

Assessment of Environmental Carrying Capacity Using Principal Component Analysis

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Abstract

Regional environmental carrying capacity (ECC) is nonlinear and spatially specific. A hierarchy index system including resources, environmental and socio-economic elements was established using an analytic hierarchy process. Principal component analysis (PCA) was used to estimate the regional size and differences of environmental carrying capacities. Main information of four principal components, *i.e.*, carrying capacity of resources supply, carrying capacity of environmental quality, carrying capacity of social economy and carrying capacity of infrastructure construction, was extracted. The ECC evaluation value was divided into five levels of lowest carrying capacity, low carrying capacity, medium carrying capacity, high carrying capacity and highest carrying capacity, respectively. The results showed that on the whole ECC was at the medium carrying capacity level. ECC was generally highest in Guanzhong plain, followed by Loess Plateau, and was lowest in Qiba mountain. The carrying capacity of water resources and environmental quality was relatively low, and the infrastructure carrying capacity was highest among the four components. The temporal spatial variation of ECC was closely related to vulnerability of the natural resources and environment in the regions. Verification was proven that PCA was a useful tool when applied to evaluate ECC and reflect the spatial distribution of large-quantity ECC indices on a large regional scale. This study provides a basis for comprehensive understanding of resources, environment and management for regional balanced development.

Keywords

Environmental Carrying Capacity, Principal Component Analysis, Spatial Difference, Evaluation of Indicators

1. Introduction

Resources and the environment are the basis of human survival. Rapid social and economic development has brought issues of resources and environment, such as excessive resources consumption, environmental degradation and pollution, and the issues have become increasingly prominent especially across the globe [1]-[3]. Therefore, resource and environment carrying capacity has become a great concern of research interest. Environmental carrying capacity includes multiple factors such as atmospheric environment, land environment, social economy and dilution-related self-purification capacity of water environment, and reflects the threshold of supporting capacity in a region with specific natural resources and ecological environment. Studies on environmental carrying capacity are mainly focused on single factors, such as spatial variation of comprehensive carrying capacity in China [4] [5], different resource carrying capacities of cities [6] [7] [8], change characteristics of ecosystems carrying capacity [9] [10] [11] [12], variation of carrying capacity of resources and environment in mountain areas [13], water resources carrying capacity [14] [15] [16] and regional land resources carrying capacity [17] [18]. Those studies indicated that environmental degradation, resource exploitation and utilization have caused seriously adverse effects on ecological environment, and resource and environment carrying capacity has been substantially reduced. Currently, methods used for studying resource and environment carrying capacity include the system dynamics model, the ecological footprint method, the analytic hierarchy process and the entropy method [19]-[24]. Although extensive work with different methods has been carried out on resource and environment carrying capacity, there are several limitations and an integrated ECC assessment is still lacking. Therefore, this study takes Shaanxi Province as an example, using PCA to establish a comprehensive ECC system to analyze spatial distribution of ECC in Shaanxi Province. This study is expected to better explain the relationship between the regional resource environment and the coordinated development of social economy, more effectively guide the regional planning and layout decision-making, and promote a more balanced and sustainable regional development.

2. Materials and Methods

2.1. Materials

Shaanxi is located in the northwest hinterland of China's inland, 870-km long along the north-south direction, 200 to 500-km wide along the east-west direction, across the two regions of Northern and Southern China. The terrain is high in the north and south, and low in the middle. The terrain is divided into three sections; namely, northern Loess Plateau (including Yan'an, Yulin), Guanzhong plain (including Xi'an, Xianyang, Baoji, Weinan, Tongchuan) and southern Qinba mountain (including Hanzhong, Ankang, Shangluo). Spatial and temporal distribution of water resources and fossil energy are not uniform in Shaanxi

Province. With the population growth and increase of energy production, environmental pollution and other issues, the scarce resources and fragile environment are facing great pressure. Meanwhile, strong anthropogenic activities have led to over-exploitation of the resources and environment beyond the regional resource and environmental carrying capacity. Limited resources and serious environmental problems have become a key factor restricting the development of regional economy. Therefore, the study of environmental carrying capacity in Shaanxi Province is typical in arid regions of Northwest China. The social, economic and environmental data used in this paper were obtained from local Hydrology and Water Resources Survey, Land and Resources Bureau, Environmental Protection Agency and State Statistics Bureau in shaanxi province, China. Samples from eleven regions were selected, using the digital elevation model (DEM) data of China, and the 1:250,000 county-level area vector of landform and terrain elevation of Shaanxi Province were obtained with ArcGIS as shown in (Figure 1).

