ECOLOGICAL SECURITY EVALUATION, OBSTACLE DEGREE ANALYSIS, AND EARLY WARNING BASED ON THE PRESSURE–STATE–RESPONSE MODEL IN HUANGSHAN CITY, CHINA

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Abstract. Urban ecological security evaluation is helpful for improving urban environmental quality and enhancing urban ecological system stability. This study takes Huangshan City, China as an example. By utilizing the pressure–state–response (PSR) conceptual model, the urban ecological security evaluation index system is established. Then, the index weights are calculated using the entropy-weight method to eliminate subjectivity. The ecological security comprehensive index method is used to evaluate the ecological security level. Ecological security barrier factors are calculated using the obstacle model. The development trend of ecological security is predicted via linear regression. Three main points can be deduced from the results. (1) The level of ecological security in 2012–2020 underwent an overall upward trend, and the level of ecological security in Huangshan City, China, from 2012 to 2020 was between 0.3540 and 0.6630. (2) The majority of the guideline barrier factors that affected ecological security were pressure barrier factors. Industrial solid waste, which was the primary impediment factor, affected ecological security. (3) The prediction results indicated that the level of ecological security showed an upward trend. This study provides a theoretical reference for urban sustainable development decision making.
Keywords: *ecological system stability, entropy method, comprehensive index method, linear regression, quantitative evaluation*

Introduction

Ecological security represents the health and integrity of the nation's and region's ecosystems. Ecological security is an important aspect of sustainable development. With the rapid growth of urbanization and industrialization in recent decades, the ecological environment has been considerably affected. People have paid more attention to ecological security. However, research on urban ecology has been limited. The strongest interaction between humans and nature occurs in urban areas, which are artificially synthesized, highly concentrated socioeconomic natural ecosystems (Hong et al., 2010; Jiang and Chen, 2011; Han et al., 2015). Frequent human activities caused by the rapid growth of urbanization and industrialization in recent decades have considerably affected the ecological environment (Liu et al., 2022). In view of protecting the ecological environment and maintaining sustainable urban development, a scientific and quantitative dynamic evaluation of urban ecological safety is required.

Presently, researchers are focusing on the conceptual content, research objects, and evaluation methods of ecological safety. For the first time in 1989, the International Institute for Applied Systems Analysis introduced the concept of ecological security, focusing on the safety of ecosystems (Huang et al., 2007). National or regional (Zhang et al., 2016, 2020; Chen, 2017; Liu et al., 2021; Wang et al., 2021), forest (Zheng et al., 2018; Lu et al., 2020; Yu et al., 2021), land (Su et al., 2009; Su, 2019; Yang et al., 2020), watershed (Gao et al., 2007; Yu et al., 2013; Shen et al., 2017; Wang et al., 2022), and other natural environmental ecosystem security are typically the focus of research. However, only a few studies on urban ecological safety have been conducted. Ecological safety evaluation methods include the digital ground model (Du et al., 2012), ecological model (Liu et al., 2018), landscape ecology model (Wu et al., 2021), and pressure–state–response (PSR) evaluation model (Huang et al., 2021). The digital ground model strategy emphasizes the effects of geographic location; the ecological model emphasizes the impact of human factors; and landscape ecology proceeds with evaluation from a single landscape perspective. In 1990, the Organisation for Economic Cooperation and Development (OECD) proposed the PSR evaluation model. This model is founded on the cause-and-effect relationship between human activities and natural processes; it is logically sound and operational from the standpoint of the interaction between the economic activities of human society and environmental protection. Consequently, the PSR model has been regarded as more convincing for ecological safety.

The majority of the research on urban ecological safety has concentrated on large cities with large populations and rapid development rates, apart from urban agglomerations. The majority of the studies were subjective. Furthermore, the number of studies was limited with respect to the quantitative dynamic evaluation of ecological safety in Southern Anhui's mountainous urban areas, China. As a typical city in the mountainous region of Southern Anhui Province, the city's ecological environment has suffered in recent years due to the accelerated urbanization process and rapid economic development. The city's ecological security is threatened. For the sustainable development of cities in the future, scientific and quantitative evaluations of ecological safety dynamics are of great importance. A systematic, scientific, and exhaustive evaluation of urban ecological safety can help to gain a thorough understanding of the city's strengths and weaknesses, and it is crucial for adjusting industrial layout and achieving transformational development.

In this study, urban ecological safety was evaluated by combining the PSR model, a mathematical model, a barrier degree model, and a linear fitting method. Huangshan City was selected as the object of study. The PSR model was used to construct the evaluation index system, and the objective entropy weight method was used to determine the weights. On this basis, an evaluation model of the urban ecological security of Huangshan City was established. Then, the comprehensive index method was introduced to calculate the ecological security index, while the barrier degree model was utilized to calculate the influencing factors affecting the city's ecological security. In addition, the future ecological security trends in Huangshan City were predicted using the linear fitting method. The results of the study can be used to quantitatively and dynamically evaluate the ecological security of Huangshan City and formulate and implement appropriate policies in response to the ecological security situation. The proposed method can also serve as a model for evaluating ecological security in other cities. The evaluation results will provide a theoretical basis for the sustainable development of Huangshan City to help local decision-makers produce scientific and feasible policy measures.

Material and methods

Study area

Huangshan City is located in the southern part of the province of Anhui, China (*Fig. 1*). It is stretched between 117°02′ and 118°55′ E longitude and 29°24′–30°24′ N latitude. The city has an area of 9807 km^2. Huangshan City covers three districts (Huangshan,

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Tunxi, and Huizhou) and four counties (Yixian, Shexian, Qimen, and Xiuning). By the end of 2020, the city had a total population of 1,489,200. Huangshan City belongs to the subtropical monsoon climate zone, which has a short spring and autumn and a long summer and winter. The precipitation in the area is abundant, with the same period of rain and heat. The area has low sunshine hours and percentage of sunshine (Lu et al., 2016; Zhu and Jiang, 2022). High cloud fog volume, high humidity, and floods occur in summer, and droughts occur in autumn (Liang et al., 2022; Huang et al., 2022). The annual average temperature is 16.4 °C, and the precipitation is between 1395 mm and 1702 mm. Most areas have no severe cold in winter, and the frost-free period is 236 days (Huangshan Statistics Bureau). The annual sunshine hours are 1628–1872 h.

