system to develop in the direction of efficient production output, low power consumption, and low pollutant emission. In addition, considering the solid basis for the environmental protection policy in Tongzhou district, there is little room to improve the regenerative metabolism, so it must maintain the current situation. From changes in four plots in Fig.1, we can see that regulation measures are efficacious.

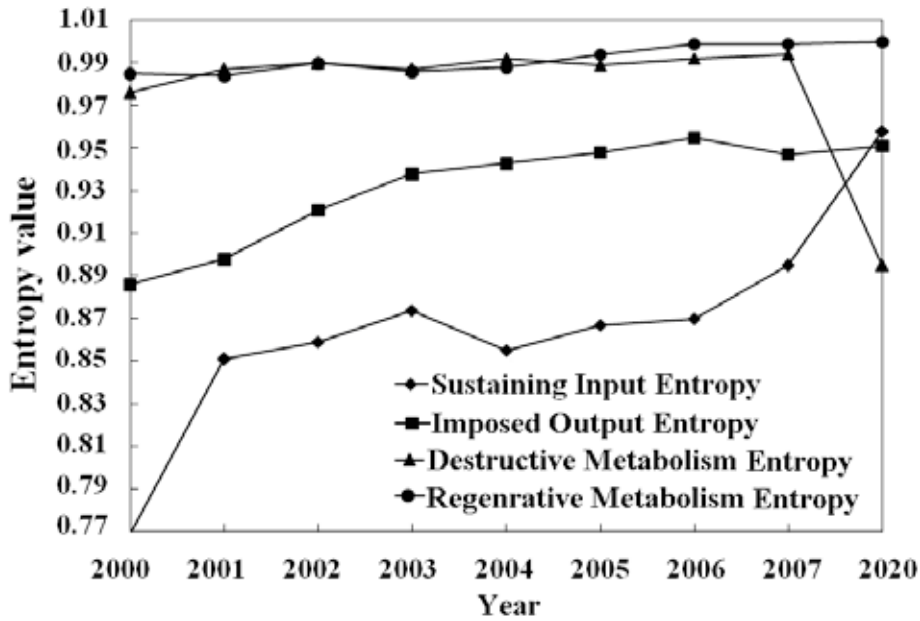


Figure 1. Four types of entropy change analysis for the regulation program of the urban ecosystem.

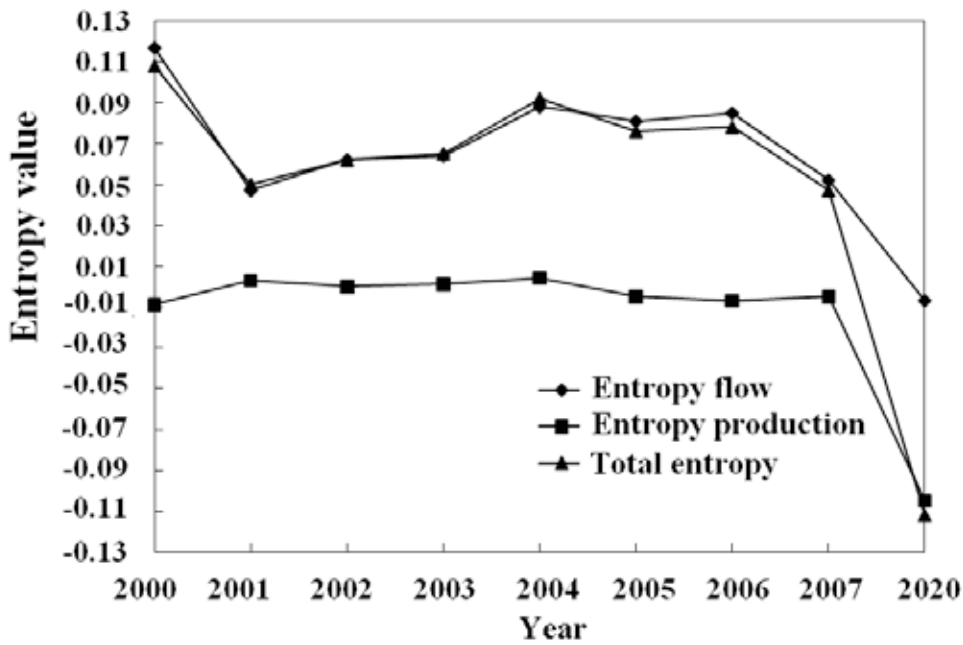


Figure 2. Change analysis of entropy flow and entropy production of the regulation program for the urban ecosystem.