2.2. Methods

Given that environmental carrying capacity is multi-element driven and affected, we employed PCA to accurately calculate complex variables. PCA is one of multivariate statistical analysis methods. It can simplify complex issues by transforming the data matrix to a limited number of variables and explain the interrelationship among the multiple variables. The main purpose of PCA is data compression in which dimension reduction and statistical simplification are achieved to facilitate data. When PCA is performed, the first principal component is extracted in such a way that it can account for as much of the whole variance as possible, and the second principal component may account as much of

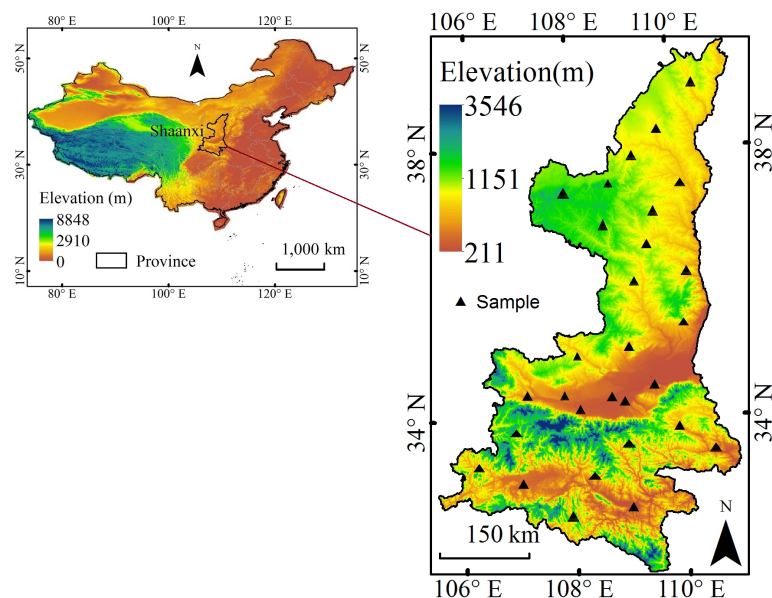


Figure 1. Landform and sample points in Shaanxi province.

the remaining variance as possible, and so forth. The number of principal components selected to represent the data set is chosen in such a way that all the selected principal components must accumulatively account for at least 85% of the total variance in the data set.

Firstly, PCA was to calculate the correlation coefficients between each pair of indices. Secondly, the eigenvalues and eigenvectors were calculated. Principal component percent contributions and cumulative percent contributions in the total variance as well as principal component loads were calculated. The percent variance contribution of the principal component was taken as the weight coefficients of the each principal component. Finally, the index of each principal component was calculated according to the standardized principal component load, and the carrying capacity of the environment was evaluated according to the index. The main calculation steps are as follows.

1) Establish the covariance matrix (correlation coefficient matrix)

If the number of the sample regions is M and the number of selected normalization indices is N , the covariance matrix \mathbf{R} can be established (Equation (1)),

$$\mathbf{R} = (r_{ij}) \quad (1)$$

where r_{ij} represents regression coefficients.

2) Calculate the percent variance contribution of each principal component (weight) as shown by Equation (2),

$$C_i = \frac{x_i}{\sum_{j=1}^k \lambda_j} \quad (2)$$

where C_i is percent variance contribution by each identified principal component, and x_i represents the i^{th} normalization sample. λ_j represents the j^{th} eigenvalue of matrix \mathbf{R} .

3) Calculate the component load matrix (score index matrix) according to Equation (3),

$$IN_{in} = \sum_{j=1}^k (r_j \times x_{ij}) \quad (3)$$

where IN_{in} is the i^{th} principal component load of the i^{th} area, and x_{ij} represents normalization samples.

