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Original Research Paper

Evaluation and Comparison of the Resource and Environmental Carrying Capacity of the 10 Main Urban Agglomerations in China

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ABSTRACT

A comprehensive evaluation index system is established in this study, and evaluation and comparison of resource and environmental carrying capacity from 2005 to 2012 are conducted from four aspects, namely, land, water resource, transportation and environment. Research results show that from 2005 to 2012, the carrying capacity of the 10 main urban agglomerations increased, except for the wing of Beijing and Tianjin urban agglomeration. A significant difference in carrying capacity was observed. Among the top 10 urban agglomerations, the resource and environmental carrying capacity of the eastern region is the highest, followed by that of the central region. The resource and environmental carrying capacity of the western region is the lowest. Traffic capacity, circular economy development level, water resource consumption, and industrial pollution emission are the main reasons for the difference in resource and environmental carrying capacity.

INTRODUCTION

Resource and environmental carrying capacity indicates that different-scale regional resource and environment systems exhibit no qualitative change in a specific period of time. When the intensity of human social activity is greater than the resource and environment carrying capacity, disorder and unsustainable development of the resource and environment system occur. This concept reveals the dialectical relations among resource, the environment and human social activity.

With economic growth and environmental deterioration, an increasing number of scholars have focused on the coordinated development of the resources, environment, and the economy. Research on the carrying capacity of resources and the environment has also increased. The studies of domestic scholars, mainly focused on a single-factor study of the environment (land, water or air). For instance, in their study on water environmental carrying capacity (WECC), Wang et al. (2011) established an evaluation index system of the main influencing factors of WECC based on natural and social characteristics. Lijiao et al. (2013) proposed a WECC evaluation index system that includes four elements, namely, resource, environment, economy and society. They also adopted the analytical hierarchy process (AHP) and entropy method for joint empowerment and conducted gray matter element analysis. They investigated the WECC of Hunan Province as well as that of eight key cities in the Dongting Lake area from 2003 to 2010. Li et al. (2014) established an index system based on the concept of generalized WECC. AHP, entropy weight and vector norm methods were adopted to evaluate the WECC of Wuhan City. Their results showed that the WECC of Wuhan City increased year by year from 2006 to 2010 and exhibited good coordination with water resource, environment and social and economic development.

In a related study on atmospheric and environmental capacity, Han et al. (2014) established an evaluation index system for atmospheric environmental carrying capacity based on atmospheric environmental protection, pollution control, and social economy. They quantified the atmospheric environmental carrying capacity of Xi'an, Tongchuan, Baoji, Xianyang and Weinan from 2006 to 2011 by using AHP and vector norm methods. They also analysed the variation trend of atmospheric environmental carrying capacity. Xu & Yong (2009) conducted a primary evaluation of land carrying capacity in Chang-Zhu-Tan megalopolis in terms of state space and proposed several measures to improve the regional land carrying capacity. Lei et al. (2013) established a land carrying capacity evaluation index system in terms of three aspects, namely, environment, society and economic feasibility, and conducted an analysis of land carrying capacity by using the multi-objective comprehensive evaluation model. Wang et al. (2012) and Gao (2013) also conducted a quantitative evalua-

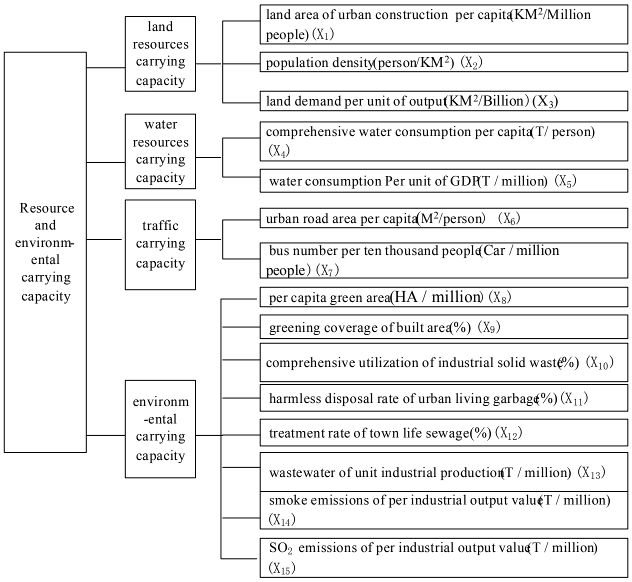

Fig. 1: Evaluation index system of resource and environmental carrying capacity.

