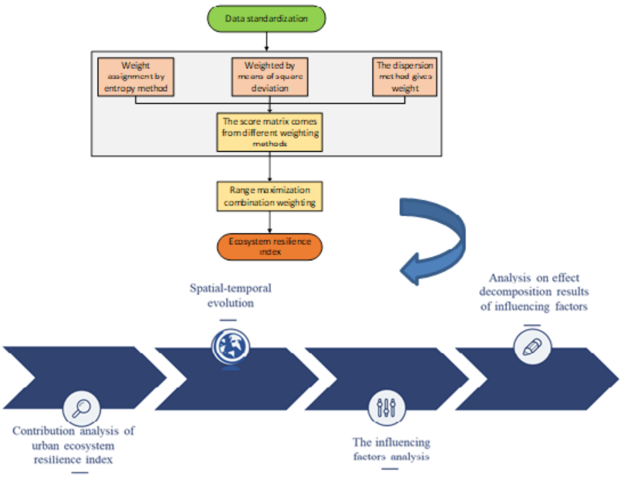
Global NEST Journal, Vol 25, No 1, pp 66-76

Spatial-temporal evolution and influencing factors of urban ecosystem resilience in the Yellow River Basin

Wang L.[1]**, Gong W.**[1,2*]**, Wang C.**[1,2]**, and Li W.**[1,2]
[1]School of Economics, Qufu Normal University, Rizhao 276826, China
[2]School of Economics and Management, Nanjing University of Aeronautics and Astronautics, Nanjing 211006, China
Received: 29/09/2022, Accepted: 31/10/2022, Available online: 04/11/2022
*to whom all correspondence should be addressed: e-mail: gongweifeng0539@163.com
https://doi.org/10.30955/gnj.004500

Graphical abstract



Abstract

Urban ecosystem resilience is a key concern in the strategy of ecological protection and high-quality development in the Yellow River Basin. This paper uses the principle of range maximization to construct an ecosystem resilience index measurement model from the four dimensions of energy, water resources, environment, and economy and society. The spatio-temporal evolution ecosystem resilience of 99 cities in nine provinces of the Yellow River Basin from 2005 to 2019 was analyzed. The spatial econometric model was used to explore the impact of technological innovation, opening to the outside world and industrial structure on the level of ecosystem resilience, so as to provide guidance for improving the level of ecosystem resilience in the Yellow River Basin. The results are concluded as follows: The level of ecosystem resilience in the Yellow River Basin generally increased first, then decreased, and then increased again. The resilience contribution of the environmental subsystem and the economic and social subsystem is relatively large, while the resilience contribution of the water resource subsystem is relatively small. How to improve the resilience level of the water resource subsystem should be considered as a key issue. Scientific and technological innovation, opening to the outside world and industrial structure had obvious spatial impacts on the resilience of the ecosystem in the Yellow River Basin.

Key words: Ecosystem resilience, maximization of range, spatio-temporal evolution, spatial durbin model

1. Introduction

The Yellow River basin is an important ecological barrier and economic development zone in China, as well as one of the main population areas in China. The weak ecological environment carrying capacity and the shortage of water resources are the biggest opportunities and challenges faced by the ecological protection and high-quality development strategy of the Yellow River Basin. With the extensive economic development, the ecological problems of the river basin have become prominent under the condition of intense human activities and unfavorable climatic conditions (Li *et al.*, 2021; Wohlfart *et al.*, 2017). In 2021, The Central Government of China issued *the Outline of the Plan for Ecological and Environmental Protection and High-quality Development in the Yellow River Basin*, specifying that major strategic achievements will be made in ecological and environmental protection and high-quality development in the Yellow River Basin by 2035. Urban unit is an important carrier of coordinating regional development and constructing ecological civilization, and the relationship between high-quality development and ecological protection should be well handled to meet the needs of sustainable development. Therefore, under the background of high-quality development, it is of great significance to study the urban ecosystem in the Yellow River Basin, and this research can also provide reference for other cities or countries.

At present, the ecological environment of the Yellow River basin is mainly studied in the loess plateau, oasis-desert ecotone and other geographical units (Ippolito *et al.*, 2010; Shi *et al.*, 2020), Some scholars also study small-scale administrative units such as provinces, cities, counties, urban agglomerations or resource-based cities (Lv *et al.*, 2019; Hu *et al.*, 2021; Xie *et al.*, 2021). From the perspective of research angle, most of them are studies on ecological risk (Ai *et al*., 2022) ecological vulnerability (Wu *et al*., 2021). In recent years, the study of ecological carrying capacity (Tang *et al*., 2022) has gradually become a research hotspot. Scholars also made a series of innovations in research methods, such as analytic Hierarchy Process (AHP) (Hu *et al*., 2021) fuzzy evaluation method (Ippolito *et al*., 2010) coefficient of variation method (Li *et al*., 2019). In the process of evaluating the ecological environment, the focus is still on a single aspect such as ecological carrying capacity and ecological resilience (Yuan *et al*., 2022; Xiao *et al*., 2021), few scholars put forward comprehensive evaluation model and evaluation index. Resilience was first used in mechanics and physics, Holling (1973) first introduced the term resilience in ecology and social ecology to describe the continuity of the internal structure of a system and its ability to resist interference from external factors. Ecosystem resilience should not only reflect the characteristics of ecological carrying capacity, but also reflect the ecological resilience of the region. Li *et al*. (2016) quantitatively evaluated urban infrastructure resilience, and Chen and Li (2019) established an evaluation index system for water ecological resilience. However, there are few comprehensive studies on the long-term resilience of urban ecosystems in the Yellow River Basin. There has been a lack of systematic index system and research on the spatial and temporal patterns and dynamic changes of ecological problems in the Yellow River Basin, and provincial and urban agglomeration units are relatively large, which cannot accurately represent the differences within the basin. Therefore, it is necessary to explore the resilience level of the Yellow River Basin ecosystem from the perspective of cities.

There have been studies on the influencing factors of ecological environment, mainly focusing on the analysis of temporal and spatial differences and influencing factors of carbon emissions (Mo and Wang, 2021; Qin *et al*.,2022,), and spatial spillover effects and influencing factors of haze pollution (Liu *et al*., 2022), Some scholars believe that labor force, export volume of goods and population density have ecological pressure on carbon footprint, while energy structure and international trade influence energy intensity has inhibitory effect on ecological pressure (Sun *et al*., 2018). Ecology includes environment, economy, energy, water resources and other aspects, so it also has certain spatial characteristics, and its influencing factors have spatial spillover effect. In the Yellow River Basin, the ecological background is poor, and the water resource is short. It is of great significance to study the spatial influencing factors of the ecological problems in the Yellow River Basin. When considering the influencing factors of ecological protection and economic development in the Yellow River Basin, the existing studies rarely combine the characteristics of the Yellow River basin and lack of analysis of specific influencing factors from the perspective of space.

