Comparison and Analysis of Resource and Environmental Carrying Capacity of Typical Rare Earth Mining Areas in China

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Research Article

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Abstract

Rare earth is a non-renewable and important strategic resource, and China is rich in rare earth resources. However, the process of massive exploitation has caused the migration, diffusion transformation and accumulation of pollution sources, which in turn has a profound impact on the ecological environment of mining areas. Accurate evaluation of resource and environmental carrying capacity (RECC) is important for the green development of mining areas. In this paper, the fuzzy comprehensive evaluation method based on AHP and entropy combination assignment method is used to study the RECC of mine area in terms of both support capacity and pressure. The Bayan Obo mine in Inner Mongolia; Longnan mine in Jiangxi; Weishan mine in Shandong; Mianning mine in Sichuan; Pingyuan mine in Guangdong; and Chongzuo mine in Guangxi, which have typical representatives, were selected for the horizontal comparison. The results show that, with the exception of Bayan Obo, the support index is greater than the pressure from mining and human activities in all the mining areas. The RECC index ranks for each mining area were: Bayan Obo > Longnan > Mianning > Pingyuan > Weishan > Chongzuo. In addition, an obstacle degree model was used to identify and extract the main factors affecting the ecological quality of the mine site. The ratio of investment in environmental pollution control to GDP is the most important factor limiting the improvement of the mine support index. The results of this paper were given for the different evolutionary processes and differences of RECC in typical rare earth mining areas, which could provide valuable references for achieving the green and comprehensive development of rare earth industry.

1. Introduction

1.1. Background

Rare earth is a key element indispensable for the transformation of traditional industries, the development of new industries and the national defense science and technology industry, as it is a non-renewable and important strategic resource. At present, the world economy is slowly recovering, and the global industrial value chain is developing rapidly in the direction of high-end, intelligent and green. Rare earths have excellent optical, magnetic and superconducting functions, and are known as "industrial vitamin", "mother of new materials" and "metal of science and technology". Rare earth functional materials in new energy vehicles, national defense equipment, rare earth permanent magnet motor, energy saving and environmental protection, rail transportation, new materials, new energy and other key areas of vigorous development[1−5], drive the demand for rare earth products synergistic growth, promote the steady development of rare earth industry. The strategic value and economic value of rare earths are becoming more and more prominent.

Global rare earth resource reserves are abundant and widely distributed in 38 countries in six continents: Asia, Europe, Africa, Oceania, North America, and South America, with identified resource reserves of over 200 million tons[6]. With the discovery and exploitation of new rare earth resources in every country, the pattern of rare earth resources reserves in the world is changing. China is abundant in rare earth resources, with complete types of deposits and rare earth resources distributed in 22 provinces (Figure.1), It is widely distributed and relatively concentrated, with the world's largest reserves, accounting for 23% of the world's total, but supplying more than 90% of the world's rare earth market. China has contributed too much rare earth products to the world[7]. Since rare earth elements are very scattered in the earth's crust, mining is difficult and extremely expensive, and the process of resource development has a negative impact on local water bodies, atmosphere, soil, organisms, and other environmental elements that are closely related to human survival. Mining has become the most important destroyer of ecological environment and source of pollution and disaster today. The development of rare earth resources, due to its unique form of extraction and metallurgy, has caused more damage to the local ecological environment.

Cross-sectional comparison among rare earth mining areas helps to fill the gaps in the study of RECC in rare earth mining areas; clarify the development differences among rare earth mining areas in terms of ecology, environment and economy; and dynamic change analysis helps to capture the development fluctuations of each mining area in time scale. This paper selects the typical representatives of Inner Mongolia Bayan Obo mine, Jiangxi Longnan mine, Shandong Weishan mine, Sichuan Mianning mine, Guangdong Pingyuan mine and Guangxi Chongzuo mine as the research objects, these mining areas account for more than 90% of the total rare earths mined in China, so the mining areas are selected to be representative. The results of this study can be used to formulate strategic policies according to local conditions.