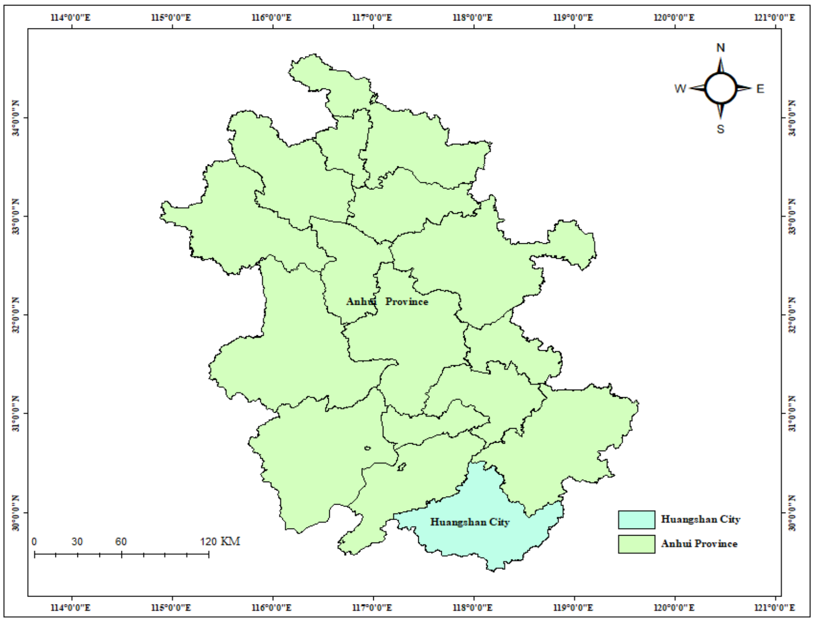

Figure 1. *Geospatial overview of Huangshan City in Anhui Province, China*

Data type and source

The data types used in this study included vector data and socioeconomic statistical data (2012–2020). The vector data were derived from the vector boundary data of Huangshan City, which included two parts, namely, the JSON data were obtained by the Alibaba Cloud Data Datavisualization platform and applied conversion tool (http://doc.gopup.cn), from which each of the district counties' vector data could be determined. The sources of the social statistics were the "Huangshan City Statistical Yearbook" (2012–2020), "Huangshan City Statistical Bulletin" (2012–2020), and "Anhui Province Statistical Yearbook" (2012–2020).

Evaluation methods

Model selection and construction of the index system

The PSR model was developed jointly by the United Nations Environment Programme and the OECD. This model is a widely accepted model in the field of ecological security evaluation. The PSR model could effectively consider the pressure caused by human activities on the ecological environment and the state of natural resources, and then

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measures were taken to reduce environmental degradation. As the model could determine the causal chain affecting ecological security from multiple perspectives, it enabled the development of an evaluation index system that was scientifically and practically feasible. In accordance with the principles of science, operability, representativeness, comprehensiveness, and comparability of evaluation indicators, a framework system for evaluating the ecological security of Huangshan City was developed (*Fig. 2*).

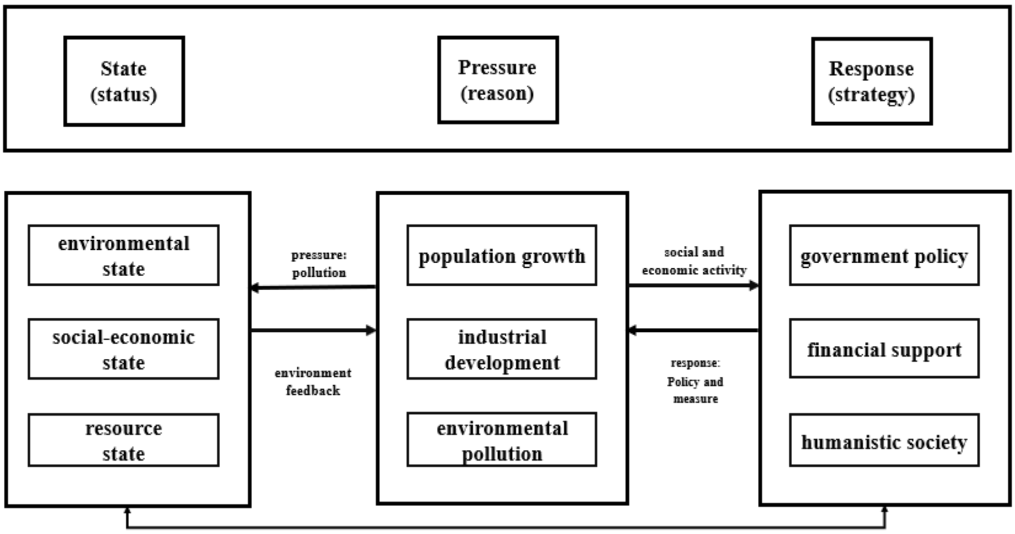

Figure 2. *Ecological security evaluation model for Huangshan City*

Apart from jointly assessing the actual situation of Huangshan City and available data, we also referred to related research results. *Table 1* shows a 24-indicator index system that included the natural population growth rate, average annual temperature, and comprehensive utilization of industrial solid waste, among others. The indicator system comprised three layers, namely, the target layer, criterion layer, and indicator layer. The pressure indicators at the indicator layer corresponded to the origin of urban ecological security issues. The status indicators of the indicator layer represented the current state of urban ecological security concerns. The response indicators of the indicator layer provided an index of human capabilities and measures pertaining to environmental security issues.

Dimensionless processing of indicators

The indicator level entailed inconsistent indicator properties. Thus, a dimensionless operation was applied to the indexes via the polarization method to allow the data to be comparable. The calculation steps are described below.

First, we constructed the matrix of the k-th evaluation index of the j-th evaluation object.

$$x = (x_{jk})_{(a \sim b)}..\ j=1,2,3\ldots a;\ k=1,2,3\ldots b \qquad \text{(Eq.1)}$$

where a indicates the indicator sample object, and b is the number of evaluation indicators.