To sum up, there are still some deficiencies in the current ecological research. We have made contributions in the following three aspects in this paper: Firstly，considering the particularity of the Yellow River basin, this study constructed a complete ecosystem resilience evaluation index system, including water resources and energy resources, to better evaluate the entire ecosystem of the Yellow River Basin. Then, a range maximization comprehensive evaluation model was established to calculate the ecosystem resilience index and analyze the spatio-temporal level of ecosystem resilience. Finally, the impact of technological innovation and the opening-up on the resilience of the Yellow River Basin ecosystem was studied from a spatial perspective.

2. Research methods and data description

2.1. Study area

The Yellow River basin has a large geographical span from east to west, and some provinces it flows through, such as Inner Mongolia, Qinghai and Gansu, have a large area. There is a big gap in urban environment, energy, water resources and economic and social development within each province. Taking prefecture-level cities along the Yellow River basin as the research object is more conducive to exploring the current situation of ecological development in the Yellow River basin in a reasonable and detailed way, analyzing the coordinated characteristics of distribution pattern and spatial relationship, and providing reference for the implementation of ecological protection and high-quality development strategy in the Yellow River Basin.

2.2. Index system

The existing research on ecological environment is mostly based on the energy-economy-environment (3E) system, which interacts with each other and develops harmoniously. With the deepening of research, social system has also been included in the scope of research, forming the energy-economy-environment-society (3E1S) system with a high degree of coupling and coordination (Zhao *et al*.,2019). Considering the ecological fragility of the Yellow River basin and the particularity of water resource shortage, it is very necessary to take water resource as a special perspective to see the development state of the whole ecosystem. Based on this, this paper constructed the whole ecosystem evaluation index system including wate resource subsystem, energy subsystem, environment subsystem, economic and social subsystem (Table 1).

Water resource subsystem is a special Angle in the assessment of ecosystem resilience in the Yellow River Basin. The utilization and development degree of regional water resources is reflected in the water quantity and quality of the region, which indirectly affects the sustainable development of water resources (Tang, 2021). Water consumption per unit GDP, per capita water consumption and total water resources can reflect the resilience of water resources subsystem.

Energy subsystem should be reflected in energy capacity, energy structure and energy efficiency (Fang, 2020). We use per capita energy consumption to represent energy capacity, which reflects the regional energy wealth and the state of energy reserve; The proportion of natural gas in total energy consumption represents the index of energy structure; Energy efficiency is reflected in the relationship with economic development, so energy consumption per unit GDP can better reflect the benefits brought by energy consumption.

Table 1. Evaluation index system of ecosystem resilience

Destination layer	Criterion layer	İndex layer	Attribute	Unit
Ecosystem resilience	Environmental subsystem	$PM_{2.5}$	minus	Micrograms per cubic meter
		Discharge of industrial wastewater	minus	ten thousand tons
		Industrial smoke (powder) dust emission	minus	ton
		Comprehensive utilization rate of industrial solid waste	Plus	%
		Harmless treatment rate of household garbage	Plus	%
		Domestic sewage treatment rate	Plus	%
	energy subsystem	Energy consumption per unit of GDP	Plus	Tons ten^{-1} thousand yuan
		Per capita energy consumption	minus	Tons per person
		Proportion of natural gas in energy consumption	Plus	%
	Water resource subsystem	Water consumption per unit of GDP	minus	Cubic meters yuan^{-1}
		Per capita water consumption	Plus	Cubic meters per person
		Total water resources	Plus	hundred million cubic meters
	Economic and social subsystem	Gross regional product per capita	Plus	yuan
		Education spending as a percentage of GDP	minus	%
		Public library collection per 100 people	Plus	One book
		Registered urban unemployment rate at year-end	Plus	%
		Spending on science	Plus	ten thousand yuan
		The population density	minus	People km2^{-1}
		Natural population growth rate	minus	permillage

Table 2. Ecosystem resilience indicator contributions by different empowerment approaches

İndex	Entropy method	Mean square deviation	Deviation method	Maximum of range
PM2.5	0.00281	0.03130	0.03648	0.07059
Discharge of industrial wastewater	0.00924	0.02143	0.02206	0.05273
Industrial smoke (powder) dust emission	0.04625	0.01114	0.00359	0.06098
Comprehensive utilization rate of industrial solid waste	0.00183	0.03857	0.04217	0.08258
Harmless treatment rate of household garbage	0.00161	0.03790	0.03806	0.07757
Domestic sewage treatment rate	0.00275	0.03896	0.04455	0.08626
Energy consumption per unit of GDP	0.01389	0.01235	0.01030	0.03654
Per capita energy consumption	0.02345	0.00908	0.00579	0.03832
Proportion of natural gas in energy consumption	0.00927	0.02817	0.03097	0.06840
Water consumption per unit of GDP	0.03157	0.00387	0.00068	0.03612
Per capita water consumption	0.04916	0.00383	0.00041	0.05339
Total water resources	0.01545	0.00887	0.00714	0.03146
Gross regional product per capita	0.00590	0.01705	0.01725	0.04021
Education spending as a percentage of GDP	0.00424	0.02103	0.02059	0.04587
Public library collection per 100 people	0.01461	0.00413	0.00161	0.020352
Registered urban unemployment rate at year-end	0.00396	0.01586	0.01540	0.035224
Spending on science	0.02226	0.00917	0.00582	0.037255
The population density	0.00713	0.03107	0.03572	0.073911
Natural population growth rate	0.00229	0.02355	0.02642	0.052256

Environmental subsystem is the most important aspect in the process of ecological protection in the Yellow River Basin. Environmental problems should not only be reflected in environmental pollution, but also include environmental governance. $PM_{2.5}$, industrial wastewater discharge, industrial smoke (powder) dust discharge are respectively representative of air pollution, water pollution and solid waste pollution, and the comprehensive utilization rate of industrial solid waste, harmless treatment rate of domestic waste, and domestic sewage treatment rate reflect the situation of regional environmental control.