1.2. Literature review

An extensive literature review of current research on the ecological perspective of rare earth mining areas, Wang et al.[8] conducted a detailed investigation on the concentration, spatial distribution, pollution level, and ecological risk of rare earth elements around the Bayan Obo mining area. Jsla et al.[9] evaluated the effects of Tb and carbon nanotube exposure on the accumulation and metabolic capacity, oxidative status, and neurotoxicity of natural and invasive clams. Gt et al.[10] determined the Gd concentrations in marine and freshwater environments and the biological responses induced by Gd exposure and its bioaccumulation in different aquatic invertebrates. Xu et al.[11] combined with economic theory to suggest that rare earth resource development and ecological environmental protection are essentially a game of interests between enterprises and governments. Yin et al.[12] reviewed the toxicity levels, biochemical mechanisms, and physiological effects of REEs on different organisms from a multidisciplinary perspective to identify and discuss the potential environmental risks to Canada in future rare earth development. It is obvious that the current studies for rare earth mining sites are filtered according to rare earth and environmental themes focusing on ecological risk, bioaccumulation, bioremediation, biotoxicity, environmental pollution and quantification of environmental costs, as shown in Table 1. Currently there is still a gap in the horizontal comparative evaluation of RECC of rare earth mining areas. The establishment of a comprehensive resource and environment evaluation index system applicable to rare earth mining areas is beneficial to the integrated development of rare earth resource-based areas through horizontal comparative evaluation.

Table 1
The main types of research in the direction of rare earth ecology and environment

Research Directions	Research author
Ecological risks	8,12–14
Bioaccumulation	9,15,16
Bioremediation	17–20
Biotoxicity	21,22
Environmental pollution and protection	11,23–25
Quantification of environmental costs	14

Carrying capacity is determined according to the relationship between the "carrier" and the "carrying object". Carrying capacity is defined as the ability of the carrier to support the "carrying object"[26]. Hadwen and Palmer.[27] considered carrying capacity as the number of lives that can be sustained without destroying the ecosystem, emphasizing the mission of not destroying the ecosystem in order to achieve sustainable development. In 1970s, Holling[28] introduced the concept of RECC as the ability of an ecosystem to resist external disturbances and maintain the relative stability of its original ecological structure. With the development of economy and society, people gradually pay attention to the impact of human activities on ecological environment, Chapman et al.[29] noted that RECC overload has become a common problem in countries around the world.

In fact, RECC was involved in an evolutionary process because it was influenced by various dynamic factors, such as human activities, energy structure and consumption, and climate change. Therefore, from an evolutionary point of view, it is necessary and appropriate to examine RECC in time. However, unlike physical objects, ecosystems are not static, but dynamic and variable[30]. Thresholds for RECC do not actually occur because of the inability to conduct anthropogenic system destruction experiments[31].

Carrying capacity research was mostly carried out regionally, and due to the variability of each region, most of them first analyzed the type of carrying capacity, determined the indicators affecting the carrying capacity, established the evaluation index system, determined the index weights, and then completed the evaluation through various evaluation methods[32–34];In the evaluation process, the researcher determines the results of the study in two ways: the first process assumes that resource, environmental, economic, social and other criteria are additive through the positive and negative characteristics of the indicators[35,36]the other process is to construct a pressure-state-response as a system layer[31,32]. Most studies dividing the RECC system into ecological, environmental and human-social criteria and calculating the indices of each criterion layer as a whole, ignoring the supporting capacity of the resource environment and the overall pressure of human activities on these systems, is not conducive to further understanding of the supporting activities of the resource environment and the impact of human activities on these systems. The attribute characteristics of these two relatively independent systems are not portrayed to facilitate the understanding of the current status of these two systems[32,37].

2. Research Methodology And Data Sources

2.1. Theoretical content and construction of RECC indicator system

Ideally, the ecosystem itself will maintain its functions in a relatively dynamic state of equilibrium[31]. However, as human activities increase the load on the resource environment or degrade the supporting capacity will make this balance break down, load pressure > supporting capacity. This study integrates the interaction between carriers and loads by examining the relationship between RECC ecosystem loads and ecosystem carriers.

