Evaluation of Urban Ecological Carrying Capacity Based on State-space method

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Abstract: Urban ecological carrying capacity is an important standard to measure the sustainable development of urban ecology. In this paper, the evaluation index system of urban ecological carrying capacity is established from three aspects of the ecological elastic force, the supporting force of carrying media and the pressure of carrying objects. A new expression of state-space method for evaluation carrying capacity is presented innovatively. The new method and index system were applied to the evaluation of five provinces in the lower reaches of the Yangtze river. The results showed that the order of urban ecological carrying capacity was Jiangxi > Shanghai > Zhejiang > Jiangsu > Anhui. Finally, some suggestions for future development are put forward according to the evaluation results of each province, which is helpful to the formulation of ecological civilization construction policies.

1. Introduction

Half of the population now lives in cities, and by 2030 nearly 60% of the world's population (about 5 billion) will live in cities [1]. With the acceleration of industrialization, new-type urbanization in China is also developing rapidly. From 1978 to 2015, the urbanization rate has increased from 17.9% to 56.1%, the net resident population of cities increased by 660 million, and the number of cities has increased rapidly. On the one hand, the rapid development of urbanization promotes the sustained and stable development of the national economy and improves the living standards of residents. On the other hand, sudden and mass environmental events are also increasing rapidly, such as atmospheric haze, water pollution and solid waste pollution, which seriously threaten the urban ecological security and the quality of human settlements [2].

Urban ecological carrying capacity refers to: in a certain period of time, under the condition of ensuring the rational development and utilization of resources and the virtuous cycle of ecological environment, the capacity of urban ecological system to carry the population and social scale and the corresponding economic total amount [3]. The level of urban ecological carrying capacity is an important basis for the measurement of sustainable development capacity of city, which is characterized by dynamic change, relative threshold, controllability and openness. Accurate and effective research can provide reference for the sustainable development of a city. The lower reaches of the Yangtze river, as the most economically developed region in China, has a series of environmental problems caused by highly rapid urbanization. How to quantitatively measure and internally compare the urban ecological carrying capacity of this region has important guiding significance for the region to formulate economic development policies and plays a leading role in ecological construction.
2. Method
State-space method is a method used to quantitatively describe the system state in Euclidean geometry space. It usually consists of three mutually perpendicular state space axes, which represent three state vectors of the system respectively. Different points in space can represent different states of the system, and the vector modulus connecting the point and the origin is the carrying capacity of the system [4]. State space method is essentially a time-domain analysis method. Its advantage is that it can not only express linear, continuous and univariate systems, but also be more suitable for in-depth study of nonlinear, discrete and multivariate systems, and it can reflect the internal state and performance of the system.

In the three-dimensional state space of a city, the three axes can respectively represent the resource axis, the environment axis and the human activity axis. In reference to this meaning, this study divides the urban ecological carrying capacity into three parts, namely, the ecological elastic force, the supporting force of carrying media and the pressure of carrying objects. At any time, the state of a city in these three parts will correspond to a point in space, as shown in Fig 1"A". The modulus of the space vector from any point to the origin represents its urban ecological carrying capacity, and the mathematical expression is:

\[ UECC = |OA| = \sqrt{\sum_{i=1}^{n} w_i x_{i,1}^2} \] (1)

Where UECC is the urban ecological carrying capacity; |OA| is the module of directed vector representing the urban ecological bearing capacity as shown in Fig 1; \( x_{i,1} \) is the coordinate value of each index in the state space \( i=1,2,\ldots,n \), \( n \) is the number of selected indicators, and \( w_i \) is the weight of each indicator.

![Figure 1. Schematic diagram of State-space method](image)

In the application of the model, we found that this expression of urban ecological carrying capacity was defective. The model only showed the size of urban ecological carrying capacity, but did not reflect the coordination between subsystems. For example, two of the three subsystems in an area perform better, but one performs worse, and the calculation results will be better, but in fact, a low score of any one of the subsystems will bring harm to the urban ecosystem. Therefore, based on
previous studies [5], this paper proposes a new three-dimensional state-space method model, defining an angle $\theta$ as the angle between the original expression vector of ecological carrying capacity and the triaxial equilibrium development vector, as shown in Fig 1. The expression of $\theta$ is:

$$
cos \theta = \frac{1}{\sqrt{3}} \times \frac{F + S + P}{\sqrt{F^2 + S^2 + P^2}}
$$

(2)

Where $F$, $S$, and $P$ are the states of the three subsystems. Therefore, the ecological carrying capacity can be divided into two parts to calculate, one is the absolute state, the other is the coordination, the formula is as follows:

$$
UECC = \frac{1}{\sqrt{3}} \times \frac{F + S + P}{\sqrt{F^2 + S^2 + P^2}} \times \sqrt[3]{F \times S \times P}
$$

(3)

This model is also calculated according to formula 1 in the subsystem calculation, but formula 3 is adopted in the final superposition of the three subsystems. This model can avoid the significant change of the result caused by the change of a single subsystem. The smaller $\theta$ is, the better the coordination of the three parts.

3. Model application

3.1. The indicator system

Referring to the previous research results [6], an evaluation index system represented by the ecological elastic force, the supporting force of carrying media and the pressure of carrying objects was established, with a total of 26 indicators. As shown in Table 1.