As an important part of ecosystem, the subsystem of economy and society is highly coordinated with the subsystem of energy, environment and water resources, Combined with the construction of high-quality development indicators under the five development concepts (Xu , 2020), the per capita regional GDP, the proportion of education expenditure in GDP, public library collection per 100 people, urban registered unemployment rate at the end of the year, science expenditure, population density, and natural population growth rate are selected as indicators to measure economic and social development.

2.3. Data sources

The Yellow River Basin flows through 9 provinces. Due to serious data loss in some regions, 99 prefecture-level cities in 9 provinces of the Yellow River Basin were selected as research objects based on data availability, with a time span from 2005 to 2019. The data mainly come from China Urban Statistical Yearbook, the provincial statistical yearbook of the provinces involved, the bulletin of water resources of each province, and the statistical yearbook of prefectural cities. The $PM_{2.5}$ concentration source data used in this paper are from Chen Shiyi (2018). The data are latitude and longitude raster data, which were calculated by incorporating satellite and ground monitoring data into a two-stage spatial statistical model. Due to the large amount of data, interpolation method and thermal filling method are used to complete the missing data.

2.4. Model construction and description

In this study, the normalized method was used to preprocess the data, and the entropy weight method, mean square method and deviation method were used to assign weights to each evaluation index of ecosystem resilience. The range maximization method was used to calculate the comprehensive weight of each index and the ecosystem resilience index. The temporal and spatial analysis of ecosystem resilience index was carried out. Finally, the Spatial Durbin Model was used to analyze the impact of technological innovation, industrial structure and opening to the outside world on ecosystem resilience.

2.4.1. Calculation model of ecosystem resilience index based on maximum range

According to entropy method, mean square method and deviation method formula, the weight of each index of the ecosystem and its subsystems was assigned. For the evaluation scores obtained from *n* object and *m* methods, It can be represented by the following matrix *Z*

In order to maximize the overall difference between different evaluation objects, the adjusted weight matrix coefficient $\lambda=(\lambda_1,\lambda_2,\ldots,\lambda_m)^T$)) is introduced, that is, the variance of the evaluation score adjusted by the weight coefficient of λ is the largest.

i.e.

$$H=(Z^*)^T Z^* \quad (1)$$

Since $z_1^*,z_2^*,\cdots,z_m^*$ are the normalized value, *Z** is the matrix normalized to *Z*, The matrix *H* is the covariance matrix of *Z**. According to the difference principle of maximizing the range of evaluation objects, the problem of solving λ is transformed into the following planning problem:

$$\begin{cases} \max & \lambda^T H\lambda \\ s.t. & \lambda^T\lambda=1 \end{cases} \quad (2)$$

According to the literature, the optimal solution of model (2) is the feature vector *W* corresponding to the largest characteristic root of covariance matrix *H*, which is normalized to obtain the weight vector $\lambda=(\lambda_1,\lambda_2,\ldots,\lambda_m)^T$.

$$\theta_i=\lambda_1\alpha_i^{(1)}+\lambda_2\alpha_i^{(2)}+\lambda_3\alpha_i^{(3)} \quad (3)$$

Where, θ_i is the combination weight of the *i* indicator, namely, the contribution degree of resilience, which is the final contribution degree of resilience of each indicator; λ_i is the adjusted weight of the *i* weight; $\alpha_i^{(1)}$ is the entropy weight of the *i* index; $\alpha_i^{(2)}$ is the mean square deviation method weight of index *i*; $\alpha_i^{(3)}$ is the deviation weight of index *i*.

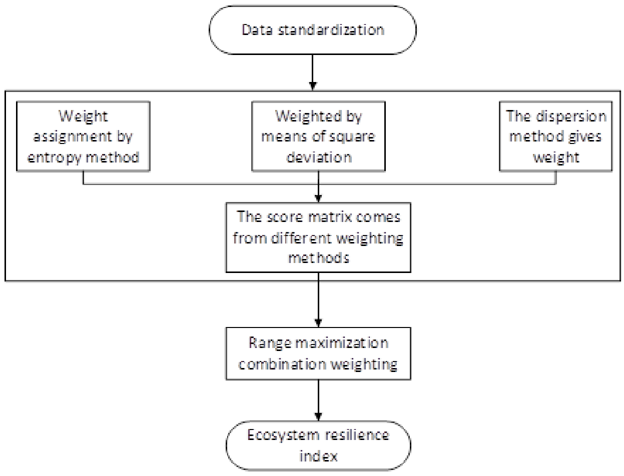


Figure 1. Framework of ecosystem resilience index measurement model based on maximum range

According to the adjustment weight vector, the calculation of ecosystem resilience index *ER* is:

$$ER=\sum_{i=1}^{19} x_{ik}\theta_i \quad (4)$$

2.4.2. Spatial influencing factor model

2.4.2.1 Spatial weight matrix

In the process of spatial econometric analysis, the spatial weight matrix should be set first and the spatial correlation test should be carried out. In addition to interactions between urban regions, cities with faster urban economic growth also have an impact on the ecosystem resilience of neighboring regions, therefore, it is more significant to construct weight matrix considering economic factors, and in order to consider the robustness, geographical distance spatial weight matrix and economic-geographical distance spatial weight matrix are adopted. Geographical distance spatial weight matrix:

$$W_{ij}^d=1/d^2, i\neq j; W_{ij}^d=0, i=j) \quad (5)$$

Economic-geographical distance spatial weight matrix:

$$\begin{cases} W_{ij}^e=w_{ij}\times \text{diag}(\frac{\overline{y_1}}{\overline{y}},\frac{\overline{y_2}}{\overline{y}},\cdots,\frac{\overline{y_n}}{\overline{y}}) \\ w_{ij}=1/d, i\neq j; w_{ij}=0, i=j) \\ \overline{y_i}=\frac{1}{t_1-t_0+1}\sum_{t=t_0}^{t_1} y_{it}; \overline{y}=\frac{1}{n(t_1-t_0+1)}\sum_{j=1}^{n}\sum_{t=t_0}^{t_1} y_{it} \end{cases} \quad (6)$$

In the above formula, W_{ij}^{d} is the spatial weight matrix of geographical distance, W_{ij}^{e} is the spatial weight matrix of economy-geographical distance, w_{ij} is geographical inverse distance matrix, diag(·) is diagonal matrix; *d* is the geographical distance between cities. $\overline{y_i}$ is the average value of regional economic output from time t_0 to t_1 of city *i* in the study period, $\overline{y}$ is the average value of economic output in all urban areas from time t_0 to time t_1 during the study period. *n* is the total number of cities.