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Table 1. *Evaluation index system of the ecological security of Huangshan City*

Target layer (A)	Criterion layer (B)	Index layer (C)	Unit	Impact
Evaluation of ecological security in Huangshan (A1)	Pressure (B1)	C1 Population density	People per square kilometer	-
		C2 Urbanization rate	%	+
		C3 Natural growth rate of population	‰	-
		C4 Use of agricultural fertilizers	10000 tons	-
		C5 Domestic sewage discharge	10000 tons	-
		C6 Per capita GDP	Yuan	+
		C7 Pesticide usage	Ton	-
		C8 Industrial solid waste production	10000 tons	-
		C9 Occurrence area of pests and disasters	Hectare	-
		C10 Number of geological hazards	Times	-
	State (B2)	C11 Unit of GDP energy consumption	Tons of standard coal/10000 yuan	-
		C12 Sulfur dioxide	Microgram/m^3	-
		C13 Inhalable particles	Microgram/m^3	-
		C14 Forest coverage rate	%	-
		C15 Nitrogen dioxide	Microgram/m^3	+
		C16 Superior rate of ambient air quality	%	-
		C17 Average of regional environmental noise	Decibel	+
	Response (B3)	C18 Green coverage rate of urban built-up area	%	-
		C19 Comprehensive utilization amount of industrial solid waste	%	+
		C20 Centralized treatment rate of urban sewage treatment plants.	%	-
		C21 Proportion of the tertiary industry	%	+
		C22 Pest control rate	%	+
		C23 Investment in geological disaster prevention	10000 yuan	+
		C24 Fiscal expenditure on environmental protection	10000 yuan	+

Then, the standardization metrics were applied as follows:
Positive indicators:

$$x_{jk} = x_i - x_{min} \quad \text{(Eq.2)}$$

Negative indicators:

$$x_{jk} = x_{max} - x_i \quad \text{(Eq.3)}$$

In *Eqs. (2) and (3)*, x_{jk} represents the standardized values for the indicators, x_i is the original value of the index, and x_{max} and x_{min} are the maximum and minimum values of the index, respectively.

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Weight determination

The entropy weight method was utilized to determine the weights (Zhang et al., 2006). After dimensionless treatment of the indicators, the information entropy was calculated according to *Eqs. (4) to (6).*

Information entropy:

$$E_j = -k \sum_{i=1}^{n} E_j \times \ln E_j \tag{Eq.4}$$

$k = 1/\ln n \ (j = 1,2,3 \ldots b)$

Nondifference coefficient of the evaluation index:

$$G_j = 1 - E_j \ \ (j = 1,2,3 \ldots b) \tag{Eq.5}$$

Calculating weight:

$$W_j = G_j \div \sum_{j=1}^{b} G_j \ \ (j = 1,2,3..b) \tag{Eq.6}$$

Calculation of the ecological security composite index

The ecological safety index (ESI) reflected the degree to which the indicator factors influenced ecological safety and the capacity of an ecosystem to resist stress (Ghulam et al., 2004; Hongwei et al., 2011; Bezsonov et al., 2016). The greater the index, the more secure the environment. After performing the preceding calculations, the weights and normalized values of the indexes were obtained (Gao et al., 2013; Shvartsburg et al., 2017). The indicators' weights were multiplied by the standard values to obtain the pressure index, state index, response index, and ecological safety composite index (Demidova et al., 2021). The ESI calculation formula was given by

$$U_i = \sum_{j=1}^{b} X_{jk} \times W_j \quad j = 1,2,3 \ldots b \tag{Eq.7}$$

where U_i is the value of the composite index for the i-th year; W_j is the weight value of the j-th evaluation index; and X_{jk} is the standardized value of the j-th evaluation index. The composite index value was set to be between 0 and 1. The closer the security composite index is to 1, the higher the ecological security of the study area. By contrast, the closer the security composite index is to 0, the lower the ecological security of the study area.

Classification of ecological security level

The ecological safety status of Huangshan City was evaluated by combining the characteristics of the study area and those reported in the relevant literature (Liang et al., 2010; Bai and Tang, 2010; Lai et al., 2022). The ecological safety was classified into five

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levels in equal intervals (*Table 2*) as follows: 0–0.2 for the unsafe level, 0.2–0.4 for the less safe level, 0.4–0.6 for the critical safety level, 0.6–0.8 for the safer level, and 0.8–1.0 for the safe level.

Table 2. *Ecological secure grading standards*

Composite index	Security level	Indicator explanation
[0–0.2]	Unsafe	Ecosystem functions are nearly collapsed and dysfunctional, and recovery and reconstruction are basically impossible
[0.2–0.4]	Less secure	The ecosystem functions are severely degraded, and ecosystems are more difficult to restore and rebuild
[0.4–0.6]	Critical secure	The ecosystem is somewhat damaged but can still maintain their basic functions and are functioning
[0.6–0.8]	More secure	The ecosystem is slightly damaged, and the system is more resilient and can withstand most external disturbances
[0.8–1.0]	Secure	The ecosystem is in an ideal state, i.e., basically undamaged and undisturbed, with a reasonable ecological structure and a strong ability to function and repair itself

Diagnosis of the impairment degree factor

The barrier factor identifies the main impact factors that create barriers to ecological safety. The formula for calculating the barrier factor is given by

$$1 - X_{jk} = V_{jk}$$

$$M_{jk} = \frac{V_{jk} \times W_j}{\sum_{j=1}^{24} V_{jk} \times W_j} \times 100\% \quad P_{jk} = \sum M_{jk} \qquad \text{(Eq.8)}$$

where W_j is the weight of the indicator; X_{jk} is the standardized value of the indicator; M_{jk} is the barrier degree of a single indicator; and P_{jk} is the barrier degree of the criterion layer in year i.

Results

Change in the ecological security composite index in Huangshan City

On the basis of the PSR model, we constructed an index system for evaluating ecological safety in Huangshan City, used the entropy weighting method to determine the weights of 24 ecological security indicators (*Fig. 3*), and acquired an ecological security index according to the comprehensive index method. *Table 3* shows the ecological security level in Huangshan City from 2012 to 2020.

From 2012 to 2020, the overall comprehensive ecological security index of Huangshan City exhibited fluctuating upward trends, increasing from 0.3540 in 2012 to 0.6630 in 2020 (*Fig. 4*). These trends could be divided into five categories. (1) The ecological security composite index presented an upward trend from 2012 to 2015, increasing from 0.3540 in 2012 to 0.4473 in 2015. (2) The ecological security composite index presented a downward trend from 2015 to 2016, decreasing from 0.4473 in 2015 to 0.3888 in 2016. (3) The ecological security composite index presented an upward trend, increasing from 0.3888 in 2016 to 0.6196 in 2018. (4) The ecological security composite index presented

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a downward trend from 2018 to 2019, decreasing from 0.6196 in 2018 to 0.5855 in 2019. (5) The ecological security composite index presented an upward trend, increasing from 0.5855 in 2019 to 0.6630 in 2020.