Table 1. Evaluation index system of urban ecological carrying capacity

| Target hierarchy | Rule hierarchy | Index hierarchy | Units |
|------------------|----------------|----------------|-------|
| Ecological elastic force | Climate and hydrology | Mean annual precipitation | mm |
| | | Per capita water resources | $m^3$/person |
| | Resources and energy | Steel product quantity | $\times 10^4$t |
| | | Electric energy production | $\times 10^8$kw·h |
| | Food supply | Grain output | $\times 10^4$t |
| | | Total vegetable production | $\times 10^4$t |
| | Pollution abatement | Treatment rate of domestic sewage | % |
| | | The percentage of industrial solid wastes that are comprehensively utilized | % |
| | | Life garbage treatment rate | % |
| | | The proportion of environmental protection input | % |
| | Social progress | The number of beds in a health facility per 10,000 people | - |
| | | Water supply pervasion | % |
| | | Green coverage of built-up area | % |
| | Economic development | Per capita GDP | Yuan |
| | | Urban residents’ education cultural entertainment expenses | Yuan per person |
| | | Urban per capita disposable income | Yuan |
| | | Rural per capita disposable income | Yuan |
### 3.2. Results and discussions

The data of the five provinces were standardized and then substituted into the model for calculation. The results are shown in Fig 2.

![Figure 2. Urban ecological carrying capacity score](image)

As can be seen from the Fig 2, among the five provinces, Jiangxi province has the fastest growth of urban ecological carrying capacity and the best development situation. It has been the top of the five provinces since 2007. The ranking of other provinces is as follows: Shanghai > Zhejiang > Jiangsu > Anhui. Although the ecological carrying capacity score of Zhejiang province is higher than that of Shanghai in some years, its stability is not good. In 2011 and 2013, there was a significant decline, so it ranked third. In addition, although the score of some years fluctuates slightly, the overall development trend of the five provinces all was good, indicating that the effect of ecological civilization construction is good.
Combined with the analysis of subsystem scores and ecological development coordination scores, it can be found that: The ranking of coordination score is the same as that of urban ecological carrying capacity score. Jiangxi province developed from the worst in 2005 to the highest coordination score after 2009. The decisive factor is “the supporting force of carrying media”. Since 2005, Jiangxi province has carried out economic development and environmental management simultaneously, and its “the supporting force of carrying media” has been growing rapidly. Although “the supporting force of carrying media” of Jiangxi was still the worst among the five provinces by 2015, it is not far behind. Jiangxi is far ahead of the other two sub-systems, so coordination is now the best of the five provinces. In the future, we should continue to keep pace with economic development and environmental control, so as to avoid administration after the contamination. Similar to Jiangxi province, Shanghai has a high score for the two subsystems of “the ecological elastic force” and “the supporting force of carrying media”, but “the pressure of carrying objects” is far lower than that of the other four provinces. The
reason lies in the huge population density of Shanghai, which puts great pressure on the ecosystem. In addition, due to the small area of Shanghai, the average pollutant emission per unit area is huge. What should be done in the future is to control the growth rate of population, so as to reduce the pressure on the urban ecosystem, and on the other hand, to disperse the heavily polluted industries, so as to avoid the centralized pollution of cities. All the three subsystems in Zhejiang province scored at the medium level, so it ranked third in both the ecological carrying capacity score and the coordination score. Future work should focus on improving ecosystem stability, especially the stability of "the ecological elastic force". For example, building water conservancy facilities to store water in the dry season to cope with drought." The supporting force of carrying media "of Jiangsu province is comparable to that of Shanghai, but the other two subsystems score is low, which affects the overall ecological coordination. On the one hand, the pollution discharge of Jiangsu province has not been well controlled in the process of economic development. On the other hand, due to the large economic and climatic differences between southern and northern Jiangsu, it doesn’t have an advantage in terms of resource and energy output after the average calculation. The focus of future work is to disperse heavy polluting enterprises and reduce local pressure. In addition, attention should be paid to the coordinated development between cities. The population pressure and pollution emission of Anhui province are in the middle level, so “the pressure of carrying objects” was in the middle level. Anhui province is relatively far away from the Yangtze river delta and has a weak economic radiation effect, so "the supporting force of carrying media " is relatively weak, only better than Jiangxi province. In the future, Anhui province needs to strengthen construction in all aspects, including economic construction, pollution control, infrastructure improvement, etc.

4. Conclusion

In this paper, a new state-space model was proposed to evaluate the urban ecological carrying capacity. In addition, a multi-subsystem evaluation index system of urban ecological carrying capacity has been established from three aspects of the ecological elastic force, the supporting force of carrying media and the pressure of carrying objects, which can provide reference for future studies in this field. Finally, this paper found out the restrictive factors of the development of the five provinces in the lower reaches of the Yangtze river and pointed out the development direction for the sustainable development of cities.

Acknowledgments

This work was supported by the National Key Research Program of China (No. 2017YFC0506603, 2016YFC0401305), the Project of National Natural Foundation of China (No. 51379013, 51679007), and the State Key Program of National Natural Science of China (No. 41530635).

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