tion of land carrying capacity from different angles. In addition, several scholars focused on tourism and resource environmental carrying capacity (Liu et al. 2013, Yan et al. 2011).

Apparently, early literature mainly focused on single-element research on land, water or atmospheric environment. The research scope mainly covered only a single region or a single city. However, a close relationship among resource, environment and other elements has been observed, where a "short board" of element may lead to the deterioration of the regional comprehensive carrying capacity. When the distance of urban spaces is relatively close, deterioration of urban agglomeration inevitably occurs. Therefore, research on the carrying capacity of a single element or a single city cannot reflect regional sustainable development. Based on these reasons, this study regards the main urban agglomerations of China as the research object; their resource and environmental carrying capacity is measured and compared to provide a theoretical basis and scientific plan for the sustainable development of urban agglomerations.

CONSTRUCTING AN EVALUATION INDEX SYSTEM AND MEASUREMENT OF THE RESOURCE AND ENVIRONMENTAL CARRYING CAPACITY

Constructing an evaluation index system: Many studies on the carrying capacity have been conducted. Existing literature indicates that most evaluation index systems were constructed from the aspects of economic and social development, resources and the environment. An evaluation index is comprehensive and includes economic development indicators (e.g., economic growth rate, per capita gross domestic product or GDP, industrial structures, and income) and social development indicators (e.g., population growth, educational level, living area, and health of residents). However, the measurement results of an index reflect only the comprehensive development level and carrying capacity of a region and may exhibit a large deviation with regard to the measurement of resources and the environment. In terms of data availability, an index is scientific and complete. In this study, we selected 15 indicators to construct an evaluation index system from four aspects, namely, land resource capacity, water resource capacity, traffic capacity and environmental capacity. The developed index was utilized to measure the resource and environmental carrying capacity of the main urban agglomerations in China.

Evaluation method: AHP, entropy fuzzy matter-element method and principal component analysis (PCA) were utilized to evaluate multiple index systems. Considering the weight defect subjectivity of AHP and entropy fuzzy matter-element method and the dynamic variability of resource and environmental carrying capacity in different urban agglomerations, PCA was adopted in this study. The principle of PCA is to use dimension reduction on the premise of less loss of information. The statistical method of PCA changes the original multiple index into a few new representative indices, which can ensure that the original data information is preserved and can avoid the subjective randomness of empowerment. However, this method is only utilized for static analysis of sample variables and cannot easily reflect the dynamic evolution trend of the research object with time. Sequential global PCA is a combination of time series and global principal components and is based on traditional PCA; in sequential global PCA, a new variable replaces the original global variables to describe the dynamic changes of the study object. The structure of sequential global 3D data can be expressed as

$$F = \left\{ \lambda_t K_{n \times p}, t = 1, 2, \cdots, T \right\}, \qquad ...(1)$$

Where, n is the sample, with each sample having a p index and producing an $n \times p$ matrix of $K_{n \times p}$; t is the year. In the t stage, the data can be expressed as follows:

$$\begin{bmatrix} x_{11}^t & x_{12}^t & \cdots & x_{1p}^t \\ x_{21}^t & x_{22}^t & \cdots & x_{2p}^t \\ \vdots & \vdots & & \vdots \\ x_{n1}^t & x_{n2}^t & \cdots & x_{np}^t \end{bmatrix} = \begin{bmatrix} e_1^t \\ e_2^t \\ \vdots \\ e_3^t \end{bmatrix}. \qquad ...(2)$$

Before applying PCA, standardized data processing was implemented to avoid disparity among various indicator unit levels. For the positive effect index with more extensive and better characteristics, the processing formula is: $\dot{x}_{ij} = \left(x_{ij} - \min x_{ij}\right) / \left(\max x_{ij} - \min x_{ij}\right)$.