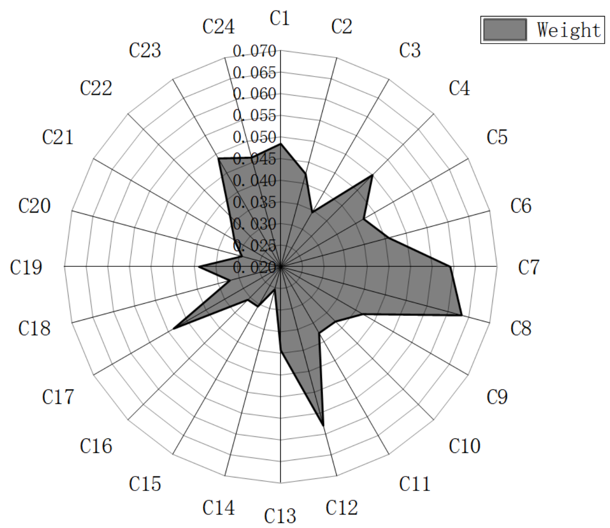

Figure 3. *Weights of 24 ecological security indicators indexes in Huangshan City*

Table 3. *Ecological Security Composite Index (2012–2020)*

Year	Pressure index	State index	Response index	Composite index	Security level
2012	0.1430	0.1227	0.0883	0.3540	Less secure
2013	0.1694	0.0922	0.1207	0.3823	Less secure
2014	0.1746	0.1117	0.1180	0.4044	Critical secure
2015	0.1740	0.1523	0.1210	0.4473	Critical secure
2016	0.2036	0.0804	0.1048	0.3888	Less secure
2017	0.2800	0.0995	0.1566	0.5361	Critical secure
2018	0.3304	0.1801	0.1092	0.6196	More Secure
2019	0.3418	0.1487	0.0950	0.5855	Critical secure
2020	0.3362	0.2240	0.1028	0.6630	More secure

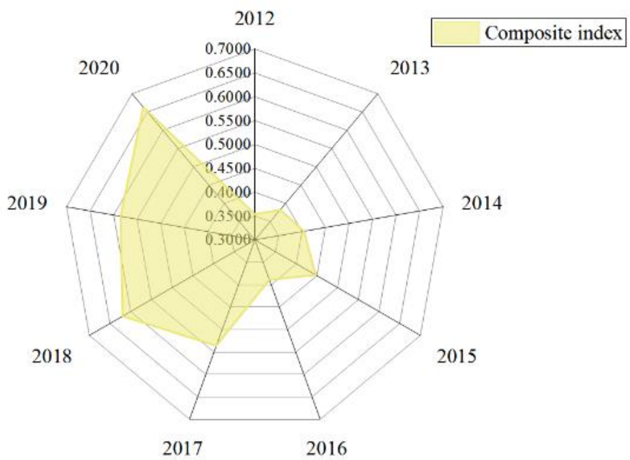

Figure 4. *Changes in the composite ecological security index of Huangshan City (2012–2020)*

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During 2012–2020, the ecological security composite indexes were between lower security levels and higher security levels. The trends could be divided into three categories. (1) The ecological security composite index was less secure in 2012, 2013, and 2016. (2) The ecological security composite index was critically secure in 2014, 2015, 2017, and 2019. (3) The ecological security composite index was more secure in 2018 and 2020.

Change in the ecological security pressure index

From 2012 to 2020, the overall ecological security pressure index of Huangshan City showed an upward trend, increasing from 0.1430 in 2012 to 0.3362 in 2020 (*Fig. 5*). The specific trend could be divided into two categories. (1) The ecological security pressure index presented a consistent ascent from 2012 to 2019, and the ecological security pressure index increased from 0.1430 to 0.3418. (2) The ecological security pressure index presented a downward trend from 2019 to 2020, decreasing from 0.3418 to 0.3362.

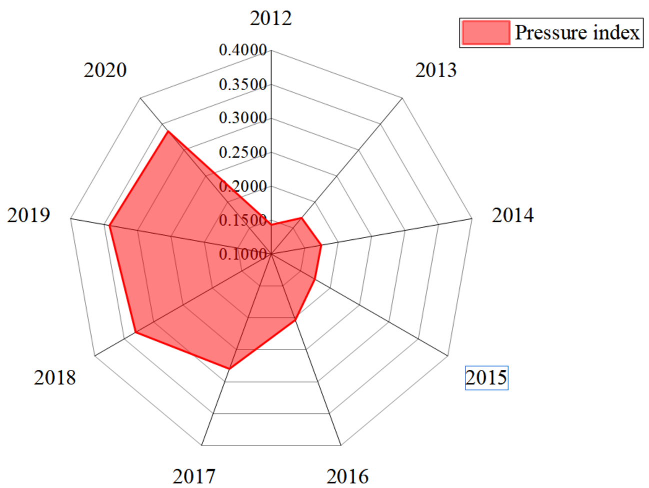

Figure 5. *Changes in the ecological security pressure index in Huangshan City (2012–2020)*

During 2012–2020, the ecological security pressure index of Huangshan City was between unsafe and less secure. The ecological security pressure index was unsafe from 2012 to 2015. The ecological security pressure index gradually increased. The ecological security pressure index ranged from 0.1430 in 2012 to 0.1740 in 2015. The ecological security pressure index was less secure from 2016 to 2020. The ecological security pressure index increased from 0.2036 in 2016 to 0.3362 in 2020.

Change in the ecological security state index

From 2012 to 2020, the overall ecological security state index of Huangshan City presented a general upward trend (*Fig. 6*), increasing from 0.1227 in 2012 to 0.2240 in 2020. The specific trend could be divided into six categories. (1) The ecological security status presented a downward trend from 2012 to 2013, decreasing from 0.1227 to 0.0922 during 2012–2013. (2) The ecological security state index presented an upward trend from 2013 to 2015, increasing from 0.0922 to 0.1523 during 2013–2015. (3) The ecological security state index presented a downward trend from 2015 to 2016, decreasing from 0.1523 to 0.0804 during 2015–2016. (4) The ecological security state index presented an

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upward trend from 2016 to 2018, increasing from 0.0804 to 0.1801. (5) The ecological security state index presented a downward trend from 2018 to 2019, decreasing from 0.1801 to 0.1487 during 2018–2019. (6) The ecological security state index presented an upward trend from 2019 to 2020, increasing from 0.1487 to 0.2240 during 2019–2020.