2.4.2.2 Moran index

In order to test the interdependence and aggregation of different cities, the global correlation test was used to study the spatial distribution pattern of ecosystem resilience in the Yellow River Basin. The global Moran index was used to test the spatial correlation of ecosystem resilience and describe the overall spatial correlation of each city. Moran index is defined as follows:

$$Moran'sI = \frac{\sum_{i=1}^{n}\left(\sum_{j=1}^{m} W_{ij}(Y_i-\bar{Y})(Y_j-\bar{Y})\right)}{\left(S^2\sum_{i=1}^{n}\sum_{j=1}^{m} W_{ij}\right)} \quad (7)$$

Where, Y_i and Y_j are the observed values, $S^2=\frac{1}{n}\sum_{i=1}^{n}(Y_i-\bar{Y})^2$, $\bar{Y}=\frac{1}{n}\sum_{i=1}^{n}Y_i$, and W_{ij} is the element of the weight matrix. The value of Moran's I is generally between -1 and 1. If it is greater than zero, it indicates positive autocorrelation, that is, high value is adjacent to high value and low value is adjacent to low value, while it's less than zero if it's negative autocorrelation, the high value is adjacent to the low value, and if it is close to zero, there is no spatial autocorrelation.

2.4.2.3 Spatial Dubin model

Due to the strong spatial agglomeration characteristics of ecosystem resilience in the Yellow River basin, a spatial econometric model was adopted to explore the influencing factors of urban ecosystem resilience in the Yellow River basin by incorporating spatial effect factors into the model analysis. SDM model is selected for analysis through parameter testing.

$$ER = \alpha WER + X\beta + WX\gamma + \mu + \varepsilon \quad (8)$$

ER is the resilience index of each urban ecosystem in the Yellow River Basin, *α* is the spatial autoregressive coefficient, which represents the impact of the improvement of ecosystem resilience in other regions on the level of ecosystem resilience in this region. *β* represents the effect of the explained variable *WXγ* represents the influence of adjacent independent variable, The explanatory variables were scientific and technological innovation index, opening-up index and the proportion of tertiary industry in GDP. *μ* is for space specific effects, *ε* is the random perturbation term.

2.4.2.4 Effect decomposition model of influencing factors of ecosystem resilience

Drawing on the concepts of average total effect, average direct effect and average indirect effect proposed by LeSage and Pace (2009), the spatial Dubin model is organized as follows:

$$ER = \sum_{r=1}^{3} S_r(W)X_r + (I_N - \rho W)^{-1}(\mu + \varepsilon) \quad (9)$$

Where, $S_r(W)=(I_N-\rho W)^{-1}(I_N\beta_r+W\delta_r)$, *r*is the independent variable (r=1,2,…6), The average value of all elements on the main diagonal of $S_r(W)$ is the direct effect of the *r* independent variable on the resilience level of the ecosystem. The average value of elements outside the main diagonal of $S_r(W)$ is the indirect effect, which reflects the spatial effect of the *r* independent variable of other cities on the resilience level of their own urban ecosystem. The average of the sum of all elements $S_r(W)$ is the total effect of this independent variable on the level of ecosystem resilience.

3. Results and discussion

3.1. Contribution analysis of urban ecosystem resilience index in the Yellow River Basin

There is the contribution degree of each index calculated by entropy method, mean square deviation method and deviation method to ecosystem resilience show in Table 2. Due to the different directions of emphasis, the weights obtained by different weighting methods show great differences. The range maximization principle is used to combine and optimize the results of different weights to make the results more convincing. The resilience contribution of Domestic sewage treatment rate, Comprehensive utilization rate of industrial solid waste, Harmless treatment rate of household garbage and $PM_{2.5}$, Industrial smoke (powder) dust emission are bigger. Thus, the resilience of ecosystem is mainly determined by the resilience of environmental subsystems. In addition, the proportion of natural gas in energy consumption and population density also contribute significantly to ecosystem resilience. However, the contribution of water consumption per unit GDP and total water resources in the water resources subsystem is small. It can be seen that there is a huge development potential in improving the toughness of water resources subsystem.

Figure 2 shows the resilience status and evolution characteristics of each subsystem dimension of urban ecosystem resilience in the Yellow River Basin from 2005 to 2019. The resilience indexes of ecosystems, environmental subsystems and economic and social subsystems are shown by the primary ordinate axis, while the resilience indexes of other subsystems are shown by the secondary ordinate axis. The environmental subsystem resilience index was the highest, followed by the economic and social subsystems. During the research period, the environmental subsystem resilience and economic and social subsystems resilience were fluctuating upward, while the energy subsystem resilience was in a stable fluctuation state and the increase was not obvious. The water resource subsystem resilience index was small, but it still rising steadily. The environmental governance efforts and environmental protection policies were constantly improving, so the Environmental subsystem resilience index was high. On the other hand, China was in the stage of rapid economic development, and the population structure and social security system were constantly optimized, which made the resilience index of economic and social subsystems relatively high. Energy subsystem and water subsystem resilience indexes were relatively low, but still rising, Therefore, the fluctuation trend of different subsystems led to the overall increase of the resilience level of the urban ecosystem in the Yellow River Basin. How to improve the resilience level of the energy and water resources subsystems should be considered as a key issue.

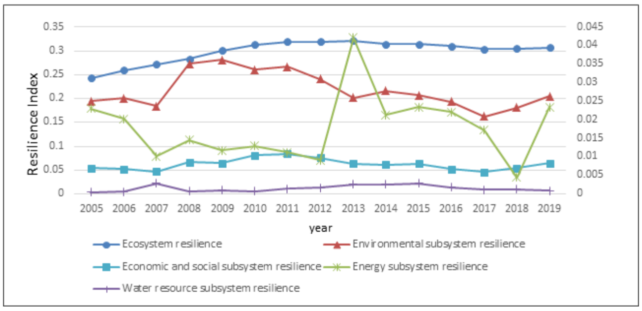


Figure 2. Temporal variation characteristics of dimensions of ecosystem resilience index in the Yellow River Basin

3.2. Spatial and temporal distribution of ecosystem resilience in the Yellow River Basin

In order to compare and analyze the differences in the ecological environment quality in each region, it is necessary to classify the ecological environment quality in each region. This study was mainly classified by using the natural breakpoint method (Jenks), The classification standard for each time period shall be unified, otherwise the comparative analysis cannot be conducted (Zhang J., 2016). Thus, the 2017 grading criteria were adopted from 2005 to 2019. It is divided into five levels: Areas with low resilience, Areas with relatively low resilience, Areas with median resilience, Areas with relatively high resilience, Areas with high resilience, The specific classification is shown in Figure 4.