Through the analysis of numerous factors affecting the ecological carrying capacity, we obtained the final system of carrying capacity indicators. In this study, the carrying capacity was divided into two aspects: the support surface was divided into four intermediate layers of climatic conditions, resource endowment, environmental management and economic development, and the pressure surface was divided into three intermediate layers of ecological damage loss, environmental pollution loss and social pressure. The support system included climatic conditions and resources, as well as social resources such as environmental governance and good economic development formed through human capital, production and technology, such as comprehensive utilization rate of industrial solid waste, urban sewage treatment rate, and harmless treatment rate of domestic waste. Human activities constituted the pressure side of the RECC system, the ecological damage and environmental pollution losses caused by the activities of human society such as economic growth, social development entertainment, personal enjoyment, and the mining and smelting activities of rare earth mines.

Incorporating 30 indicators within the evaluation indicator system of the RECC for rare earth mining areas, Among them, 18 indicators shown in Table 2 were the basic indicators for the development of mining areas, which were common indicators of previous studies on ecological carrying capacity, and 12 new indicators, S_{2-4}、S_{2-5}、S_{4-3}、P_{1-1}、P_{1-2}、P_{1-3}、P_{1-4}、P_{2-1}、P_{2-2}、P_{2-3}、P_{2-4}、P_{3-6} represented the characteristic indicators of rare earth mining areas. 16 support indicators and 14 pressure indicators were identified by combining the data availability of the 6 mining areas (Table 3). In the selection of indicators, the percentage category and per capita category were particularly selected to maintain consistency in the evaluation. In certain indicators describing local characteristics, such as GDP per capita and share of secondary industry in GDP, county-level administrative district data were particularly selected for use; as the most basic government unit in China, the county (district) level can better capture the heterogeneity of mining areas than provinces and cities.

Table 2
Summary of typical ecological base evaluation indicators in previous studies

Indicators (units)		References
S_{1-1}	Frost free period (days)	38
S_{1-2}	Annual average relative humidity (%)	39
S_{1-3}	Annual average temperature (℃)	38,39
S_{2-1}	Total annual precipitation (mm)	40
S_{2-2}	Arable land to regional area (%)	37,41–44
S_{2-3}	Forest-grassland coverage (%)	37,41,45
S_{2-6}	Water resources per capita (m^3)	43,44,46
S_{3-1}	Comprehensive utilization rate of industrial solid waste (%)	44,46,47
S_{3-2}	Urban sewage treatment rate (%)	33
S_{3-3}	Harmless treatment rate of domestic waste (%)	37
S_{3-4}	Environmental pollution control investment to GDP ratio (%)	33
S_{4-1}	Foreign exchange earnings from tourism (USD million)	40
S_{4-2}	GDP per capita (RMB)	42–44
P_{3-1}	Urban registered unemployment rate (%)	37
P_{3-2}	Share of secondary industry in GDP (%)	37,43,44,48
P_{3-3}	Urban per capita daily domestic water consumption (L)	33
P_{3-4}	Natural population growth rate (%)	37,44
P_{3-5}	Energy consumption of 10,000 Yuan GDP (t standard coal)	37,44,46

Table 3
Evaluation index system of the RECC

System	Criteria layer	Indicators (units)	System	Criteria layer	Indicators (units)
Support	Climate Conditions	S_{1-1} Frost free period (days)	Pressure	Ecological damage loss	P_{1-1} Loss of ecological value volume of organic matter due to rare earth mining Ten thousand yuan)
		S_{1-2} Annual average relative humidity (%)			P_{1-2} Rare earth mining leads to the loss of value quantity of released O^2 and fixed CO^2 (Ten thousand yuan)
		S_{1-3} Annual average temperature (°C)			P_{1-3} Rare earth mining leads to the loss of water conservation value amount (Ten thousand yuan)
	Resource Endowment	S_{2-1} Total annual precipitation (mm)			P_{1-4} Rare earth mining leads to the loss of soil conservation value amount (Ten thousand yuan)
		S_{2-2} Arable land to regional area (%)			
		S_{2-3} Forest-grassland coverage (%)		Environmental pollution loss	P_{2-1} Rare earth smelting water pollution treatment cost accounting (Ten thousand yuan)
		S_{2-4} Rare earth resources reserves (million tons)			P_{2-2} Rare earth smelting air pollution treatment cost accounting (Ten thousand yuan)