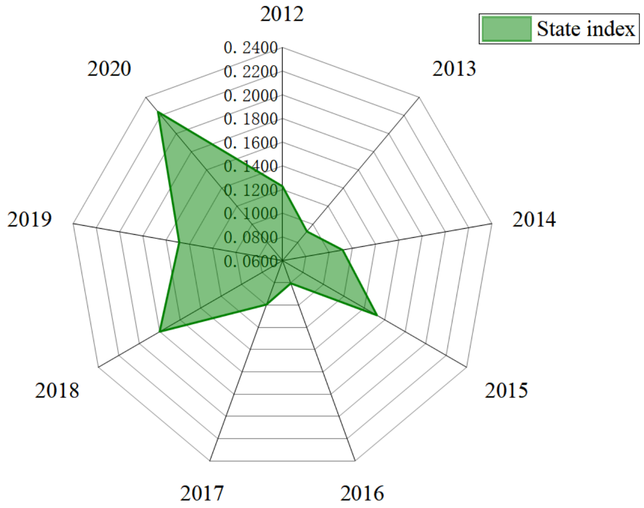

Figure 6. *Changes in the ecological security state index of Huangshan City (2012–2020)*

During 2012–2020, the ecological security state index of Huangshan City was between unsafe and less secure. The ecological security status of Huangshan City was unsafe during 2012–2019. The ecological security status of Huangshan City was less secure in 2020.

Change in ecological security response index

From 2012 to 2020, the overall ecological security response index of Huangshan City showed a general upward trend (*Fig. 7*), increasing from 0.0883 in 2012 to 0.1028 in 2020. The specific trend could be divided into seven categories. (1) Ecological security presented an upward trend from 2012 to 2013. The response index increased from 0.0883 to 0.1207 during 2012–2013. (2) Ecological security presented a downward trend from 2013 to 2014, and the response index decreased from 0.1207 to 0.1180 during 2013-2014. (3) Ecological security presented an upward trend from 2014 to 2015, and the response index increased from 0.1180 to 0.1210 during 2014–2015. (4) Ecological security presented a downward trend from 2015 to 2016, and the response index decreased from 0.1210 to 0.1048 during 2015–2016. (5) Ecological security presented an upward trend from 2016 to 2017, and the response index increased from 0.1048 to 0.1566 during 2016-2017. (6) Ecological security presented a downward trend, and the response index decreased from 0.1566 to 0.0950 during 2017–2019. (7) Ecological security presented an upward trend, and the response index increased from 0.0950 to 0.1028 during 2019–2020.

During 2012–2020, the ecological security status of Huangshan City was unsafe. The ecological security response index values were all lower than 0.2.

Obstacle factor analysis on the ecological security index layer

The obstacle degree of each ecological security index was determined using the obstacle model (*Eq. 8*). As mentioned earlier, this study considered a large number of

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layer factors for the indexes. Only the five most significant obstacle factors from 2012 to 2020 are listed in *Table 4*. The frequencies of these significant obstructions are presented in *Table 5*.

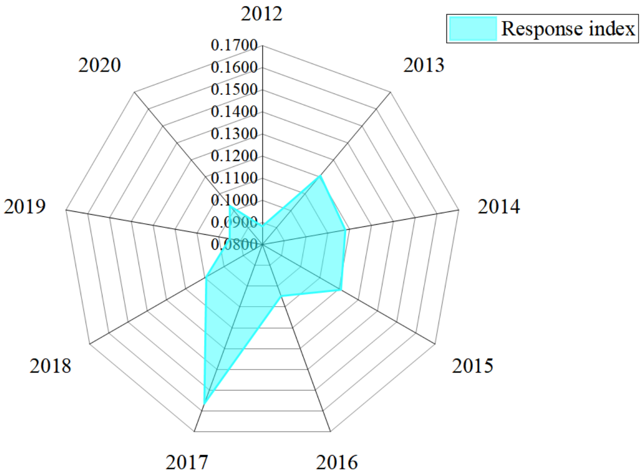

Figure 7. *Changes in the ecological security response index of Huangshan City (2012–2020)*

Table 4. *Identification of obstacle factors to the ecological security index layer of Huangshan City (2012–2020)*

Index obstacle order	First	Second	Third	Fourth	Fifth
2012	C8 9.79%	C12 8.98%	C7 7.94%	C4 7.73%	C6 7.10%
2013	C8 9.88%	C7 9.58%	C17 7.87%	C12 7.30%	C4 7.10%
2014	C8 10.25%	C7 9.75%	C12 8.65%	C4 7.34%	C23 6.72%
2015	C8 11.01%	C7 9.63%	C4 7.91%	C23 6.50%	C6 6.41%
2016	C12 9.49%	C24 7.53%	C17 6.96%	C7 6.60%	C23 6.50%
2017	C12 9.72%	C9 9.04%	C1 7.50%	C7 7.26%	C18 6.94%
2018	C23 11.73%	C1 10.15%	C24 8.58%	C19 6.80%	C12 6.77%
2019	C23 11.80%	C1 11.68%	C17 11.00%	C19 7.80%	C22 7.80%
2020	C1 13.76	C5 12.50%	C9 12.22%	C19 11.53%	C22 10.85%

From 2012 to 2015, the most significant obstacles to ecological security in Huangshan City were industrial solid waste production, pesticide use, agricultural fertilizer use, sulfur dioxide, and investments in geological disaster prevention. From 2016 to 2020, population density, industrial solid waste production, investments in geological disaster prevention and control, and sulfur dioxide constituted the greatest obstacles.

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***Table 5.** Frequency of obstacles to the ecological security of Huangshan City (2012–2020)*

	Obstacle factors	C8	C12	C7	C4	C6	C17	C23	C1
2012–2020	Frequency of occurrence	7	6	6	4	2	3	5	4
	Frequency (%)	15.56%	13.33%	13.33%	8.89%	4.44%	6.67%	11.11%	8.89%
2012–2015	Frequency of occurrence	4	3	4	4	2	1	2	0
	Frequency (%)	20%	15%	20%	20%	10%	5%	10%	0%
2016–2020	Frequency of occurrence	3	3	2	0	0	1	3	4
	Frequency (%)	12%	12%	8%	0%	0%	4%	12%	16%

Overall, from 2012 to 2020, industrial solid waste was regarded as the most prevalent barrier indicator, followed by sulfur dioxide, pesticide use, and investment in geological disaster prevention.

Obstacle factor analysis on the ecological security criteria layer

According to the obstacle diagnosis model, the mean values of pressure, state, and response for the ecological security barriers in Huangshan City from 2012 to 2020 were 50.58%, 24.19% and 24.08%, respectively (*Fig. 8* and *Table 5*). Therefore, the comprehensive ranking of the index barriers of the criterion layer impacting Huangshan's ecological security was in the order of pressure factor > state factor > response factor. Both pressure safety and state safety were the primary obstacles to the improvement of the ecological security level in Huangshan City.

