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A Study on Ecosystem Vulnerability Evaluation of the Mining Area Based on Fuzzy Mathematics

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Abstract: Vulnerability evaluation of the ecological environment has become a research hotspot in recent years, especially in the mining area. Based on the scientificity, objectivity, systemacity, operability and dominant factors first principles, we build the evaluation indicator system of ecosystem vulnerability for the mining area. By using analytic hierarchy process (AHP), weights are calculated for each indicator and the ecosystem vulnerability is divided into 5 levels: very vulnerable, vulnerable, moderate, moderate, strong and very strong. On this basis, the fuzzy mathematical model is established and the evaluation is carried out combining with expert scoring. The model built is of scientificity, professionalism and reasonability, providing reference for vulnerability evaluation of the ecosystem in the mining areas.

Keywords: *Fuzzy mathematics, weight, ecosystem, vulnerability, evaluation*

1. Introduction

Ecosystem vulnerability evaluation has been studied extensively in recent years, especially in the mining areas due to increasing deterioration, pollution and damage under the current exploitation mode. The sustainability and ecosystem safety of the mining areas are being severely threatened.

The existing studies on ecosystem vulnerability evaluation of the mining areas have made significant contributions to ecosystem protection and land use planning of the mining areas. In China, ecosystem vulnerability evaluation of the mining areas is still at its starting stage and mainly addresses the causative or influencing factors of the ecological problems of the mining areas. The commonly used methods include analytic hierarchy process (AHP), variation coefficient method, GIS-based spatial analysis and grey correlation analysis. These research methods still contain the subjective factors and the findings can hardly reflect the realistic situation of ecosystem in the study areas.

Based on literature survey, we build the ecosystem vulnerability evaluation indicator system for the mining areas and the fuzzy mathematical model for vulnerability level classification. The research results can provide reference for policy making.

2. Ecosystem Vulnerability Evaluation Indicator System for the Mining Areas

2.1 Principles of indicator selection

(1) Scientificity

Scientificity principle states that the indicators selected must have reasonable meanings and can be clearly defined and accurately quantified. Not only the indicators, but also the standardized values of the indicators should be scientific and reflective of the real situation.

(2) Objectivity

The evaluation indicator system should be built based on an objective understanding of the real situation using reliable data. The meanings of the indicators should be definite and accurate, and the calculation methods be rigorously standardized.

(3) Systematicity

The ecosystem of the mining area is a highly complex system, in which the ecological factors are mutually dependent and influencing. The evaluation indicator system should be comprehensive and cover all possible dimensions of ecosystem vulnerability at its best. The indicators should all conform to the overall goal of ecosystem vulnerability evaluation and show certain degree of representativeness.

(4) Operability

Operability principle refers to the easy availability of the indicator data. Both indicators of simplicity and complexity should be incorporated and they must be easily applicable.

(5) Dominant factors first

Influencing factors of ecosystem vulnerability in the mining areas are divided into dominant factors and less dominant factors. The former has a larger impact, while the latter has a smaller impact on vulnerability. When selecting the influencing factors of ecosystem vulnerability, the dominant factors should be preserved and the less dominant factors deleted.

2.2 Building the ecosystem vulnerability evaluation indicator system for the mining areas

Following the above-mentioned principles, the indicators of reasonability, scientificity and professionalism should be selected. After literature review, a 3-level evaluation indicator system consisting of target layer, primary indicators and secondary indicators is built, as shown in Table 1.

Table 1. *Vulnerability evaluation indicator system for the mining area*

Overall goal	**Primary indicator**	**Secondary indicator**
Ecosystem vulnerability evaluation of the mining area P	Eco-environmental pressure A	(1) Density of major mines A1; (2) Types of major minerals A2; (3) Mining method A3; (4) Production scale of the mines A4; (5) Coverage area of the mines A5;
	Eco-environmental status B	(1) Vegetation coverage B1; (2) Area of occupied land B2; (3) Number of toxic mines B3; (4) Number of geological disasters B4; (5) Degree of damage to the landscape B5; (6) Amount of waste B6;
	Eco-environmental response C	(1) Per capital GDP in the mining area C1; (2) Annual investment on environmental management C2; (3) Economic contribution rate of the mines C3; (4) Percentage of personnel engaged in technology and environmental protection C4; (5) Significance of location of the mines C5

2.3 Weight calculation of vulnerability indicators

Weights of the vulnerability indicators are calculated by AHP, and the hierarchy diagram is shown in Figure 1. Pairwise comparison matrices, weights, maximum eigenvalues and consistency ratios of the vulnerability indicators are shown in Table 2-5.