System	Criteria layer	Indicators (units)		System	Criteria layer	Indicators (units)	
		S_{2-5}	Rare earth resources reserves (million tons)			P_{2-3}	Rare earth smelting solid waste pollution treatment cost accounting (Ten thousand yuan)
		S_{2-6}	Water resources per capita (m^3)			P_{2-4}	The radioactivity (nGy/h)
	Environmental Governance	S_{3-1}	Comprehensive utilization rate of industrial solid waste (%)				
		S_{3-2}	Urban sewage treatment rate (%)		Social pressure	P_{3-1}	Urban registered unemployment rate (%)
		S_{3-3}	Harmless treatment rate of domestic waste (%)			P_{3-2}	Share of secondary industry in GDP (%)
		S_{3-4}	Environmental pollution control investment to GDP ratio (%)			P_{3-3}	Urban per capita daily domestic water consumption (L)
	Economic Development	S_{4-1}	Foreign exchange earnings from tourism (USD million)			P_{3-4}	Natural population growth rate (%)
		S_{4-2}	GDP per capita (RMB)			P_{3-5}	Energy consumption of 10,000 Yuan GDP (t standard coal)
		S_{4-3}	Number of Rare Earth Related Employees (Number)			P_{3-6}	Annual mining volume (million tons)

The steps of RECC calculation in this study are divided into (1) construction of standardized evaluation matrix; (2) standard normalization of indicators; (3) determination of indicator weights using a combination of AHP and entropy value method; and (4) use of linear weighting method to obtain support index, pressure index and RECC index. Since the support side and pressure side rely on the same weighting method, the support side is described as an example.

2.2 Construction of standardized evaluation matrix

Suppose there are m evaluation indicators and n evaluation objects, then the value of indicator j in object i is taken as A_{ij}, then the decision matrix of all objects can be expressed as:

$$S=\begin{bmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots \\ S_{m1} & \cdots & S_{mn} \end{bmatrix} \quad (1)$$

Since the values of selected indicators in ecological carrying capacity are not uniform in magnitude, in order to solve the problem of uniformity in the magnitude of model parameters, so that the interval of values after eliminating the magnitude with the original data is limited between 0 and 1, it is necessary to standardize the data of different units for further comparative analysis and comprehensive calculation on the same scale. In this paper, the normalization process is carried out using the polar difference standardization method.

$$r_{ij}=\frac{a_{ij}-\min\left(a_{ij}\right)}{\max\left(a_{ij}\right)-\min\left(a_{ij}\right)} \quad (2)$$

Then, the normalized decision matrix can be obtained as:

$$R=\begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{bmatrix} \quad (3)$$

2.3. Defining the weighting values for RECC indicators

A reasonable assignment of weights plays a crucial role in the scientific rationality of evaluation results, and a reasonable assignment method should assign weights to decision indicators based on both the intrinsic laws between indicator data and expert experience. In this study, a comprehensive subjective and objective assignment method is used to solve this problem. Since AHP is the most common and dominant method in the subjective assignment method. In the objective assignment method, the entropy method is the most frequently used, objective and stable assignment method, so the integrated assignment method uses a combination of these two methods.

(1) AHP

The analytic hierarchy process (AHP) was formally introduced by American operations research scientists[49]. It was a systematic and hierarchical analysis method combining qualitative and quantitative. The comprehensive evaluation system established in this paper has a hierarchical structure and was well suited to be analyzed by hierarchical analysis.

The judgment matrix was defined as the relative importance of the relevant elements in the hierarchy assuming that the elements in level A are related to the elements in level B. In constructing the matrix, the expert evaluates the importance of factors at the same level based on a 9-point scale (Table 4) for these factors and forms a judgment matrix.

Table 4
Definitions of 9-point scale grades.