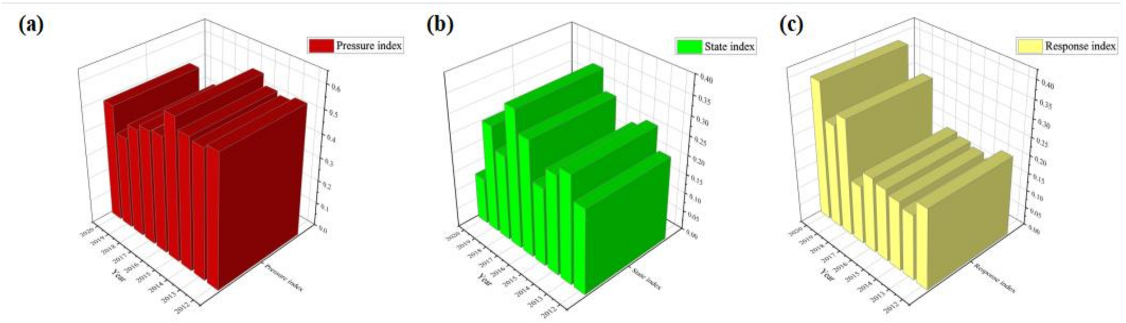

***Figure 8.** Identification of obstacles to the ecological security criteria layer of Huangshan City (2012–2020)*

Analysis of early warning results of ecological security in Huangshan City

The level of ecological security in Huangshan City can be better predicted using a single regression equation to fit the ecological security level from 2012 to 2020 (*Fig. 9*). Here, the following equation was constructed (*Eq. 9*):

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$$y = 0.0393x - 78.978 \quad \text{(Eq.9)}$$

where x is the time series and y is the ecological security level of Huangshan City.

The goodness of fit was $R^2 = 0.868$, and the results of the T test and F test showed that the model could meet the required accuracy. Thus, the monadic linear regression model was used to predict the ecological security level of Huangshan City, and x = 2025 and x = 2030 were substituted in *Eq. (9)*. The ecological security levels of Huangshan City in 2025 and 2030 are forecast to be 0.8070 and 1.004, respectively. This finding indicated that the ecological security of Huangshan City would likely remain in a safe state in the coming years.

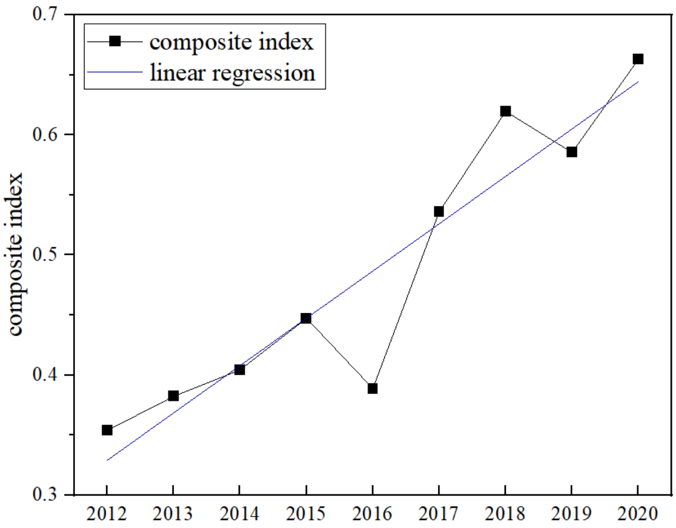

Figure 9. *Early warning results of the time series of the ecological security level in Huangshan City*

Discussion

Ecological security is fundamental to the development of human society in cities. Hence, the ecological security of Huangshan City should be taken seriously. The structure and function of urban resources and natural resources required for coordinated development are important for ecological security (Guo et al., 2021). Although previous research has evaluated urban ecological security, studies taking the perspective of ecological sustainability development have been limited (Yang and Cai, 2020). This study applied the PSR model to construct an ecological security indicator system, the entropy weight method was used to determine the weights of the ecological security indicators, the obstacle model was used to identify the ecological security obstacle factor, and linear regression was used to predict the ecological security trend. The entropy weight method was more suitable for determining the weight of ecological security evaluation indicators (Tao, 2010; Zhang et al., 2022), in which the weight method could always screen those indicators that change quickly and have a large weight (Liu et al., 2017). Moreover, compared with previous studies, we combined the entropy weight method, obstacle model and linear regression based on the PSR model to evaluate urban ecological security. This combination excluded the interference of subjective factors, and the evaluation results were more realistic. The urban ecological security evaluation index system was proposed

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by us and has a wider range of applications. Our results indicated that Huangshan City's ecological security presented a fluctuating upward trend from 2012 to 2020, with three upward trends and two downward trends. Ecological security presented an upward trend during 2012–2015. This finding could be attributed to Huangshan City starting a three-year national ecological city construction from 2012 to 2015. During the creation of the ecological city, Huangshan City focused on the implementation of ecological forestry, tourism, industry and six other major projects through provincial ecological city technical acceptance. At the same time, Huangshan City implemented the green quality improvement action. Examples include promoting the protection of forest resource management and water source protection and launching the pilot ecological compensation mechanism of the Xin'an River Basin (Yu et al., 2020; Ren et al., 2021; Sheng and Han, 2022). Ecological protection measures were taken during the creation of the national ecological city, resulting in an upward trend of ecological security from 2012 to 2015. However, our research found a downward trend in ecological security in Huangshan City from 2015 to 2016. A good explanation is that Huangshan City was facing downward economic pressure and did not invest much in ecological protection financially. In addition, Huangshan City experienced a major flooding natural disaster in 2016, and the combination of an economic downturn and natural disasters led to a downward trend in ecological security in Huangshan City from 2015 to 2016. Our research also found that the ecological security of Huangshan City increased from 2016 to 2018. This finding can be explained by the Chinese government comprehensively launching central environmental protection inspectors in July 2016. Carrying out environmental protection inspections was of great significance to strengthen the construction of ecological civilization, solve the problems of ecological damage and maintain ecological security (Lin et al., 2021; Ren et al., 2021). Huangshan City actively responded to the central environmental protection inspectors and had taken measures to improve the ecological security. For instance, Huangshan City developed the "Huangshan City Geological Disaster Prevention and Control Plan" to strengthen geological disaster prevention and control, promoted the prevention and control of air, water and soil pollution, implemented a comprehensive plan to meet the emission standards of pollution sources in key industries, and strictly implemented the lifelong accountability and compensation system for ecological and environmental damage. The implementation of these response measures significantly improved the ecological security of Huangshan City. Consequently, Huangshan City's ecological security increased from 2016 to 2018. Ecological security presented a downward trend in 2019, but ecological security presented an upward trend in 2020. This finding could be explained by the relatively small scale of the green industry, the low benefits of the green economy, and the transformation of lucid waters and lush mountains into gold and silver mountains, which should be further expanded. Therefore, ecological security decreased in 2019. In particular, at the end of 2019, the COVID-19 pandemic started (Ciotti et al., 2020; Pokhrel and Chhetri, 2021), which weakened social economic activities, and many industrial enterprises stopped working in Huangshan City. The ecological environment had been effectively improved. Therefore, ecological security increased in 2020.