Comparing the variation trend of entropy flow, entropy production, and total entropy (Fig. 2), we can see that an entropy decrease is apparent. Changes of entropy flow and entropy production in each year are similar. It is obvious that after implementation of the regulation program, negative entropy flow increases, and metabolism entropy production within the system decreases. Until 2020, total entropy will reduce

compared with the evaluation time period (2000-2007), and system order will be significantly improved. Both Fig. 1 and Fig. 2 reveal that the regulation program is efficacious for reducing entropy and increasing system order.

4.3. Developmental degree and harmonious degree analysis of the urban ecosystem regulation program

Scores of entropy flow and entropy production in the urban ecosystem can reflect the harmonious degree of urban ecosystem development. Only when both the developmental degree and harmonious degree increase at the same time can the urban ecosystem achieve sustainable development. Based on urban nature-economy-society complex ecosystem theory, reference [8] developed a model by drawing lessons from the harmonious developmental degree model, which was developed by production of possibility curves. This model applied development curves $y=1/2-x^3$, $y=3/4-x^3$, and $y=1-x^3$ and the significance of each district, then changed scores of sustaining input entropy, imposed output entropy, destructive metabolism entropy, and regenerative metabolism entropy to developmental degree, harmonious degree, and leaning harmonious degree [8]. This model can reflect the possible trend of the system developmental degree and harmonious degree and ultimately determine the balanced development between ΔeS_2 and ΔeS_1 , as well as ΔiS_2 and ΔiS_1 . Using this model, Fig. 3 and Fig. 4 show assessment indicator calculation results of entropy flow and entropy production based on the urban ecosystem regulation program.

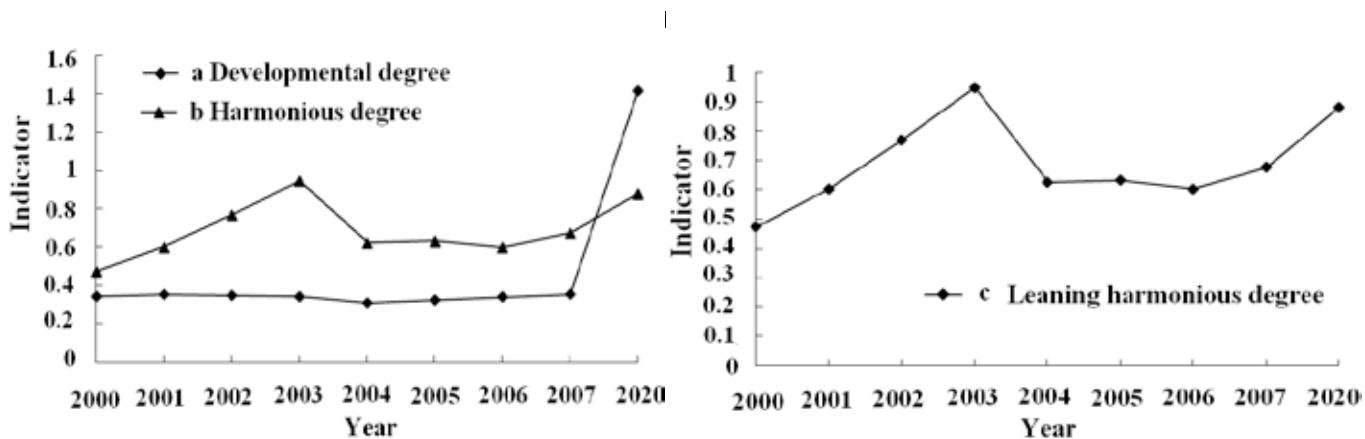


Figure 3. Developmental degree, harmonious degree, and leaning harmonious degree of entropy flow in the urban ecosystem regulation program.

As shown in Fig. 3 (left), due to rapid economic growth, the system developmental degree increases greatly after system regulation. Considering system harmonious development, the change of the harmonious degree fluctuated gently after the inflection point in 2004. Until 2020, indicator values calculated with regulation program data are basically the same as those in 2003, so it can be observed that the regulation emphasis of the urban ecosystem is to promote the synchronous development of the environment and economy in Tongzhou district. This will be accomplished by adjusting the industrial structure, as well as adopting an economic growth mode with high efficiency, low energy consumption, and low pollution. Fig. 3 (right) demonstrates that the leaning harmonious degree of the urban ecosystem

has a consistent trend with the system harmonious degree. This result indicates that the Tongzhou ecosystem has been continuously adjusting its social-economic structure, and the harmful inertia influence to the ecosystem environment caused by rapid development of society and the economy is also improved. As a result of establishing a business restructuring plan, the harmonious ability of the system will be gradually enhanced.