4) Calculate the comprehensive evaluation index (CIN_i) according to Equation (4),

$$CIN_i = \sum (IN_{in} \times C_i) \quad (4)$$

2.3. Evaluation Index Systems

The establishment of a scientific valuation index system of ECC should take into account its objectiveness, comprehensiveness and accessibility. Multiple aspects of environment and social economy all have a strong influence on the carrying capacity. Therefore, we took into account the actual situation and relevant stu-

dies reported previously and selected twenty indicators to establish the evaluation indexes system using the analytic hierarchy process, in which three systems comprised of target and index layers of resources, environment, social and economic aspects were included (**Table 1**). Among them, the resource system consisted of eight indicators covering both natural and social aspects including energy, water, land and human resources, the environmental system consisted of seven indicators related to atmospheric environment, water and solid waste, and the socio-economic system consisted of five indicators including economic data, the regional infrastructure construction data and social development data.

3. Results

3.1. Principal Component Analysis

The first four principal components (C1-C4) of PCA explained more than 85% of the total variance in the data set. The load matrix and coefficient matrix of C1-C4 are shown in (**Table 2**), and percent variance explained by C1-C4 is listed in (**Table 3**). Among the four principal components of ECC, the principal component load information extracted by each group of data has the same consistency.

Table 1. Evaluation index system of environmental carrying capacity.

system	Index	Indicators impact
Resources	IN1 total annual water supply	Positive
	IN2 total natural gas supply	Positive
	IN3 common cultivated land area	Positive
	IN4 grain production	Positive
	IN5 permanent residents	Positive
	IN6 population	Negative
	IN7 energy consumption per unit GDP	Negative
	IN8 Precipitation	Positive
Environment	IN9 utilization of general industrial solid wastes	Positive
	IN10 daily rate of clean air	Positive
	IN11 wastewater treatment facilities capacity	Positive
	IN12 total industrial emissions	Negative
	IN13 smoke and soot emissions	Negative
	IN14 total discharge of industrial wastewater	Negative
	IN15 cumulative area of soil erosion control	Positive
Social economy	IN16 per capita disposable income of urban residents	Positive
	IN17 per capita GDP	Positive
	IN18 gas penetration rate	Positive
	IN19 urban pipe network coverage	Positive
	IN20 per capita park green area	Positive

Table 2. Load and coefficient of principal components of ECC.

index	Load				Coefficient			
	C1	C2	C3	C4	C1	C2	C3	C4
IN1	0.956	-0.142	-0.162	0.013	0.152	-0.021	-0.068	-0.089
IN2	0.956	-0.114	-0.047	-0.104	0.162	-0.011	-0.034	-0.144
IN3	0.169	0.805	0.286	0.419	-0.022	0.147	0.047	0.104
IN4	0.562	0.484	-0.158	0.571	0.032	0.083	-0.087	0.151
IN5	0.850	0.135	-0.215	0.340	0.102	0.021	-0.094	0.045
IN6	-0.001	0.353	0.804	-0.349	0.021	0.064	0.244	-0.170
IN7	-0.862	-0.062	0.245	0.115	-0.154	-0.058	0.122	0.170
IN8	0.033	0.958	0.164	0.158	-0.012	0.232	-0.023	-0.033
IN9	0.917	-0.038	0.233	0.108	0.126	-0.042	0.074	-0.030
IN10	0.499	0.296	0.767	-0.077	0.070	0.021	0.239	-0.087
IN11	0.691	-0.006	0.233	0.493	0.049	-0.081	0.097	0.179
IN12	0.381	0.439	0.187	0.696	-0.019	0.022	0.055	0.255
IN13	0.801	0.139	0.179	0.480	0.070	-0.033	0.060	0.140
IN14	-0.089	0.134	-0.312	0.829	-0.096	-0.033	-0.082	0.381
IN15	0.862	0.165	0.225	-0.011	0.132	0.029	0.047	-0.107
IN16	0.296	-0.659	0.455	0.327	-0.003	-0.265	0.241	0.231
IN17	-0.054	-0.975	-0.004	-0.184	0.008	-0.249	0.083	0.033
IN18	0.003	-0.845	-0.447	-0.007	0.008	-0.192	-0.084	0.075
IN19	-0.879	-0.153	-0.050	-0.395	-0.094	0.006	-0.004	-0.081
IN20	0.349	-0.056	-0.876	-0.098	0.086	0.081	-0.331	-0.126

Table 3. Total variance index of principal component of ECC.