Value	Definition
1	Factors i and j have the same degree of importance
3	The importance of factor i is slightly higher than that of factor j
5	The importance of factor i is significantly higher than that of factor j
7	The importance of factor i is much higher than that of factor j
9	The importance of factor i is extremely higher than that of factor j
2,4,6,8	Median value between the two adjacent values

Based on the above judgment matrix, the eigenvectors and eigenroots of the matrix are calculated. The maximum eigenvector $w = \left(w_1, w_2, w_3, \ldots, w_m\right)$, of the judgment matrix, where the components are the weights of the elements in the target layer. The judgment matrix needs to satisfy the consistency judgment condition (Eq. (4)).

$$CR = \frac{\frac{\lambda_{max} - n}{n-1}}{RI} \quad cript > \qquad (4)$$

where λ is the maximum characteristic root and RI is the average random consistency index; the RI values are shown below (Table 5).

Table 5
RI values.

n	1	2	3	4	5	6	7	8	...
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	...

n was the judgment matrix order, when CR < 0.1, the consistency of the judgment matrix was acceptable; otherwise it was otherwise to reconstruct the pairwise judgment matrix until a satisfactory consistency was achieved.

(2) The entropy method

The objective weighting method determines the weights of indicators based on their intrinsic information, which can eliminate artificial interference and make the results more factual. The entropy method was to determine the weight of the index based on the amount of information, which is one of the objective fixed weighting methods[50]. Then, the information entropy of the jth index can be expressed by Eq. (5).

$$e_j = -\frac{1}{\ln m}\sum_{i=1}^{m} P_{ij}\ln P_{ij} \quad (5)$$

Here, n was the number of evaluation levels and P_{ij} satisfied $\sum_{j=1}^{m} P_{ij} = 1$.When $P_j = 0$, $e_j = 0$.Then, the entropy weight of the jth evaluation factor can be expressed as in Eq. (6).

$$w'_j = \frac{1-e_j}{\sum_{j=1}^{m}(1-e_j)} \quad (6)$$

The weights of evaluation indexes obtained by AHP and entropy weight method were $w = w_1, w_2, w_3, \ldots, w_m$, $w' = w'_1, w'_2, w'_3, \ldots, w'_m$, and the combination weights obtained by using fuzzy comprehensive evaluation method were:

$$W_i = 0.5w_i + 0.5w'_i \quad (7)$$

2.4. Calculation of RECC index

According to the normalized values of each indicator and the corresponding weights, the support index and pressure index are obtained using the linear weighting method, as shown in equations (8) and (9):

$$\boldsymbol{S_i = \sum_{i=1}^{n} S_{ij}W_i^s} \quad \textbf{(8)}$$

$$P_i = \sum_{i=1}^{n} P_{ij}W_i^p \quad (9)$$

The RECC index for the study area was equal to the ratio of the stress index to the support index.

$$C_i = \frac{P_i}{S_i} \quad (10)$$

2.5. RECC level classification and coupling mechanism

2.5.1. Support surface and pressure surface evaluation grade classification

A hierarchical approach was used to classify RECC for more targeted guidance of human activities. This was previously shown to be an effective method for analyzing trends in results[34].

First, the support and pressure surfaces were divided into low, medium, and high grades for measurement. The equal scoring method was used for grading, and this method was also applied in the previous study[33,51]. According to this, the three levels were equally distributed in the range of (0,1). The support index is set to S and the pressure index is set to P (Table 6). A total of 9 blocks were divided into □, □, □, □, □, VI, □, □, and □, representing 9 different support and pressure indices integrated conditions within the mine area, details of which are shown in Table 6 and Figure.2.

Table 6
Evaluation grade classification of support surface and pressure surface.

Evaluation grade division	Low level (L)	Medium level (M)	High level (H)
P	$0 \le P \le 0.33$	0.33 □P ≤ 0.66	0.66 □P ≤ 1
S	$0 \le S \le 0.33$	0.33 □S ≤ 0.66	0.66 □S ≤ 1

2.5.2. RECC coupled model

Theoretically, there were three results of the bearing capacity index, depending on the magnitude of the support and pressure indices, C < 1(P < S), C = 1(P = S), C > 1(P > S); when C < 1(P < S), the pressures generated by human activities were less than the capacity of the resource-environment system to support them, such as □, □, VI. When C = 1(P = S), The supporting capacity of resource and environmental enrichment was basically equal to the pressure generated by human activities, such as □, V and □. When C > 1 (P > S), The pressure generated by human activities was greater than the capacity of the resource environment system to support it, and the RECC in the area was overloaded. Such as □, □ and □.