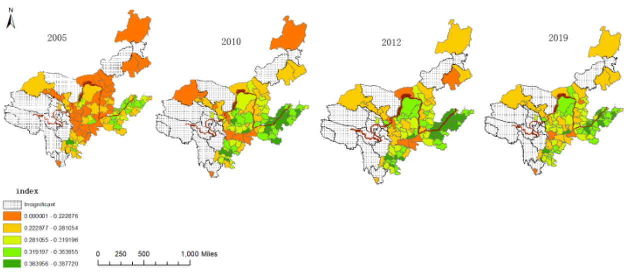


Figure 3. Spatial distribution of the ecosystem resilience index in the yellow river basin

From Figure 3, during the study period, the level of the urban ecosystem resilience in the Yellow River basin moved up overall. Specifically, in 2005, only Chengdu belongs to the Areas with high resilience. Shangluo, Jinchang, Ankang, Tongchuan, Shuozhou and other cities in the upper and middle reaches are located in the low value area of toughness, accounting for a large proportion and showing spatial centralized distribution. There are some problems in these cities such as backward production technology and weak environmental awareness, which lead to serious phenomena such as waste of energy and water resources and environmental pollution. The cities in Areas with relatively high resilience were mainly downstream cities such as Jinan, Zhengzhou, Weifang and Anyang, most of which were provincial capitals and cities with high level of development, with relatively high level of urban infrastructure construction, strong environmental governance capacity, and relatively reasonable utilization of energy and water resources.

In 2010, the number of cities in areas with high resilience increased significantly, and there was a spatial centralized distribution, while the number of cities in areas with low resilience decreased significantly. In addition, the number of cities in areas with median resilience increased significantly. Similar to 2010, in 2012, the ecosystem resilience showed a clear spatial concentration of distribution, and the overall level was further improved. The distribution of cities in areas with high resilience has significantly expanded; Cities in areas with relatively high resilience were concentrated in the middle and upper reaches of the region, showed the characteristics of "small agglomeration and large dispersion". The scope of cities in areas with low resilience was further narrowed. On the one hand, the implementation of the ecological civilization construction strategy has improved the environmental governance capacity and enhanced the awareness of ecological protection. On the other hand, during this period, the improvement of the industrialization development level led to the development of urbanization and infrastructure construction.

In 2019, compared with 2012, Kaifeng, Linyi, Zibo, Weifang, and other cities in areas with high resilience were "downgraded", the possible reason was that the rapid urbanization development has caused great pressure on the environmental, economic development and infrastructure construction of these cities. The proportion of the cities in areas with median resilience accounted for the largest, showing an obvious spatial centralized distribution. The ecosystem resilience index of cities in areas with relatively low resilience was "upgraded". Only four cities: Shangluo, Longnan, Shuozhou and Panzhihua were in areas with low resilience, and the cities in areas with low resilience were scattered, the gap between the level of each urban ecosystem resilience was reduced.

In terms of the time series, ecosystem resilience has declined in recent years, although it rebounded in 2018, but the increase was small. How to make the improvement of ecosystem resilience bigger and achieve the upgrade of resilience and steady growth is a major problem we are facing now. This paper tries to find solutions by exploring the influencing factors of ecosystem resilience. The spatial analysis showed that ecosystem resilience had obvious aggregation characteristics. Therefore, it was necessary to take spatial factors into account to explore the spatial influencing factors of ecosystem resilience.

3.3. Global spatial autocorrelation analysis

Taking the ecosystem resilience index of 99 cities in the Yellow River Basin flowing through the province as a variable, the global *Moran's I* index from 2005 to 2019 was calculated using the geographic distance spatial weight matrix and the economic-geographic distance weight matrix, respectively. The result is shown in Figure 4. In the study area from 2005 to 2019, it passed the test at the significance level of 1%, and there was a positive spatial autocorrelation, and the *Moran's I* showed a trend of first increasing and then decreasing. The result indicates that the ecosystem resilience of the Yellow River Basin has the characteristics of aggregation during the study period, and the cities are not isolated or randomly distributed. The ecosystem resilience index of the Yellow River Basin has spatial correlation, and a spatial econometric model can be used for regression analysis.

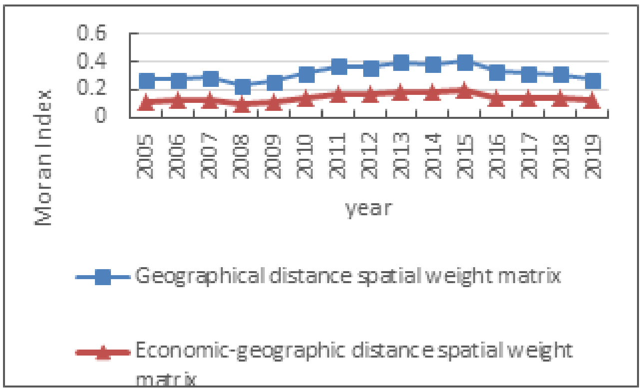


Figure 4. 2005-2019 Moran index of resilience index in yellow river basin ecosystem

3.4. The influencing factors analysis of the yellow river basin ecosystem resilience index

3.4.1. Scientific and technological innovation

Scientific and technological innovation is reflected in technological innovation in environmental protection and environmental governance, innovation in the utilization of energy and water resources, and innovation in the development of economic development, production and manufacturing, and medical technology. Considering the impact of scientific and technological innovation on ecosystem resilience, this paper selects four indicators, namely, R&D personnel, R&D internal expenditure, number of patent authorizations and number of patent applications, uses the method for maximizing range to calculate the scientific and technological innovation index, and take it as the first influencing factor of ecosystem resilience, the influence coefficient may be positive.