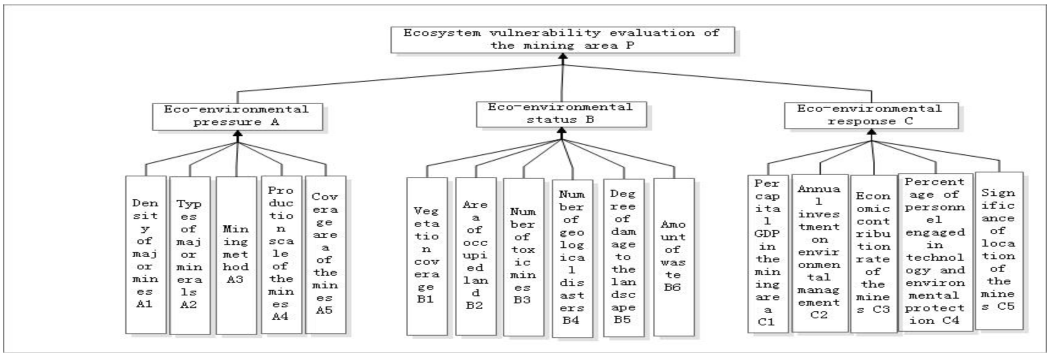

Figure 1. *Hierarchy diagram of vulnerability evaluation indicators*

Table 2. *Pairwise comparison matrix and test result of primary indicators with respect to overall goal P*

Overall goal	**Ecosystem vulnerability evaluation of the mining area P**				**Maximum eigenvalue**	**Consistency ratio**
Primary indicator	**Eco-environmental pressure A**	**Eco-environmental status B**	**Eco-environmental response C**	**Weight**		
Eco-environmental pressure A	1	3	6	0.6393	3.0540	0.0520
Eco-environmental status B	1/3	1	4	0.2737		
Eco-environmental response C	1/6	1/4	1	0.0869		

Table 3. *Pairwise comparison matrix and test result of secondary indicators with respect to the primary indicator of eco-environmental pressure A*

Primary indicator	**Eco-environmental pressure A**						**Maximum eigenvalue**	**Consistency ratio**
Secondary	**Density of**	**Types of**	**Mining**	**Production**	**Coverage**	**Weight**		

indicator	major mines A_1	major minerals A_2	method A_3	scale of the mines A_4	area of the mines A_5			
Density of major mines A_1	1	1/3	1/6	1/2	2	0.0793		
Types of major minerals A_2	3	1	1/4	3	5	0.2332		
Mining method A_3	6	4	1	4	7	0.5112	5.1808	0.0404
Production scale of the mines A_4	2	1/2	1/4	1	3	0.1270		
Coverage area of the mines A_5	1/2	1/5	1/7	1/3	1	0.0493		

Table 4. *Pairwise comparison matrix and test result of secondary indicators with respect to the primary indicator of eco-environmental status B*

Primary indicator	Eco-environmental status B								
Secondary indicator	Vegetation coverage B1	Area of occupied land B2	Number of toxic mines B3	Number of geological disasters B4	Degree of damage to the landscape B5	Amount of waste B6	Weight	Maximum eigenvalue	Consistency ratio
Vegetation coverage B1	1	3	6	3	3	7	0.3774		
Area of occupied land B2	1/3	1	3	2	1/2	4	0.1597		
Number of toxic mines B3	1/6	1/3	1	1/4	1/6	2	0.0516		
Number of geological disasters B4	1/3	1/2	4	1	3	6	0.1979	6.5622	0.0892
Degree of damage to the landscape B5	1/3	2	6	1/3	1	4	0.1770		
Amount of waste B6	1/7	1/4	1/2	1/6	1/4	1	0.0366		