Using $y = x^2$ and $y = \sqrt{x}$ as criteria to classify the carrying capacity index into 4 regions[32,52], As shown in Table 7 and Figure.2.

Table 7
Significance of the partition of the coupling mechanism between the support index and the pressure index.

partition state	$0 \le y \le x^2$	$x^2 \le y$cript >	$x \le y$cript >	$\sqrt{x} \le y \le 1$
$0 \le x \le 1$	High-value Surplus area	Low-value Surplus area	Low-value Load area	High-value Load area

2.6. The obstacle degree model

On the basis of the carrying capacity indicator system, each indicator should be further analyzed to diagnose the main etiological factors hindering the development of the study area, with reference to the existing literature[32,34], the main purpose is to diagnose the obstacle factors using two indicators: indicator deviation degree and obstacle degree, and the basic arithmetic formula is:

$$I_i = 1 - X_i \qquad (11)$$

$$A_i = \frac{I_i W_i}{\sum_{j=1}^{m} I_i W_i} \qquad (12)$$

Here, X_i is the standardized value of a single indicator, I_i is the difference between the evaluated value of a single indicator and 100%, i.e., the indicator deviation, W_i is the weight of the ith single indicator, A_i is the indicator barrier, and *m* is the number of evaluation indicators.

2.7. data sources

This study aims to assess and compare the ecological and environmental carrying capacity of six typical rare earth mining areas in China during the period 2012–2019. The raw data for most of the indicators listed in Table 2 were obtained from the 2012–2017 statistical yearbooks of the administrative regions where each study area is located and The China County Statistical Yearbook and Department of Rural Social and Economic Survey[53], Baotou City Bureau of Statistics[54], Jiangxi Bureau of Statistics[55], Jining Bureau of Statistics[56], Liangshan Yi Autonomous Prefecture People's Government[57], Liao[58], Chongzuo local history compilation committee[59]. The original data of rare earth resource reserves and the proportion of medium and heavy rare earth resources are from Rare Earth Mining and Environmental Protection[60], Some of the data and calculation methods of ecological damage loss and environmental pollution loss indicators were obtained from The Ecological and Environmental Cost Assessment of Rare Earth Resource Development in China from 2001-2013[61], and details of the methodology are described in Part 4 and Part 5 of the Supplementary Material. and the original data of radioactivity are from research papers [62–66], and data on rare earth policies and the annual mining volume of rare earths were obtained from national database statistics (http://www.mnr.gov.cn/dt/ywbb/).

3. Results

3.1. To obtain the comprehensive weights of evaluation indexes by AHP and entropy method

According to the construction of the evaluation indicator system, the weights of each indicator were first determined (Figure.3). The indicators with greater weight in the pressure system were loss of value quantity of water connotation due to rare earth mining (0.1331) > accounting for the cost of air pollution control of rare earth smelting (0.1255) > loss of ecological value quantity of organic substances due to rare earth mining (0.1145) > loss of value quantity of soil conservation due to rare earth mining ((0.0983) > radioactivity (0.0948). The loss of water connotation value quantity due to rare earth mining, the loss of organic matter ecological value quantity due to rare earth mining, and the loss of soil conservation value quantity due to rare earth mining were indicators of ecological damage loss. Rare earth smelting air pollution control cost accounting, radioactivity belongs to the indicators of environmental pollution losses. The weights of each subsystem of the pressure system were: 0.4183 (ecological damage loss), 0.3809 (environmental pollution loss), and 0.2008 (social pressure).

The indicators with higher weights in the support system were investment in environmental pollution control to GDP ratio (0.1006) > rare earth resource reserve (0.0877) > rare earth policy (0.0809) > number of rare earth related employees (0.0799) > total annual precipitation (0.0767). The ratio of investment in environmental pollution control to GDP belongs to the indicator of environmental control, the amount of rare earth resource reserves belongs to the indicator of resource endowment, the rare earth policy and the number of rare earth-related employees belong to the indicator of economic development, and the total annual precipitation belongs to the indicator of climate. The weights of the subsystems of the support system were 0.1282 (climatic conditions), 0.3723 (resource endowment), 0.2104 (environmental governance), and 0.2892 (economic development).