3.4.2. Opening to the outside world

Opening up to the outside world has an impact on China's ecological environment, but it's just China's thirst for short capital, which masks its negative impact on the ecological environment (Li, 2007). Environmental pollution is highly mobile and can flow across national boundaries. There will be a series of environmental problems in the process of opening to the outside world. It can be seen that the level of opening to the outside world has a great impact on the ecosystem. In this paper, we select three indicators: the amount of goods imported, the amount of goods exported, and the amount of foreign capital actually used in the current year, and use the method for maximizing range to calculate the opening-up index, which is regarded as another factor affecting the level of the ecosystem resilience， and it is uncertain whether the influence coefficient is positive or negative.

3.4.3. Industrial structure

Different industries have different degrees of dependence on resources and different environmental pollution conditions. Therefore, there are different effects on the environment, as well as energy consumption and water resource utilization from industrial structures. There is a long-term cointegration relationship between industrial structure and ecological environment. The optimization of industrial structure plays an important role in the sustainable improvement of ecological environment (Zhang *et al*., 2021). Taking the proportion of the tertiary industry in GDP as an indicator to measure the industrial structure, it is of great significance to explore its impact on the resilience of the ecosystem in the Yellow River Basin, and it is uncertain whether the influence coefficient is positive or negative.

3.5. Analysis of spatial Dubin model regression results

In this paper, the Spatial Lag Model (SLM), Spatial Error Model (SEM) and Spatial Dubin Model (SDM) are selected for analysis. The sample panel data were tested for stability, and the results showed that the sample data were stable. By performing LM test on the model, the test results are shown in Table 3. Under the two weight matrices, LM spatial lag test and LM spatial error test are significant at the level of 1%, while the robust LM spatial lag test and robust LM spatial error test are also significant at the level of 1%, the original assumptions of no spatial lag explained variable and no spatial autocorrelation error term are rejected, and the spatial Dobbin model is considered for analysis.

The geographical distance spatial weight matrix and the economic-geographic distance weight matrix are used to further test the model. Among the Hausman test results, the results of the Hausman test using the geographical distance spatial weight matrix are not significant, therefore, the random effect model is selected. The economic geographical distance weight matrix is used to determine the fixed effect model through Hausman test. From the results, the analysis results of the spatial Durbin model using the geographic distance space weight matrix are consistent with the results under the economic-geographic distance weight matrix. Due to the geographic distance is not the only factor in the production of space effect, the ecosystem resilience level in different areas will be influenced by differences in the levels of economic development. Setting the spatial weight matrix from the perspective of economic attributes can analyze the degree of economic dependence among cities and help to further explore their spatial influence relationship. Therefore, in order to conduct a comprehensive analysis of the influencing factors of ecosystem resilience, this paper selects the SDM under the economic-geographic distance weight matrix for analysis. Next, the Wald test was performed. The results of Wald reject the original assumption that SDM can be degraded to SLM and SEM. Therefore, SDM model is optimal in this study. After testing, the SDM time fixed effect model under the economic-geographic distance weight matrix is finally selected to analyze the influencing factors of ecosystem resilience in the Yellow River Basin.

Table 3. LM inspection results

	Space lag-LM	**Robust spatial lag-LM**	**Spatial error-LM**	**Robust spatial error-LM**
Geographic distance weight matrix	210.998***[0.000]	88.198***[0.000]	414.898***[0.000]	292.098***[0.000]
Economic geographical weight matrix	596.560***[0.000]	255.152***[0.000]	1921.604***[0.000]	1580.196***[0.000]

Note: *** p<0.01, ** p<0.05, * p<0.1. The p value of the test is given in [].

Table 4. Spatial measurement estimation results

Variable	**Geographic distance spatial weight matrix**		**Economic-geographic distance spatial weight matrix**	
	Parameter estimation	**T value**	**Parameter estimation**	**T value**
x1	0.130***	3.4946	0.235***	10.0858
x2	0.0164	0.4530	-0.0439**	-2.0905
x3	0.0237	0.7476	-0.106***	-3.5452
W* x1	-0.175***	-2.6395	0.101	0.8938
W* x2	0.179**	2.2072	0.176*	1.7778
W* x3	-0.00842	-0.2251	-0.806***	-5.7571
W*ER	0.715***	30.1688	0.796***	17.0815
Observations	1485	1,485		
Log-likelihood	2221 4146	1580 895 99		
Number of id	99	99		

Note: *, **, *** indicate statistical significance at 10%, 5%, 1% levels, respectively.

From the results in Table 4, it can be seen that the coefficient of the spatial lag term of the ecosystem resilience index is significant at the 1% level, and the coefficient is positive 0.796, which indicates that ecosystem resilience has a positive spatial effect between regions. The improvement of the level of the ecosystem resilience in adjacent areas can drive the improvement of the level of the ecosystem resilience in the region. The improvement of the level of the ecosystem resilience in adjacent areas can also reflect the improvement of the comprehensive development level of the region in the four aspects of energy, environment, water resources, economy and society, which is conducive to the common improvement of the resilience level of the ecosystem among regions.

Scientific and technological innovation is significant at the level of 1%, and the coefficient is positive, but the spatial lag coefficient is weak. The level of scientific and technological innovation only has a significant impact on the region, the impact of changes in the level of scientific and technological innovation in the surrounding areas on the resilience of the local ecosystem is relatively weak. By increasing the number of R&D personnel, R&D internal expenditure, and promoting the increase of R & D projects of scientific researchers, the region will affect the level of the regional ecosystem resilience.

The regional opening-up level will significantly affect the level of the regional ecosystem resilience and have a negative impact on itself. The increase in the actual use of foreign capital will further expand the production scale, bring greater energy and resource consumption, and lead to increased pressure on ecosystem resilience. In the process of regional foreign investment and goods import and export trade, the "high pollution and high energy consumption" industries will inevitably aggravate the environmental pollution problems in the region, and then reduce the level of the local ecosystem resilience. The level of opening up of surrounding areas has a positive conduction effect on the level of ecosystem resilience in the current area. The reason for this phenomenon may be that the improvement of the opening-up level of the surrounding areas can drive the improvement of the current regional economic development level.

The industrial structure is significant at the level of 1%, and the coefficient is negative, indicating that the surrounding areas have a negative conduction effect on the level of the local ecosystem resilience. The improvement of the resilience level of the ecosystem should be reflected not only in quantity but also in quality. We should not overemphasize increasing the proportion of the tertiary industry in the GDP and blindly pursue the rapid expansion of the scale of the tertiary industry. If the balance ratio of traditional industry transformation and modern service industry development is ignored, it will have the opposite effect.