By obstacle factor analysis and line fitting to predict the ecological security of Huangshan City, although the results showed that the ecological security presented an excellent trend, to maintain the ecological security situation, the following measures should be incorporated into the overall plan for social and economic development. The concept of "clear waters and lush mountains are invaluable assets" optimizes the structure of the ecosystem, rationally arranges the value structure of ecological services, and promotes diversified development. Some areas with serious damage to the ecosystem should be designated "forbidden zones" for human activities on a regular basis to ensure ecosystem natural recovery. These measures can improve the ecological environment and reduce the pressure on ecological security.

Conclusion

Huangshan City is a national key ecological function area. Thus, evaluating its ecological security is imperative. The ecological security of Huangshan City is influenced by many aspects and entails a complex and dynamic change. This study investigated the ecological security status and dynamic characteristics of Huangshan City between 2012 and 2020. The conclusions can be summarized as follows:

1) The PSR model was utilized to establish an evaluation index system that includes a target layer, three criterion layers and 24 index layers. The ecological security index should be measured, with the development of the city taken as a whole, along with the level of the quantitative evaluation of its state of security. The ESI of Huangshan City increased from 2012 to 2020.
2) This study applied the concept of barrier degree to the evaluation of urban ecological security. By calculating and comparing the barriers of each indicator to the overall ecological security index, the important indicators affecting the ecological security of the city can be accurately obtained.
3) The development trend of the ecological security of Huangshan City was derived via linear fitting. By 2025, the ecological security index value of Huangshan City will likely reach 0.8070; by 2030, it will likely reach 1.004. The ecological security situation of Huangshan City manifests a good trend.

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REFERENCES

[1] Bai, X., Tang, J. (2010): Ecological security assessment of Tianjin by PSR model. – Procedia Environmental Sciences 2: 881-887.
[2] Bezsonov, Y., Andreev, V., Smyrnov, V. (2016): Assessment of safety index for water ecological system. – Eastern-European Journal of Enterprise Technologies 6(10): 24-34.
[3] Chen, H. (2017): Evaluation and analysis of eco-security in environmentally sensitive areas using an emergy ecological footprint. – International Journal of Environmental Research and Public Health 14(2): 136.
[4] Ciotti, M., Ciccozzi, M., Terrinoni, A., Jiang, W., Wang, C., Bernardini, S. (2020): The COVID-19 pandemic. – Critical Reviews in Clinical Laboratory Sciences 57(6): 365-388.
[5] Demidova, S., Balog, M., Chircova, T., Kulachinskaya, A., Zueva, S., Akhmetova, I., Ilyashenko, S. (2021): Development of methodology and assessment of ecological safety of the EAEU and CIS regions in the context of sustainable development. – Economies 9(3): 100.

[6] Du, P., Xia, J., Du, Q., Luo, Y., Tan, K. (2012): Evaluation of the spatio-temporal pattern of urban ecological security using remote sensing and GIS. – International Journal of Remote Sensing 34(3): 848-863.
[7] Gao, J., Zhang, X., Jiang, Y., Ou, X., He, D., Shi, J. (2007): Key issues on watershed ecological security assessment. – Chinese Science Bulletin 52: 251-261.
[8] Gao, J., Lv, S., Zheng, Z, Feng, C., Ye, S., Zhang, C. (2013): Ecological safety assessment in Hulunbeier steppe based on the landscape pattern. – Advanced Materials Research 726: 1121-1129.
[9] Ghulam, A., Qin, Q., Wang, L., Zhan, Z., Wang, D. (2004): Development of broadband Albedo based ecological safety monitoring index. – 2004 IEEE International Geoscience and Remote Sensing Symposium 6: 4115-4118.
[10] Guo, D., Wang, D., Zhong, X., Yang, Y., Jiang, L. (2021): Spatiotemporal Changes of Land Ecological Security and Its Obstacle Indicators Diagnosis in the Beijing–Tianjin–Hebei Region. – Land 10(7): 706.
[11] Han, B., Liu, H., Wang, R. (2015): Urban ecological security assessment for cities in the Beijing–Tianjin–Hebei metropolitan region based on fuzzy and entropy methods. – Ecological Modelling 318: 217-225.
[12] Hong, Q., Meng, Q., Wang, P., Wang, H., Liu, R. (2010): Regional aquatic ecological security assessment in Jinan, China. – Aquatic Ecosystem Health & Management 13: 319-327.
[13] Huang, J., Wang, R., Zhang, H. (2007): Analysis of patterns and ecological security trend of modern oasis landscapes in Xinjiang, China. – Environmental Monitoring and Assessment 134: 411-419.
[14] Huang, Q., Peng, B., Elahi, E., Wan, A. (2021): Evolution and driving mechanism of ecological security pattern: A case study of Yangtze River urban agglomeration. – Integrated Environmental Assessment and Management 17(3): 573-583.
[15] Huang, S., Hu, Q., Wang, S., Li, H. (2022): Ecological risk assessment of world heritage sites using RS and GIS: A case study of Huangshan Mountain, China. – Chinese Geographical Science 32(5): 808-823.
[16] Jiang, M., Chen, B. (2011): Integrated urban ecosystem evaluation and modeling based on embodied cosmic exergy. – Ecological Modelling 222(13): 2149-2165.
[17] Lai, S., Sha, J., Eladawy, A., Li, X., Wang, J., Kurbanov, E., Lin, Z., Wu, L., Han, R., Su, Y. (2022): Evaluation of ecological security and ecological maintenance based on pressure-state-response (PSR) model, case study: Fuzhou city, China. – Human and Ecological Risk Assessment: An International Journal 28(7): 734-761.
[18] Li, H. W., Lv, M., Ye, S. (2011): The research and practice of ecological safety evaluation methods (I) evaluation index and model. – Procedia Environmental Sciences 11: 1204-1210.
[19] Liang, P., Liming, D., Guijie, Y. (2010): Ecological security assessment of Beijing based on PSR model. – Procedia Environmental Sciences 2: 832-841.
[20] Liang, Q., Su, T., Zhang, C., Wang, J., Zhou, L. (2022): Research on ecological quality evaluation of Huangshan City based on improved remote sensing ecological index. – Progress in Geophysics 37(4): 1448-1456.
[21] Lin, J., Long, C., Yi, C. (2021): Has central environmental protection inspection improved air quality? Evidence from 291 Chinese cities. – Environmental Impact Assessment Review 90: 106621.
[22] Liu, Y., Li, S., Huang, S. (2017): Ecological security assessment of county-scale cultivated land based on PSR and improved entropy method. – Acta Agriculturae Jiangxi 29(8): 114-118.
[23] Liu, X., Fu, J., Jiang, D., Luo, J., Sun, C., Liu, H., Wen, R., Wang, X. (2018): Improvement of ecological footprint model in National Nature Reserve Based on net primary production (NPP). – Sustainability 11(1): 2.