Table 5. *Pairwise comparison matrix and test result of secondary indicators with respect to the primary indicator of eco-environmental response C*

Primary indicator	Eco-environmental response C							
Secondary indicator	Per capital GDP in the	Annual investment on environmental management	Economic contribution rate of the mines C3	Percentage of personnel engaged in technology	Significance of location of the mines C5	Weight	Maximum eigenvalue	Consistency ratio

	mining area C1 C1	C2		and environmental protection C4				
Per capital GDP in the mining area C1	1	1/3	1/5	1/7	1/4	0.0459		
Annual investment on environmental management C2	3	1	1/3	1/3	1/2	0.1100		
Economic contribution rate of the mines C3	5	3	1	1/2	2	0.2555	5.1677	0.0374
Percentage of personnel engaged in technology and environmental protection C4	7	3	2	1	5	0.4396		
Significance of location of the mines C5	4	2	1/2	1/5	1	0.1489		

The consistency ratios (CR) of all pairwise comparison matrices for ecosystem vulnerability evaluation are below 0.10, indicating that the consistency test is passed.

The weights of vulnerability evaluation indicators are given in Table 6.

Table 6. *Weights of vulnerability evaluation indicators of the mines*

Overall goal	Primary indicator	Weight	Secondary indicator	Weight
Ecosystem vulnerability evaluation of the mining area P	Eco-environmental pressure A	0.6393	Density of major mines A1	0.0793
			Types of major minerals A2	0.2332
			Mining method A3	0.5112
			Production scale of the mines A4	0.1270
			Coverage area of the mines A5	0.0493
	Eco-environmental status B	0.2737	Vegetation coverage B1	0.3774
			Area of occupied land B2	0.1597
			Number of toxic mines B3	0.0516
			Number of geological disasters B4	0.1979
			Degree of damage to the landscape B5	0.1770
			Amount of waste B6	0.0366
	Eco-environmental response C	0.0869	Per capital GDP in the mining area C1	0.0459
			Annual investment on environmental management C2	0.1100
			Economic contribution rate of the mines C3	0.2555
			Percentage of personnel engaged in technology and environmental protection C4	0.4396
			Significance of location of the mines C5	0.1489

3. Fuzzy Mathematical Model for Ecosystem Vulnerability Evaluation

3.1 Building the evaluation factor set

The evaluation factor set is built after further treatments of the evaluation indicators. According to Table 6, the evaluation factor set is U={density of major mines u_1, type of major minerals u_2, mining method u_3, production scale of the mines u_4,coverage area of the mines u_5, vegetation coverage u_6, area of occupied land u_7, number of toxic mines u_8, number of geological disasters u_9, degree of damage to landscape u_{10}, amount of waste u_{11}, per capita GDP in the mining area u_{12}, annual investment on environmental management u_{13}, economic contribution rate of the mines u_{14}, percentage of personnel engaged in technology and environmental protection u_{15}, significance of location of the mines u_{16}}.

3.2 Judgment set and fuzzy judgment decision-making matrix

Ecosystem vulnerability of mines is divided into 5 levels: level 1- very vulnerable, level 2 – vulnerable, level 3- moderate, level 4- strong, level 5- very strong. The vulnerability grading result is shown in Table 7.

Table 7. *Vulnerability grading*

Secondary indicator	Level 1	Level 2	Level 3	Level 4	Level 5
Density of major mines A1	Very High	High	Moderate	Low	Very low
Types of major minerals A2	Very High	High	Moderate	Low	Very low
Mining method A3	Very High	High	Moderate	Low	Very low
Production scale of the mines A4	Very High	High	Moderate	Low	Very low
Coverage area of the mines A5	Very High	High	Moderate	Low	Very low
Vegetation coverage B1	Very High	High	Moderate	Low	Very low
Area of occupied land B2	Very High	High	Moderate	Low	Very low
Number of toxic mines B3	Very High	High	Moderate	Low	Very low
Number of geological disasters B4	Very High	High	Moderate	Low	Very low
Degree of damage to the landscape B5	Very High	High	Moderate	Low	Very low
Amount of waste B6	Very High	High	Moderate	Low	Very low
Per capital GDP in the mining area C1	Very High	High	Moderate	Low	Very low
Annual investment on environmental management C2	Very High	High	Moderate	Low	Very low
Economic contribution rate of the mines C3	Very High	High	Moderate	Low	Very low
Percentage of personnel engaged in technology and environmental protection C4	Very High	High	Moderate	Low	Very low
Significance of location of the mines C5	Very High	High	Moderate	Low	Very low