Year	Contribution rate	C1	C2	C3	C4
6-year average	Contribution%	38.654	22.252	15.015	13.788
	Accumulated Contribution%	38.654	60.905	75.92	89.707

Therefore, the same principal component of different years can be compared and analyzed. As shown in (Table 2), the total amount of water supply, natural gas supply and resident population in the first principal component, which was defined as the carrying capacity of resources supply, was relatively high. The comprehensive utilization of industrial solid wastes, the total emission of industrial waste gas, and the emission of smoke and soot in the second principal component was defined as the carrying capacity of environmental quality. The sum of the per capita GDP, the sunshine hours and the cumulative load of soil erosion control area in the third principal component was defined as the level of socio-economic carrying capacity. The sum of the waste water treatment facilities in the fourth principal component was defined as the carrying capacity of infrastructure construction. This study employed the natural discontinuity classification method, and the differences between the various classes may be maximized. Based on this method, therefore ECC was divided into five levels: lowest carrying capacity, low carrying capacity, medium carrying capacity, high carrying capacity and highest carrying capacity.

The resources supply carrying capacity of ECC represents limiting the degree of local sustainable development of carry capacity. As shown in (Figure 2), Xi'an had the highest resources supply capacity of ECC among all the investigated regions during the six years, and Hanzhong had the smallest supply capacity of ECC. In general, Guanzhong plain had the highest carrying capacity, followed by Loess Plateau at the medium level, while the lowest carrying capacity was identified in Qinba mountain.

Environmental quality bearing capacity of ECC indicates the extent of environmental pollution, environmental management and environmental quality during local sustainable development. It can be seen from (Figure 3), the cities in the central plain were basically between the medium carrying capacity levels. The environmental quality of Ankang and Shangluo in the south of Shaanxi Province was lowest and the smallest index was 0.14 - 0.178 in 2010 and 2013, but Hanzhong had a high index.

Socio-economic carrying capacity of ECC indicates the upper limit a sustainably developed social economy may reach. It can be seen from (Figure 4), that Yulin and Yan'an in northern Shaanxi showed high loads of carrying capacity due to energy and chemical industry (e.g., Coal, liquefied gas industry) except 2012 and the greatest index was 0.44. The cities in southern Shaanxi were primarily carrying capacity of low level and index was 0.244, except Hanzhong and Sangluo had higher level in 2012 and 2013. Guanzhong region showed high-level or medium-level carrying capacities in those years.

The carrying capacity of infrastructure construction of ECC may help tell whether the infrastructure construction is efficiently used. As shown in (Figure 5), index of the social infrastructure construction was the largest in Baoji and

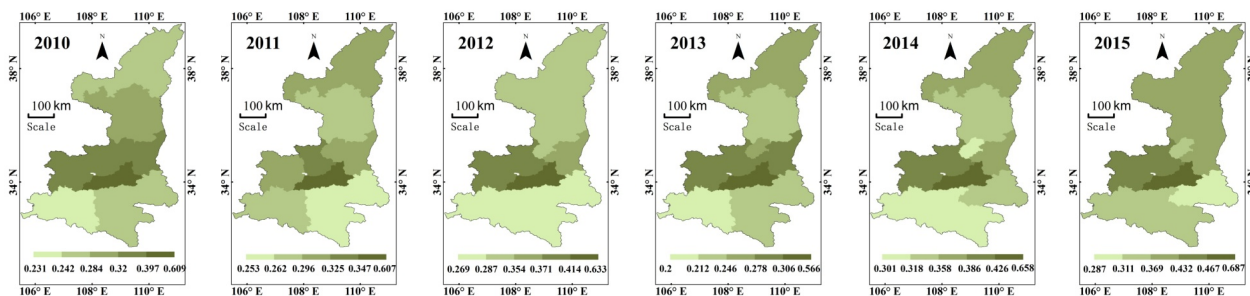


Figure 2. Spatial distribution of resource supply carrying capacity indices.