For the negative effect index with less extensive but better characteristics, the processing formula is:

$\dot{x}_{ij} = \left(\max x_{ij} - x_{ij}\right) / \left(\max x_{ij} - \min x_{ij}\right)$.

In the processing formula, $\dot{x}_{ij}$ is the standardization of data; x_{ij} is the original data; $\max x_{ij}$ and $\min x_{ij}$ represent the maximum and minimum values, respectively; i represents the sample cities; and j represents the related indicators.

In this study, we conducted standardized data processing using the PCA utility of the SPSS software. Thereafter, the characteristic value, contribution rate and cumulative contribution rate were calculated. The cumulative contribution rate of each factor should be more than 80% to reflect the information of the original variables well. The proportion of the contribution rate and cumulative contribution rate of each selected factor denotes the weight. The comprehensive index of resource and environmental carrying capacity in each region was calculated with the following formula.

$$X_i = \sum_{k=1}^{n} w_k f_{ik}, \quad ...(3)$$

Where, X_i is the carrying capacity index in region i, w_k is the weight ($w_k = \lambda_k / \sum_{k=1}^{n} \lambda_k$), λ_k is the contribution rate of the k main factors, and f_{ik} is the principal component score for the case of k main factors in region i.

EVALUATION AND COMPARISON OF RESOURCE AND ENVIRONMENTAL CARRYING CAPACITY

Data instructions: In the index system, the urban construction land area per capita is determined by the urban construction land area divided by the municipal district population. The land demand per unit of output is determined by the land area divided by GDP. The comprehensive water consumption per capita is determined by total water supply divided by the total population. The water consumption per unit of GDP is determined by the difference between the total water supply and water consumption of residents living in the area divided by GDP. Lastly, the unit industrial output in the index system is determined by industrial enterprises of a designated size. The research data were obtained from the city statistical yearbook of China.

Sample of urban agglomeration and choice of the city: The top 10 urban agglomerations of China were selected as the main research objects. The city name and specific urban agglomerations are depicted in Table 1.

Kaiser-Meyer-Olkin (KMO) and Bartlett's spherical inspection: The results of KMO and Bartlett's spherical inspection (Table 2) show that the KMO value is 0.733 (between 0.6 and 1.0). Bartlett's spherical inspection has a significant probability of 0.000 (less than 0.01). These results indicate that this index system is suitable for factor analysis.

Comparison of resource and environmental carrying capacity: Based on the previously presented ideas, the resource and environmental carrying capacities of the 10 main urban agglomerations in 2005 and 2012 were calculated and compared. The results show the following.

1. From the time perspective, the resource and environmental carrying capacity of most of the urban agglomerations increased. The mean comparison of the 10 urban agglomerations in 2005 and 2012 (Table 3) shows that the resource and environmental carrying capacity of the urban agglomerations increased, except for the wing of Beijing and Tianjin urban agglomeration. The top three urban agglomerations are the Chuan and Yu urban agglomeration, the urban agglomeration in the middle reach of Yangtze River, and the Guanzhong urban agglomeration. The resource and environmental carrying capacity of Beijing and Tianjin urban agglomeration decreased from 1.066 in 2005 to 1.037 in 2012. The wing of Beijing and Tianjin urban agglomeration has a total of 10 cities, including Beijing, Tianjin, Baoding and Cangzhou; the other six exhibited a significant decline. This decline is mainly due to the heavy industrialization of the cities' industrial structure and the unreasonable energy structure. The iron and steel, building material, petrochemical and electric power industries are concentrated in Hebei, and these industries are classified as high-pollution industries that could lead to significant environmental pollution.