3.6. Analysis on effect decomposition results of influencing factors of ecosystem resilience

From the effect decomposition in Table 5, it can be seen that the direct effect of scientific and technological innovation is significantly positive at the level of 1%, the indirect effect is significantly positive at the level of 5%. The impact of scientific and technological innovation investment on ecosystem resilience in this region may be reflected in two aspects: on the one hand, the impact of this region on ecosystem resilience may lead to the reduction of investment in adjacent areas through "free riding", which is not conducive to the improvement of ecosystem resilience level in adjacent areas; On the other hand, the improvement of the level of scientific and technological innovation in the region may promote the surrounding areas to strengthen the investment in innovation through the demonstration effect and warning effect, which will help to improve the resilience of the ecosystem. If the latter is greater than the former, the improvement of the level of scientific and technological innovation in the region will help to improve the resilience of the ecosystem in the surrounding areas, and vice versa.

The opening-up level of each region in the Yellow River Basin has a negative impact on its own ecosystem resilience. The possible explanation is that local governments have blind competition for the introduction of foreign investment and foreign trade under the pressure of political performance assessment or promotion, resulting in serious pollution problems, and then have a negative impact on the resilience of the ecosystem. However, the indirect effect is less significant, and the coefficient is positive. The excessive increase in the degree of opening to the outside world in the region is not conducive to the improvement of the resilience level of its own ecosystem, but it has a warning effect on the surrounding areas, which improves the attention of the surrounding areas to ecological issues in the process of foreign trade, thus promoting the surrounding areas to drive the improvement of the resilience level of the local ecosystem.

In terms of industrial structure, whether from the perspective of the region itself or from the perspective of other regions to the region, the impact of industrial structure is significant, and the impact effect is negative. From the perspective of the spatial distribution of China's industrial structure, the increase in the proportion of the tertiary industry in a certain region is mostly realized by transferring polluting industries to the surrounding underdeveloped areas or through industrial division and trade. This process will lead to the reduction of the local industrial output value, which is not conducive to the improvement of the resilience of the economic and social subsystem, and then affect the resilience of the local ecosystem; Secondly, the surrounding areas produce environmental pollution due to industrial transfer, which in turn affects the resilience of the local environmental subsystem. Therefore, blindly increasing the proportion of the tertiary industry will reduce the resilience of the local ecosystem.

Table 5. Spatial effect estimation results

Variable	Direct Effect		Indirect Effect		Total Effect	
	parametric estimation	T value	parametric estimation	T value	parametric estimation	T value
x1	0.253***	10.0797	1.517*	1.7239	1.770**	2.0045
x2	-0.0370*	-1.7453	0.714	1.4000	0.677	1.3223
x3	-0.155***	-4.6687	-4.598***	-2.6905	-4.754***	-6.5572

Note: *, **, *** indicate statistical significance at 10%, 5%, 1% levels, respectively.

4. Conclusions

By reading relevant literature and combining with the development status of the Yellow River Basin and the "*Plan for Ecological Protection and High-Quality Development in the Yellow River Basin*", 19 indicators were selected from four aspects of environment, energy, water resources, and economy and society to construct an evaluation index system for ecosystem resilience in the Yellow River Basin. , using the range maximization method to calculate the ecosystem resilience index of the Yellow River Basin, the spatio-temporal evolution characteristics were analyzed, and the influencing factors of ecosystem resilience were explored. The following conclusions were drawn:

(1) From the results of ecosystem resilience index, the resilience contribution of environmental subsystem is relatively large, the resilience contribution of economic and social subsystem is also relatively obvious, while the resilience contribution of water resource subsystem is relatively small. As the Yellow River basin flows through provinces and cities, the water resource subsystem is an important part of the resilience of the urban ecosystem. More attention should be paid to the resilience of the water resource subsystem to give full play to its great potential.

(2) From the perspective of spatio-temporal evolution pattern, the urban ecosystem resilience in the Yellow River Basin generally increased first, then decreased and then turned to increase from 2005 to 2019. The resilience index of ecosystems has declined in recent years. However, in 2018, the resilience index of the ecosystem showed a small upward trend, but it was not obvious. The low value area of toughness has the characteristics of dispersion, while the median value area and the high value area of toughness have the characteristics of agglomeration. The high toughness area has the characteristics of "small agglomeration and large dispersion", while the low toughness area changes from "large agglomeration" to "small dispersion". The proportion of cities in the low value area and the median value area of toughness is relatively large. How to upgrade the resilience of the ecosystem and achieve steady growth is a major issue we are facing now.

(3) From the analysis results of influencing factors, technological innovation has a positive role in promoting ecosystem resilience and can also have a positive impact on neighboring regions, The main reason is that environmental technology innovation, energy utilization technology innovation and other means can have a positive impact on ecosystem resilience. opening to the outside world has a negative impact on the local area, but

the improvement of the level of opening up in other regions has a positive impact on the local area. In terms of industrial structure, the proportion of the tertiary industry has an inhibitory effect on the local ecosystem resilience level, and its spatial effect is also negative. We should give full play to the advantages of each region and realize regional linkage, so as to realize the "great protection and great development" of the Yellow River Basin.

By constructing the urban ecosystem resilience evaluation system, analyzing the spatial-temporal evolution characteristics of urban ecosystem resilience and discussing its spatial influencing factors, it is helpful to clarify the resilience level of different urban ecosystems in the Yellow River Basin and put forward targeted suggestions. However, due to the limitations of data acquisition, the indicators selected in this paper to measure ecosystem resilience are not perfect, and there may be some deviation in the evaluation results, the evaluation index system of ecosystem resilience needs to be further improved in the future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Liping Wang: Conceptualization, Methodology, Investigation, Writing - original draft, Funding acquisition. Weifeng Gong: Validation, Formal analysis, Visualization, Writing - review & editing, Funding acquisition. Chuanhui Wang: Formal analysis, Data curation, Writing - review & editing. Wenwen Li: Data curation, Software.

Acknowledgments

The work is supported by the Research and innovation Fund for graduate dissertation of Qufu Normal University grants LWCXS202231, National Natural Science Foundation of China under grants 71804089.

References

Ai J.W., Yu K.Y., Zeng Z., Yang L.Q., Liu Y.F., and Liu J. (2022). Assessing the dynamic landscape ecological risk and its driving forces in an island city based on optimal spatial scales: Haitan Island, China, *Ecological Indicators, 1*37, 108771.

Chen S., and Chen D. (2018). Air Pollution, Government Regulations and High-quality Economic Development. *Economic Research,* **53**(02), 20–34.