3.2. Analysis of the RECC at the mine site using a coupled model

The model was used to calculate the support index, pressure index and RECC index of the rare earth mining area to graphically show the variation of RECC within the mining area (Fig. 4).

In 2019, Bayan Obo was a low-value load area. Weishan was a low-value surplus area. Mianning was a low-value surplus area. Longnan was a low-value surplus area. Pingyuan was a high-surplus area. Chongzuo was a high-value surplus area.

The high support index for Longnan and Bayan Obo stems from the amount of rare earth resources reserves, the number of rare earth related employees and the tilted rare earth policy. The ionic rare earth ore reserves in the Longnan mine account for 36% of China's proven reserves, while Bayan Obo's industrial reserves of rare earths account for 83.7% of the country's industrial reserves. The huge reserve base has strongly promoted the high-quality development of the industry and facilitated the development of employment and subsidiary industries. Form a more complete industrial chain competitive advantage. The favorable climatic conditions were the reason for the high support index of the Chongzuo mining area. The low amount of water resources per capita was the major reason affecting the Weishan Support Index. This has a lot to do with the water resources of Jining City, where the Weishan mine is located. Due to the large temporal and spatial differences in precipitation and poor natural connectivity of water systems, Jining is characterized by "many rivers, few floods, uneven abundance and overall water shortage". Investing in improving the per capita water resources and other ecological indicators in Weishan can rapidly improve the regional support index.

The pressure index of each mining area was ranked from high to low: Bayan Obo > Longnan > Mianning > Pingyuan > Weishan > Chongzuo. The high-pressure index at Bayan Obo was mainly due to the loss of environmental pollution and ecological damage, where the loss of environmental pollution greatly exceeded that of other mining areas. In recent years, Bayan Obo has been mining more than 50% of China's rare earths annually, which inevitably results in more serious ecological damage. Ecological damage loss is the main factor contributing to the high-pressure index in the Longnan mining area, with scores that greatly exceed those of other mining areas. In terms of rare earth ore types, Bayan Obo, Mianning and Weishan are light rare earth ores, while Longnan, Pingyuan and Chongzuo are medium and heavy rare earth ores. The loss of ecological damage caused by light rare earth mining is less than that of medium and heavy rare earth mining. Light rare earths are mostly gathered in northern China, where the terrain is mostly plain, and the vegetation is relatively sparse. Most of the medium and heavy rare earth mines are gathered in southern China, and the terrain is dominated by hills and mountains. However, the environmental pollution loss caused by light rare earth mining was greater than that of medium and heavy rare earths. Light rare earth mines were dominated by atmospheric pollution and radioactive pollution, while medium and heavy rare earth mines were dominated by water pollution. This was caused by the different smelting methods of rare earths.

3.3. Analysis of changes in RECC trends at the mine site

In order to more accurately grasp the changes of RECC of rare earth mining areas, the dynamic analysis of RECC of rare earth mining areas from 2012 to 2019 was conducted, and the results are shown in Fig. 5.

Bayan Obo's RECC index increased from 0.7498 (2012) to 1.2543 (2019), Bayan Obo is in □. The support index decreased from 0.4510 (2012) to 0.4188 (2019), while the pressure index increased from 0.3382 (2012) to 0.5253 (2019). Bayan Obo had the largest stress index (0.5253) among all the mining areas in 2019 and gradually moved towards □. Weishan's RECC index rose from 0.2808 (2012) to 0.3647 (2016) before falling to 0.3191 (2019). The Weishan mine was in □ from 2013–2015 and returned to I from 2016–2019, with slight fluctuations in the support index and a stable and concentrated trend in the pressure index. The RECC index for the Mianning mine rose from 0.6338 (2012) to 0.6510 (2017) and fell back to 0.6373 in 2019. mianning is in □, the support index increased from 0.4451 (2012) to 0.4731 (2015) and then decreased to 0.4073 (2019). The stress index decreased from 0.2821 (2012) to 0.2596 (2019).