Table 4 shows the average and difference of different indicators of the top 10 cities in 2005 and 2012. For the 15 indicators, the average values of X_2, X_3, X_4, X_5, X_{13} and X_{14} decreased in 2012 compared with that in 2005. These indicators generally involve resource consumption and pollution emission, which show that the unit of output requires less resource consumption and pollution for economic development. For example, the sulphur dioxide emission per unit of industrial output value was 121.41 tons/10,000 Yuan in 2005 and 20.02 tons/10,000 Yuan in 2012; these values indicate that energy conservation and emission reduction measures resulted in remarkable improvements in China in recent years. At the same time, with economic development, the urban infrastructure construction investment increased; relevant municipal roads, greening, public transportation, and garbage and sewage treatment facilities also increased. For example, the urban per capita road area was only 9.41

Table 1: Top 10 urban agglomerations and cities in China.

Top 10 urban agglomerations	Cities contained
Yangtze River Delta urban agglomeration	Shanghai, Nanjing, Suzhou, Wuxi, Changzhou, Zhenjiang, Nantong, Yangzhou, Hangzhou, Ningbo, Jiaxing, Huzhou, Shaoxing, Zhoushan, and Taizhou
Pearl River Delta urban agglomeration	Guangzhou, Shenzhen, Zhuhai, Dongguan, Foshan, Zhongshan, Huizhou, Jiangmen, and Zhaoqing
Wing of Beijing and Tianjin urban agglomeration	Beijing, Tianjin, Shijiazhuang, Tangshan, Qinhuangdao, Baoding, Zhangjiakou, Chengde, Cangzhou, and Langfang
Shandong Peninsula urban agglomeration	Jinan, Qingdao, Yantai, Weifang, Zibo, Dongying, Weihai, and Rizhao
Urban agglomeration in the middle and south of Liaoning	Shenyang, Dalian, Anshan, Fushun, Benxi, Dandong, Liaoyang, Yingkou, Panjin, and Tieling
Urban agglomeration in the west bank of the Taiwan Strait	Fuzhou, Xiamen, Zhangzhou, Quanzhou, Putian, and Ningde
Zhongyuan urban agglomeration	Zhengzhou, Luoyang, Kaifeng, Xinxiang, Jiaozuo, Xuchang, Pingdingshan, and Luohe
Guanzhong urban agglomeration	Xian, Xianyang, Baoji, Weinan, Tongchuan, and Shanluo
Urban agglomeration in the middle reach of Yangtze River	Wuhan, Huangshi, Ezhou, Huanggang, Xiaogan, Xianning, Suizhou, Jingmen, Jingzhou, Xinyang, Jiujiang, and Yueyang
Chuan and Yu urban agglomeration	Chongqing, Chengdu, Zigong, Luzhou, Deyang, Mianyang, Suining, Neijiang, Leshan, Nanchong, Meishan, Yibin, Guangan, Yaan, and Ziyang

Table 2: KMO and Bartlett's spherical inspection.

Sampling degree of KMO measurement		0.733
Bartlett's spherical inspection	Approximate chi-square	1,154.12
	df	105
	Sig.	0.000

m^2 in 2005; the value increased to 13.08 m^2 in 2012, indicating a growth rate of 39%. The energy conservation and emission reduction measures, as well as the increase in infrastructure spending, increased the resource and environmental carrying capacity in the main urban agglomerations.

2. From the lateral perspective, Table 3 shows that the difference in the resource and environmental carrying capacity in the main urban agglomerations is significant. For example, in 2012, the top six urban agglomerations were the Pearl River delta urban agglomeration (1.412), the Shandong Peninsula urban agglomeration (1.287), the Yangtze River delta urban agglomeration (1.269), the urban agglomeration in the west bank of the Taiwan Strait (1.207), the wing of Beijing and Tianjin urban agglomeration (1.037), and the urban agglomeration in the middle and south of Liaoning (1.025), followed by the urban agglomeration in the middle reach of Yangtze River (1.023) and the Zhongyuan urban agglomeration (0.944). The last two urban agglomerations are the Chuan and Yu urban agglomeration (0.937) and the Guanzhong urban agglomeration (0.897).