Chen T., and Li Y.L. (2019). Urban water environment-oriented urban design strategy from the perspective of ecological resilience. *Science and Technology Review,* **37**(8), 26–36.

Fang L., and Wei Q. (2019). Analysis on the coordinated development of water resources and energy systems in Shaanxi Province. *Research on Water Conservancy Development,* **19**(01), 43–47.

Holling C.S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology, Evolution, and Systematics,* **4**(1). 1–23.

Hu X., Ma C., Huang P., and Guo X.u. (2021). Ecological vulnerability assessment based on AHP-PSR method and analysis of its single parameter sensitivity and spatial autocorrelation for ecological protection: A case of Weifang City. *China Ecological Indicatoors,* **125**, 107464.

Ippolito A., Sala S., Faber J.H., and Vighi M. (2010), Ecological vulnerability analysis: A river basin case study. *Science of the Total Environment,* **408**(18), 3880–3890.

Ippolito A., Sala S., Faber J.H., and Vighi M. (2010). Ecological vulnerability analysis: A river basin case study, *Science of the Total Environment,* **408**(18) 3880–3890.

LeSage J., and Pace R K. (2009). Introduction to spatial econometrics. *Chapman and Hall/CRC,* 56–68.

Li C., Gao X., He B., Wu J., and Wu K. (2019). Coupling coordination relationships between urban-industrial land use efficiency and accessibility of highway networks: Evidence from Beijing-Tianjin-Hebei urban agglomeration, China. *Sustainability,* **11**, 1446–1468.

Li H. (2007). Pay attention to exertion of environmental positive effect of FDI Basing on the Research Angle of Ecologic Modernization. *International Trade,* **2007**(8), 46–49.

Li X.K., Liu K., and Tian J. (2021), ariability, predictability, and uncertainty in global aerosols inferred from gap-filled satellite observations and an econometric modeling approach. *Remote Sensing of Environment,* **261,** 112501.

Li Y., Zhai G.F., and Guo F.M. (2016). Research review on quantitative assessment methods of urban infrastructure resilience. *Urban Development Research,* **23**(6), 113– 122.

Liu Y., Tian J.W., Zheng W.F., and Lirong Yin. (2022). Spatial and temporal distribution characteristics of haze and pollution particles in China based on spatial statistics. *Urban Climate,* **41**, 101031.

Lv X., Xiao W.u., Zhao Y., Zhang W., Li S., and Sun H. (2019). Drivers of spatio-temporal ecological vulnerability in an arid, coal mining region in Western China. *Ecological Indicators,* **106**, 105475.

Mo H.B., and Wang S.J. (2021). Spatio-temporal evolution and spatial effect mechanism of carbon emission at county level in the Yellow River Basin. *Science Geography Sinca,* **41**(8), 1324–1335.

Qin Q.D., Yan H.M., Li B.X., Wei L., and Wasif Zafar M. (2022). A novel temporal-spatial decomposition on drivers of China's carbon emissions. *Gondwana Research,* **109**, 274–284.

Shi H., Lu J., Zheng W., Sun J., Li J., Guo Z., Huang J., Yu S., Yin L., Wang Y., Ma Y., and Ding D. (2020). Evaluation system of coastal wetland ecological vulnerability under the synergetic influence of land and sea: A case study in the Yellow River Delta. *China Marine Pollution Bulletin,* **161**, 111735.

Sun Q., Geng Y., Ma F., Wang C., Wang B., Wang X., and Wang W. (2018). Spatial temporal evolution and factor decomposition for ecological pressure of carbon footprint in the one belt and one road. *Sustainability,* **10**(9), 3107.

Tang J., Ding W., Li W., and Liu X. (2021). Study on Evaluation of Water Resources Carrying Capacity and Obstacle Factors in the Yellow River Basin. *People's Yellow River,* **43**(07), 73–77.

Tang Y.Z., Wang M.D., Liu Q., Hu Z.W., Zhang J., Shi T.Z., Wu G.F., and Su F.Z. (2022). Ecological carrying capacity and sustainability assessment for coastal zones: A novel framework based on spatial scene and three-dimensional ecological footprint model. *Ecological Modelling,* **466**, 109881.

Wohlfart C., Mack B., Liu G., and Kuenzer C. (2017). Multi-faceted land cover and land use change analyses in the Yellow River Basin based on dense Landsat time series: Exemplary analysis in mining, agriculture, forest, and urban areas. *Applied Geography,* **85**, 73–88.

Wu H., Guo B., Fan J., Yang F., Han B., Wei C., Lu Y., Zang W., Zhen X., and Meng C. (2021). A novel remote sensing ecological vulnerability index on large scale: A case study of the China-Pakistan Economic Corridor region. *Ecological Indicators,* **129**, 107955.

Xiao Wu., Chen W., and Deng X. (2021), Coupling and coordination of coal mining intensity and social-ecological resilience in China, *Ecological Indicators,* **131**, 108167.

Xie Z., Li X., Chi Y., Jiang D., Zhang Y., Ma Y., and Chen S. (2021). Ecosystem service value decreases more rapidly under the dual pressures of land use change and ecological vulnerability: A case study in Zhujiajian Island. *Ocean & Coastal Management,* **201**, 105493.

Xu Y., and Wang H. (2020). Construction and demonstration of regional high-quality development index system based on "five development concepts. *Statistics and Decision*, **36**(14), 98–102.

Yuan Y., Bai Z., Zhang J., Xu C. (2021). Increasing urban ecological resilience based on ecological security pattern: A case study in a resource-based city, *Ecological Engineering,* **175**, 106486.

Zhang J., Hao S.B., Zhao C.X., Zhang J., Xu P., Cao Y.W., Zhao J.Q., Li J.G. (2016). Application of principal component analysis in comprehensive indicator screening for pneumoconiosis in different regions. *Chinese Journal of Industrial Hygiene and Occupational Diseases,* **34,** 678–680.

Zhang X., Cao Z., and Dong H. (2021). Study on the coupling correlation and dynamic response of industrial structure, urbanization and ecological environment in Beijing-Tianjin-Hebei region. *Journal of Southwest University for Nationalities (Humanities and Social Sciences Edition)*, **42**(12), 121–128.

Zhao T., Yu C., and Pan H. (2019). Research on the coupling coordination degree of 3E1S system in low-carbon cities. *Statistics and Decision,* **35**(22), 131–135.