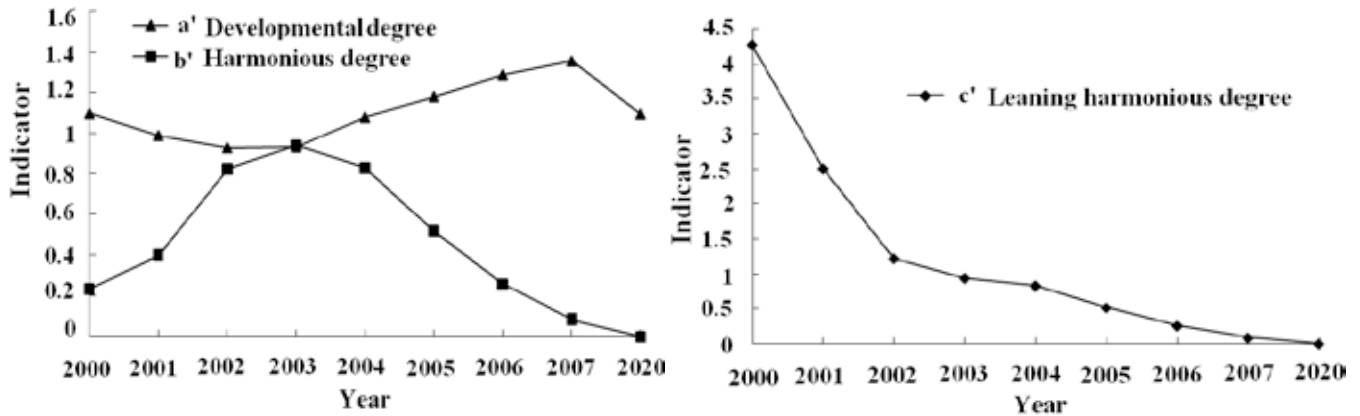


Figure 4. Developmental degree, harmonious degree, and leaning harmonious degree of entropy production in the urban ecosystem regulation program.

Fig. 4 (left) shows that after implementation of the regulation program, the developmental degree of the entropy production (i.e., metabolism) of the urban ecosystem is initially reduced, then increases, and finally decreases again after 2007. The curve indicates that the system's metabolic function is unstable, with an inflection point in 2007. The reason is that the developmental degree of the metabolic system is mainly due to the score of the destructive metabolism entropy. Implementation of environmental protection and energy saving policies require the control of pollution emission indicators, and the trend reflected by the curve demonstrates reduction of system energy. Considering the system metabolism harmonious degree, it begins to develop support for reductive metabolism after experiencing a pressure peak of the oxidized metabolism. This phenomenon indicates that the reductive ability of the eco-environment system has been continuously enhanced. In Fig. 4 (right), in the aspect of leaning harmonious degree, the urban ecosystem is always transforming from oxidative reductive metabolism, which indicates that the investment in ecological environment construction has increased yearly in Tongzhou district. This can avoid ecological environment degeneration caused by the rapid urbanization process and growing population pressure. Accordingly, from Fig. 3 and Fig. 4, it can be seen that the regulation program is effective, and the orderliness of the urban ecosystem has been significantly enhanced.

5. Conclusions

In this paper, according to the current development situation of rapid urbanization in rural areas, we extend a quantitative model of urban ecosystem evolution to develop an ecological regulation method at the town scale. This method aims to increase system order by reducing urban ecosystem entropy. Combined with ecosystem characteristics at the town scale, an entropy analysis indicator system of an

urban ecosystem is established, which contains three layers (i.e., the target, rule, and indicator layers), four principle levels (i.e., sustaining input entropy, imposed output entropy, destructive metabolism entropy, and regenerative metabolism entropy), and 31 indicators. Using Tongzhou district of Beijing as an example, with the future city development planning objects and policies about national environmental protection, energy-saving, and emission-reduction, the system entropy regulation program is established. Finally, with a quantitative model based on information entropy and the harmonious developmental degree model, we analyze entropy change, the harmonious degree, and the developmental degree of an urban ecosystem in both an evaluation time period (2000-2007) and planning year (2020). Our results indicate that after the regulation program is brought into effect, entropy flow, entropy production, and total entropy will be substantially reduced compared with the evaluation time period, and system order will be significantly enhanced. Thus, it has proven that the regulation program is feasible and effective, and this study provides a new method for urban ecological regulation in the urbanization process.

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