3.3 Result of ecosystem vulnerability evaluation

Judgment set is built by expert scoring, and the judgment matrices and fuzzy judgment matrices for each primary indicator are constructed. The evaluation result of the *i*-th secondary indicator is denoted as $(r_{i1}, r_{i2}, r_{i3}, r_{i4}, r_{i5})$ (i=1,2,…,m), and the fuzzy judgment matrix for the corresponding primary indicator is

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{15} \\ r_{21} & r_{22} & \cdots & r_{25} \\ \vdots & \vdots & & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{m5} \end{bmatrix}$$

where , r_{ij}=the number of j level experts / The total number of the judges, (i=1,2,…,m; j=1,2,…,5) is the degree of membership of the *j*-th level of the *i*-th secondary indicator.

Similarly, the fuzzy judgment matrices R_A, R_B and R_C for the three primary indicators are obtained. The comment vector for the first primary indicator is

$$V_A = W_A R_A = (\mu_{A_1}, \mu_{A_2}, \mu_{A_3}, \mu_{A_4}, \mu_{A_5}) \begin{pmatrix} r_{11} & r_{12} & r_{13} & r_{14} & r_{15} \\ r_{21} & r_{22} & r_{23} & r_{24} & r_{25} \\ r_{31} & r_{32} & r_{33} & r_{34} & r_{35} \\ r_{41} & r_{42} & r_{43} & r_{44} & r_{45} \\ r_{51} & r_{52} & r_{53} & r_{54} & r_{55} \end{pmatrix} = (\sum_{i=1}^{5} \mu_{A_i} r_{i1}, \sum_{i=1}^{5} \mu_{A_i} r_{i2}, \sum_{i=1}^{5} \mu_{A_i} r_{i3}, \sum_{i=1}^{5} \mu_{A_i} r_{i4}, \sum_{i=1}^{5} \mu_{A_i} r_{i5})$$

Similarly, for the other two primary indicators,

$$V_B = W_B R_B = (\sum_{i=1}^{6} \mu_{B_i} r_{i1}, \sum_{i=1}^{6} \mu_{B_i} r_{i2}, \sum_{i=1}^{6} \mu_{B_i} r_{i3}, \sum_{i=1}^{6} \mu_{B_i} r_{i4}, \sum_{i=1}^{6} \mu_{B_i} r_{i5});$$

$$V_C = W_C R_C = (\sum_{i=1}^{5} \mu_{C_i} r_{i1}, \sum_{i=1}^{5} \mu_{C_i} r_{i2}, \sum_{i=1}^{5} \mu_{C_i} r_{i3}, \sum_{i=1}^{5} \mu_{C_i} r_{i4}, \sum_{i=1}^{5} \mu_{C_i} r_{i5});$$

Where

$$W_A = (\mu_{A_1}, \mu_{A_2}, \mu_{A_3}, \mu_{A_4}, \mu_{A_5}) = (0.0793, 0.2332, 0.5112, 0.1270, 0.0493)$$

$$W_B = (\mu_{B_1}, \mu_{B_2}, \mu_{B_3}, \mu_{B_4}, \mu_{B_5}, \mu_{B_6}) = (0.3774, 0.1597, 0.0516, 0.1979, 0.1770, 0.0366)$$

$$W_C = (\mu_{C_1}, \mu_{C_2}, \mu_{C_3}, \mu_{C_4}, \mu_{C_5}) = (0.0459, 0.1100, 0.2555, 0.4396, 0.1489)$$

The fuzzy evaluation matrix of the 3 primary indicators is

$$R = (V_A, V_B, V_C)^T,$$

The judgment vector for ecosystem vulnerability evaluation is

$$V = WR = (\mu_A, \mu_B, \mu_C)(V_A, V_B, V_C)^T,$$

Where

$$W = (W_A, W_B, W_C) = (0.6393, 0.2737, 0.0869)$$

V is normalized and the peak is found by the maximization principle. The level of the peak is taken as the ecosystem vulnerability level of the mining area.