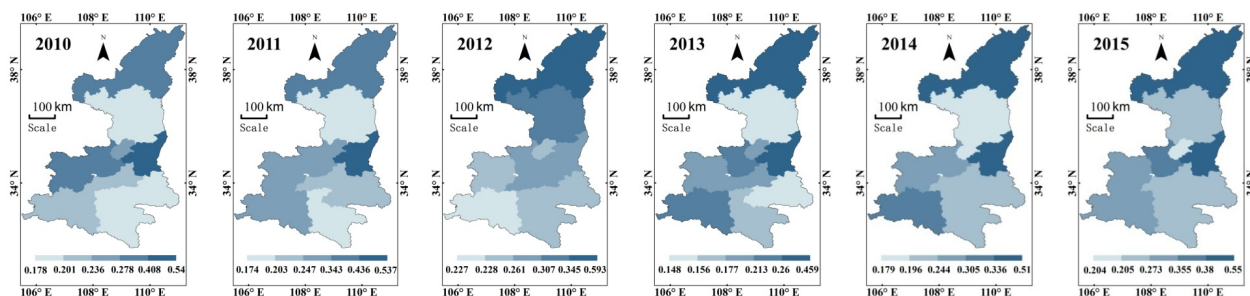


Figure 3. Spatial distribution of environmental quality carrying capacity indices.

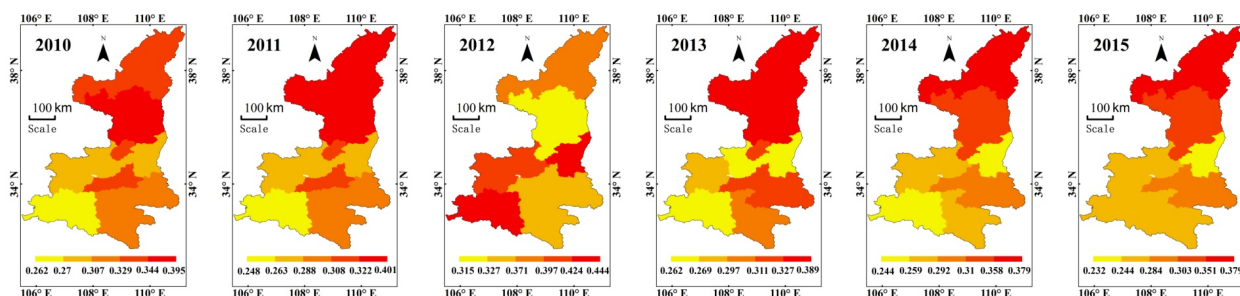


Figure 4. Spatial distribution of socio-economic carrying capacity of ECC.

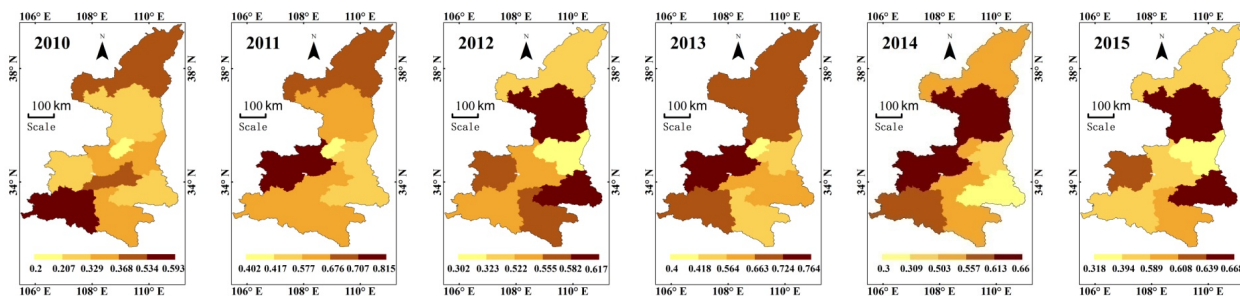


Figure 5. Spatial distribution of infrastructure construction carrying capacity of ECC.