Cause analysis of the gap: The first common factor has a large load in the five indicators of X_1, X_4, X_6, X_7 and X_8; it reflects the traffic development level and possession of land and other natural resources in a city. This factor can be defined as the city traffic development and land load factor. The second common factor has a large load in the five indicators of X_5, X_{10}, X_{13}, X_{14} and X_{15}; it mainly reflects economic growth in the process of industrial pollution emission and water resource consumption. This factor can be defined as the industrial pollution emission and resource consumption factor. The third common factor has a large load in the two indicators of X_{11} and X_{12}; it reflects garbage and sewage treatment of residents living in a city. As such, this factor can be defined as the garbage recycling factor of residents living in a city. The other common factors for the total variance contribution rate are relatively small and do not constitute the main reason for the difference in the resource and environmental carrying capacity of the urban agglomerations; thus, they were not analysed in this study.

1. Urban traffic development and land load factor: Comparison of the coefficients of variation of the factors shown in Table 5 indicates that the factor with the highest coefficient of variation is the green area per capita (0.660), followed by the bus number per 10,000 people (0.538). The Pearl River delta urban agglomeration has the largest average values of 118.08 ha/10,000 people and 22.55 m/10,000 people for the aforementioned two factors. The coefficient of variation of urban road area per capita for the top 10 ur-

Table 3: Average value of resource and environmental carrying capacity in 2005 and 2012.

Top 10 urban agglomerations	2005	2012	Difference	Ranking of growth rate
Yangtze River Delta urban agglomeration	1.215	1.269	0.054	7
Pearl River Delta urban agglomeration	1.287	1.412	0.125	4
Wing of Beijing and Tianjin urban agglomeration	1.066	1.037	-0.029	10
Shandong Peninsula urban agglomeration	1.242	1.287	0.045	8
Urban agglomeration in the middle and south of Liaoning	0.939	1.025	0.086	6
Urban agglomeration in the west bank of the Taiwan Strait	1.110	1.207	0.097	5
Zhongyuan urban agglomeration	0.918	0.944	0.026	9
Guanzhong urban agglomeration	0.750	0.897	0.147	3
Urban agglomeration in the middle reach of Yangtze River	0.850	1.023	0.173	2
Chuan and Yu urban agglomeration	0.751	0.937	0.186	1

Table 4: Average and difference of different indicators of the top 10 urban agglomerations in 2005 and 2012.

Indicators	Average in 2005	Average in 2012	Difference	Indicators	Average in 2005	Average in 2012	Difference
X_1	0.737	0.972	0.235	X_9	37.050	41.806	4.756
X_2	1,384.538	1,347.497	-37.041	X_{10}	77.239	83.145	5.906
X_3	0.294	0.139	-0.154	X_{11}	80.718	91.363	10.645
X_4	42.627	38.432	-4.195	X_{12}	53.397	84.749	31.352
X_5	29.358	9.272	-20.086	X_{13}	13.536	2.470	-11.067
X_6	9.410	13.086	3.676	X_{14}	54.433	10.465	-43.968
X_7	7.734	9.623	1.889	X_{15}	121.411	20.021	-101.390
X_8	36.517	50.157	13.640				

Table 5: Coefficient of variation for each factor of the top 10 urban agglomerations.

Factors	Coefficient of variation	Factors	Coefficient of variation	Factors	Coefficient of variation
X_1	0.112	X_6	0.362	X_{11}	0.119
X_2	0.126	X_7	0.538	X_{12}	0.084
X_3	0.165	X_8	0.660	X_{13}	0.085
X_4	0.134	X_9	0.252	X_{14}	0.087
X_5	0.138	X_{10}	0.215	X_{15}	0.153

ban agglomerations is 0.362, with the Shandong Peninsula urban agglomeration having the largest average value (19.22 m^2/person) and the Chuan and Yu urban agglomeration having the smallest average value (6.74 m^2/person). For the two indicators of integrated water consumption per capita and area of land per capita used for urban construction, the gap is small, and the coefficients of variation are only 0.134 and 0.112, respectively; these results indicate that the two indicators do not constitute the main cause of the difference in resource and environmental carrying capacity.