4. Simulation Calculation for Ecosystem Vulnerability Evaluation of a Mine

Using the fuzzy mathematical model thus built, the ecosystem vulnerability of a specific mine is evaluated by 12 experts. The evaluation result is shown in Table 8.

Table 8.*Ecosystem vulnerability grading of the mine*

Secondary indicator	Level 1	Level 2	Level 3	Level 4	Level 5
Density of major mines A1	2	5	3	2	0
Types of major minerals A2	1	7	4	0	0
Mining method A3	4	7	1	0	0
Production scale of the mines A4	5	6	1	0	0
Coverage area of the mines A5	1	8	2	1	0
Vegetation coverage B1	3	6	3	0	0
Area of occupied land B2	5	5	2	0	0
Number of toxic mines B3	0	1	7	3	1
Number of geological disasters B4	2	3	5	2	0
Degree of damage to the landscape B5	0	2	5	4	1
Amount of waste B6	0	0	6	4	2
Per capital GDP in the mining area C1	0	2	8	2	0
Annual investment on environmental management C2	0	3	6	3	0
Economic contribution rate of the mines C3	0	4	6	1	1
Percentage of personnel engaged in technology and environmental protection C4	1	4	4	2	1
Significance of location of the mines C5	0	3	6	2	1

The fuzzy judgment matrices for the 3 primary indicators are

$$R_A = \begin{bmatrix} 2 & 5 & 3 & 2 & 0 \\ 1 & 7 & 4 & 0 & 0 \\ 4 & 7 & 1 & 0 & 0 \\ 5 & 6 & 1 & 0 & 0 \\ 1 & 8 & 2 & 1 & 0 \end{bmatrix},$$

$$R_B = \begin{bmatrix} 3 & 6 & 3 & 0 & 0 \\ 5 & 5 & 2 & 0 & 0 \\ 0 & 1 & 7 & 3 & 1 \\ 2 & 3 & 5 & 2 & 0 \\ 0 & 2 & 5 & 4 & 1 \\ 0 & 0 & 6 & 4 & 2 \end{bmatrix},$$

$$R_C = \begin{bmatrix} 0 & 2 & 8 & 2 & 0 \\ 0 & 3 & 6 & 3 & 0 \\ 0 & 4 & 6 & 1 & 1 \\ 1 & 4 & 4 & 2 & 1 \\ 0 & 3 & 6 & 2 & 1 \end{bmatrix}.$$

The comment vectors are

$$V_A = W_A R_A = (3.1209, 6.7637, 1.9075, 0.2079, 0);$$

$$V_B = W_B R_B = (2.3265, 4.0622, 3.9069, 1.4050, 0.3018);$$

$$V_C = W_C R_C = (0.4396, 3.6489, 5.2120, 1.8543, 0.8440).$$

The judgment vector for the primary indicators is

$$V = (2.6702, 5.7530, 2.7417, 0.6786, 0.1560)$$

After normalization,

$$V' = (0.2225, 0.4794, 0.2285, 0.0566, 0.0130).$$

The peak is determined as 0.3864 by the maximization principle. Thus the ecosystem of this mine is considered as vulnerable.

5. Conclusion

Fuzzy mathematics is one of the three methods addressing fuzzy problems. The fuzzy synthetic evaluation method is proved to be scientific, reasonable and feasible and has found applications in the field of health care and sanitation, equipments and automobiles, and sports and civil livelihood. However, the evaluation indicators are selected by experts based on their subjective experience and some adjustments may be needed depending on the specific situations. Moreover, the membership of each vulnerability degree of the indicators is also determined by expert scoring, which provides a realistic reflection.

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