Xianyang, the carrying capacity of Xi'an changed between the high and low levels but was mostly near the medium level. On the whole, the index of infrastructure construction is higher than that of other carrying capacity. The distribution of comprehensive carrying capacity of ECC in each year is shown in (Figure 6). As can be seen that Xi'an and Yulin had the highest 6-year comprehensive carrying capacity among all the investigated cities, except Yulin in 2010. Ankang was at the low level. As shown in (Figure 7), the average resources supply of ECC was highest in Xi'an, and was lowest in Qinba mountain. The average carrying capacity of environmental quality was highest in Weinan and Yulin, and lowest in Yan'an. The average carrying capacity of socio-economic level was highest in northern and lowest in Weinan. The average carrying capacity of infrastructure construction performance was highest in Xianyang and lowest in Tongchuan. The comprehensive carrying capacity was highest in Xi'an and lowest in Ankang. On the whole, ECC was highest in Guanzhong Plain, medium in Loess Plateau of northern Shaanxi Province and lowest in Southern mountainous. It can be seen from (Figure 8), resources and environmental quality carrying capacity indices were relatively low showing a fluctuating trend. Economic and infrastructure construction carrying capacity of ECC were relatively high showing an increasing trend. It indicated that resource and environmental protection capacity were relatively fragile in those regions, but the infrastructure and the economy were in a good status.

As shown in (Figure 9), the comprehensive environmental carrying capacity was fluctuating and showed an increasing trend which indicated a medium level. To verify the above assessment results, we selected three main factors from actual monitoring data and illustrated their changes in (Figure 10). By comparison,

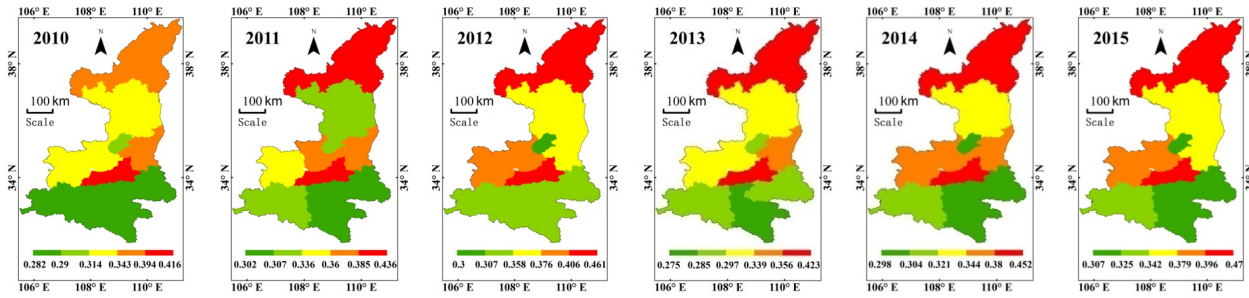


Figure 6. Spatial distribution of integrated environmental carrying capacity in 2010-2015.

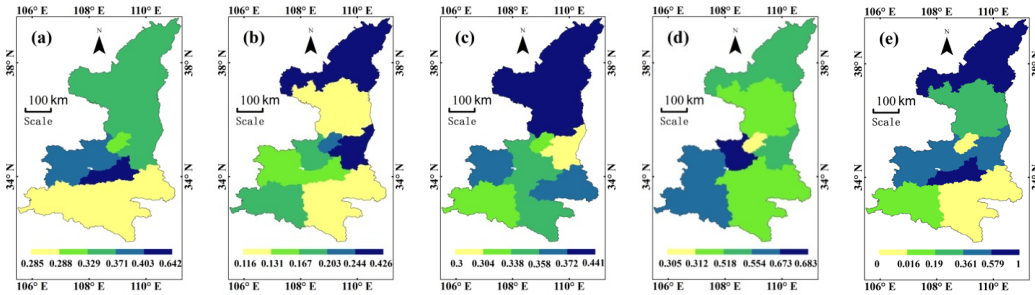


Figure 7. Spatial distribution of average environmental carrying capacity indices (a) resource supply, (b) environmental quality, (c) social economy, (d) infrastructure construction, (e) integrated.