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DOI: http://dx.doi.org/10.15666/aeer/2104_29913008

[24] Liu, Y., Zhao, C., Liu, X., Chang, Y., Wang, H., Yang, J., Yang, X., Wei, Y. (2021): The multi-dimensional perspective of ecological security evaluation and drive mechanism for Baishuijiang National Nature Reserve, China. – Ecological Indicators 132: 108295.
[25] Liu, Y., Qu, Y., Cang, Y., Ding, X. (2022): Ecological security assessment for megacities in the Yangtze River basin: Applying improved emergy-ecological footprint and DEA-SBM model. – Ecological Indicators 134: 108481.
[26] Lu, Y., Wang, X., Xie, Y., Li, K., Xu, Y. (2016): Integrating future land use scenarios to evaluate the spatio-temporal dynamics of landscape ecological security. – Sustainability 8(12): 1242.
[27] Lu, S., Tang, X., Guan, X., Qin, F., Liu, X., Zhang, D. (2020): The assessment of forest ecological security and its determining indicators: A case study of the Yangtze River Economic Belt in China. – Journal of Environmental Management 258: 110048.
[28] Pokhrel, S., Chhetri, R. (2021): A literature review on impact of COVID-19 pandemic on teaching and learning. – Higher Education for the Future 8(1): 133-141.
[29] Ren, Y., Lu, L., Yu, H., Zhu, D. (2021): Game strategies in government-led eco-compensation in the Xin’an River Basin from the perspective of the politics of scale. – Journal of Geographical Sciences 31(8): 1205-1221.
[30] Shen, Y., Cao, H., Tang, M., Deng, H. (2017): The human threat to river ecosystems at the watershed scale: An ecological security assessment of the Songhua River Basin, Northeast China. – Water 9(3): 219.
[31] Sheng, J., Han, X. (2022): State rescaling, power reconfiguration and path dependence: China’s Xin’an River Basin Eco-compensation Pilot (XRBEP). – Regional Studies 56(11): 1814-1828.
[32] Shvartsburg, L., Butrimova, E., Yagolnitser, O. (2017): Energy efficiency and ecological safety of shaping technological processes. – Procedia Engineering 206: 1009-1014.
[33] Su, S., Chen, X., Degloria, S., Wu, J. (2009): Integrative fuzzy set pair model for land ecological security assessment: A case study of Xiaolangdi Reservoir Region, China. – Stochastic Environmental Research and Risk Assessment 24: 639-647.
[34] Su, Y. (2019): Dynamic security assessment and the countermeasures analysis of land ecology in Henan province from 2007 to 2017. – RSC Advances 9(56): 32414-32424.
[35] Tao, X. (2010): Urban ecological security assessment in shenzhen city based on set pair analysis and entropy method: A case study on Shenzhen City. – In 2010 2nd International Workshop on Intelligent Systems and Applications.
[36] Wang, D., Huang, Z., Wang, Y., Mao, J. (2021): Ecological security of mineral resource-based cities in China: multidimensional measurements, spatiotemporal evolution, and comparisons of classifications. – Ecological Indicators 132: 108269.
[37] Wang, B., Yu, F., Teng, Y., Cao, G., Zhao, D., Zhao, M. (2022): A SEEC model based on the DPSIR framework approach for watershed ecological security risk assessment: A case study in Northwest China. – Water 14(1): 106.
[38] Wu, Z., Lei, S., Yan, Q., Bian, Z., Lu, Q. (2021): Landscape ecological network construction controlling surface coal mining effect on landscape ecology: A case study of a mining city in semi-arid steppe. – Ecological Indicators 133: 108403.
[39] Yang, Y., Cai, Z. (2020): Ecological security assessment of the Guanzhong Plain urban agglomeration based on an adapted ecological footprint model. – Journal of Cleaner Production 260: 120973.
[40] Yang, Z., He, X., Ashraf, M. (2020): Land-use change in plateau lake basin and its impact on urban ecological security. – Arabian Journal of Geosciences 13: 1-8.
[41] Yu, G., Zhang, S., Yu, Q., Fan, Y., Zeng, Q., Wu, L., Zhou, R., Nan, N., Zhao, P. (2014): Assessing ecological security at the watershed scale based on RS/GIS: A case study from the Hanjiang River Basin. – Stochastic Environmental Research and Risk Assessment 28: 307-318.

[42] Yu, B., Chen, L., Health, P. (2020): Interventional impacts of watershed ecological compensation on regional economic differences: evidence from Xin'an river, China. – International Journal of Environmental Research and Public Health 17: 6389.
[43] Yu, H., Yang, J., Qiu, M., Liu, Z. (2021): Spatiotemporal changes and obstacle factors of forest ecological security in China: A provincial-level analysis. – Forests 12(11): 1526.
[44] Zhang, Y., Yang, Z., Li, W. (2006): Analyses of urban ecosystem based on information entropy. – Ecological Modelling 197(1-2): 1-12.
[45] Zhang, L., Peng, J., Liu, Y., Wu, J. (2016): Coupling ecosystem services supply and human ecological demand to identify landscape ecological security pattern: A case study in Beijing–Tianjin–Hebei region, China. – Urban Ecosystems 20: 701-714.
[46] Zhang, Y., Fan, J., Wang, S. (2020): Assessment of ecological carrying capacity and ecological security in China's typical eco-engineering areas. – Sustainability 12(9): 3923.
[47] Zhang, R., Li, P., Xu, L. (2022): Evaluation and analysis of ecological security based on the improved three-dimensional ecological footprint in Shaanxi Province, China. – Ecological Indicators 144: 109483.
[48] Zheng, H., Wang, L., Peng, F., Gu, J., Lu, S., Zhang, D., Li, L. (2018): Design and implementation of an index calculation system for forestry ecological assessment in China. – Computers and Electronics in Agriculture 145: 253-274.
[49] Zhu, S., Jiang, W. (2022): A Comprehensive Evaluation of Environmental Quality for Health Ecotourism in Huangshan National Forest Park. – Mobile Information Systems. https: doi.org/10.1155/2022/8666276.