The contribution rate of the first common factor to the total variance is highest at 33.9%. Therefore, the scores have a direct decisive influence on carrying capacity. The gap is large for the three indicators of urban road area per capita, bus number per 10,000 people, and per capita green area. As such, the three indicators constitute the main cause of the difference in resource and environmental carrying capacity.

2. Industrial pollution emission and resource consumption factor: Comparison of the coefficients of variation of the factor depicted in Table 5 indicates that comprehensive utilization of industrial solid waste has the highest coefficient of variation (0.215). The comprehensive utilization rate of the Yangtze River delta urban agglomeration is the highest at 95.4%, and the wing of Beijing and Tianjin urban agglomeration is the lowest at 48.9%. The coefficients of variation of SO_2 emissions per industrial output value and water consumption per unit of GDP are 0.153 and 0.138, respectively. The water consumption per unit of GDP factor is the highest in the urban agglomeration of the middle and south of Liaoning at 14.44 tons/10,000 Yuan and lowest in the Chuan and Yu urban agglomeration at 5.97 tons/10,000 Yuan. The wastewater and smoke emissions per industrial output value are 0.085 and 0.087, respectively. As such, the gap of urban agglomeration is small.

The second common factor accounts for 19.1% of the total variance. The three indicators of comprehensive utilization of industrial solid waste, SO_2 emissions of per industrial output value, and water consumption per unit of GDP are the main reasons for the difference in resource and environmental carrying capacity in the top 10 urban agglomerations.

3. Garbage recycling factor of residents living in a city: The coefficient of variation of the rate of harmless disposal of garbage in urban areas in the top 10 urban agglomerations is 0.119. The rate of the Yangtze River delta urban agglomeration is the highest at 98.8% and that of the Chuan and Yu urban agglomeration is the lowest at 82.16%. For the municipal sewage treatment rate factor, the variation coefficient is 0.084. The rate of the Zhongyuan urban agglomeration is the highest and that of the Yangtze River delta urban agglomeration is the lowest.

The third common factor that accounts for 13.2% of the total variance is also the main reason for the difference in carrying capacity. Based on the coefficient of variation of the third common factor, the rate of harmless disposal of garbage in urban areas is also one of the important reasons for the difference in resource and environmental carrying capacity in the top 10 urban agglomerations.

DISCUSSION AND CONCLUSION

A comprehensive evaluation index system was developed, and evaluation and comparison of resource and environmental carrying capacity in 2005 and 2012 were conducted from four aspects, namely, land, water resource, transportation, and environment. The research results showed the following. First, from 2005 to 2012, the carrying capacity of urban agglomeration in Beijing and Tianjin decreased, whereas the carrying capacity of the other urban agglomerations increased. Second, the difference in carrying capacity was significant. In the top 10 urban agglomerations, the eastern region was the highest followed by the central region; the western region was the smallest. Third, analysis of the gap of urban agglomeration indicated that traffic capacity, circular economy development level, water resource consumption, and industrial pollution emission were the main reasons for the difference in resource and environmental carrying capacity.

With the rapid increase in urbanization in China, urban agglomeration has become an important form of spatial organization; it plays a principal role in the development of regions and the society. The results of this study show that the increase in the resource and environmental carrying capacity of the top urban agglomerations is largely based on the per capita and per unit of output indicators and reflects the reduction in resource consumption and pollution emission in the growth rate of the unit output. However, with the expansion of the city scale, total resource consumption and total pollution emission also increase. A relatively stable urban space inevitably leads to the deterioration of urban ecological environmental problems, such as environmental pollution, ecological destruction, and shortage of resources, especially in large cities. In recent years, several large cities in China continued to experience "hazy" weather, which signifies a real-world problem. Therefore, in the background of the current rapid urbanization in China, how to reduce the effects of industries and the relatively high population on the resource and environmental carrying capacity of small-and medium-sized cities as well as how to reduce the pressure on the city ecological environment have become important issues for government agencies and academic institutions.

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