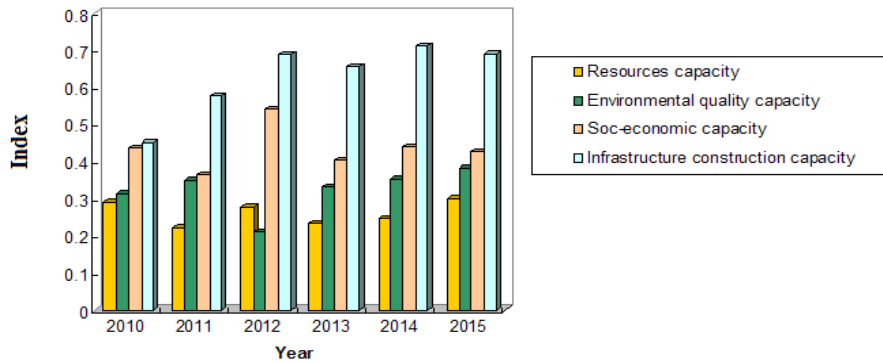


Figure 8. Time variation of four carrying capacity indices.

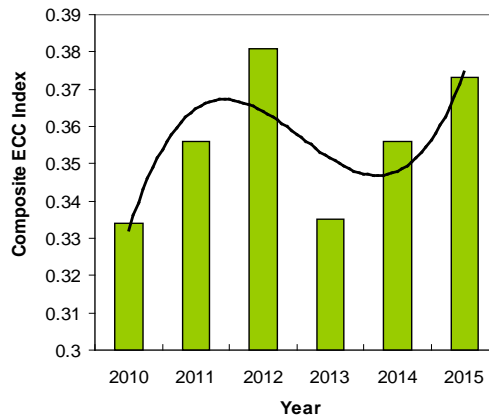


Figure 9. Time change of comprehensive environmental carrying capacity indices.

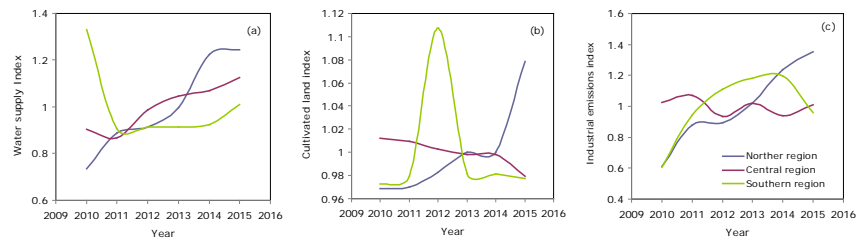


Figure 10. Index changes of water supply, cultivated land area and industrial emissions.

it can be found that the assessment results were generally consistent with the spatial distribution of the actual situation. The northern and central regions had high environmental carrying capacities while the southern regions had low environmental carrying capacities, and the overall ECC trend was consistent with the changes of the actual environmental elements.

4. Discussion

Previous studies [19], [23] indicated that comprehensive index evaluation model reported high ecological environment sensitivity and low resource carrying capacity. This study showed that the distribution of ECC in Shaanxi was affected by many factors. The environmental quality of ECC was affected by the degree of environmental protection and pollution control, and the level of economic, industrial and technological development. Terrain affects the size of resources supply. Climate change and water shortage lead to poor environmental quality and low ECC. Shaanxi's socio-economic level is determined primarily by the development of secondary and tertiary industries, and the population density also affects the magnitude of the regional socio-economic carrying capacity. On the whole, the change of environmental carrying capacity is affected by fragility of the natural environment and the destabilization of economic development. The results in this study showed that the spatial distribution of environmental carrying capacity was continuous and gradual. The results also showed that the method of PCA is a simple, easy-to-use method to evaluate the environmental carrying capacity without the interference from human factors in the index information, rendering the quantification of assessment indices objective. The PCA method can be used to extract large amount of information from regional multi-factor environment data set and evaluate environmental carrying capacities on a large regional scale.

5. Conclusion

This study demonstrates that PCA is simple, easy to use, and advantageous when applied to multi-index valuation of ECC on a large regional scale. The assessment results show that ECC was at the medium level in Shaanxi Province. The spatial distribution of ECC was different in different regions. ECC was highest in Guanzhong plain, followed by Loess Plateau and lowest in Qinba mountain. The infrastructure carrying capacity was highest followed by the socio-economic

carrying capacity, while resources supply and environmental quality carrying capacity was relatively low. The spatial distribution of ECC was closely related to vulnerability of natural geography, resource distribution, environmental protection, and development of energy economy. Therefore, the improvement of environmental quality and resource utilization efficiency in a region would increase the environmental carrying capacity.

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