Longnan's RECC index increased from 0.5575 (2012) to 0.8467 (2019), with a peak in 2016 (0.9212), and Longnan was in □ only in 2012 and □ in the rest of the years. The support index increased from 0.4894 (2012) to 0.5056 (2019), while the pressure index increased from 0.2729 (2012) to 0.4281 (2019). Both the support and stress indices were on the rise and predicted to be at □ in the longer term. Pingyuan's RECC index increased from 0.3393 (2012) to 0.3637 (2019), with a peak in 2016 (0.4124), Pingyuan is in □. Support index increased from 0.4241 (2012) to 0.4471 (2015), and then decreased to 0.4247 (2019). The pressure index increased from 0.1439 (2012) to 0.1606 (2015) and then decreased to 0.1545 (2019). Chongzuo's RECC index decreased from 0.1253 (2012) to 0.0860 (2019), with a peak in 2016 (0.1709), Chongzuo was at □ only in 2012 and □ in the rest of the years, the support index decreased from 0.3381 (2012) to 0.0.2763 (2015), and then rising to 0.4468 (2019). The pressure index decreases from 0.0424 (2012) to 0.0324 (2015) and then increases to 0.0384 (2019). Both the support and pressure indices show a decreased and then increased state.

3.3. Screening key indicators to improve the support index using the obstacle degree model

The analysis of the support surface of each mine area was carried out based on the obstacle degree calculation method. The obstacle degree of each indicator of the mine area was obtained. Selected the five indicators with the largest obstacle degree and arranged from left to right, as shown in Figure.6, the total obstacle degree of the five indicators of each mine area was > 50%.

The ratio of investment in environmental pollution control to GDP, GDP per capita, and rare earth resource reserves were common factors limiting the sustainable development of mining areas. In 2012, the ratio of investment in environmental pollution control to GDP (5times), rare earth resource reserves (5times), GDP per capita (4times), the proportion of medium and heavy rare earth resources (4times), total tourism revenue (4times), number of rare earth related employees (4times), total annual precipitation (2times), water resources per capita (1times), and forest grassland coverage (1times) were the main obstacles to improve the support capacity of the mining area. In 2019, environmental pollution control investment to GDP ratio (6times), rare earth resource reserves (5times), number of rare earth related employees (5times), GDP per capita (4times), medium and heavy rare earth resources share (4times), total annual precipitation (2times), water resources per capita (1times), and forest grassland coverage (1times) were the main obstacles to improve the support capacity of mining areas. The indicators that appear more frequently belong to the economic development system and the resource system, which indicates that the common barriers that constrain the support of most cities were the existence of the economic development system and the resource system. The low ratio of investment in environmental pollution management to GDP was a common problem limiting the achievement of sustainable development in mining areas. Although the importance of environmental protection in China has been increasing and the investment in environmental management has been growing steadily, the ratio of investment in environmental pollution to GDP is still at a relatively low level.

The obstacle degrees of the primary indicators could be obtained by summing up the obstacle degrees of the secondary indicators. Calculated obstacle degrees for the four support subsystems (Table 8).

Table 8
Obstacle degree and standard deviation of each mine subsystem.

Criteria layer		**Climate**	**Resources**	**Environment**	**Economic Development**
mining area	Bayan Obo	0.2137	0.3998	0.1860	0.2004
	Weishan	0.1073	0.4469	0.1403	0.3055
	Longnan	0.0582	0.3786	0.2225	0.3406
	Mianning	0.0489	0.4425	0.1029	0.4057
	Pingyuan	0.0241	0.4051	0.2036	0.3672
	Chongzuo	0.0069	0.3888	0.2546	0.3498
Standard deviation		0.0701	0.0341	0.0563	0.0755

Affecting the improvement of support index in Bayan Obo, Weishan, Longnan and Pingyuan. Economic development was the major obstacle to the improvement of the Mianning Support Index. Furthermore, the standard deviation of the climatic conditions was 0.0701, with the climatic conditions varying widely from mine to mine depending on their geographical location. The standard deviation of socioeconomic pressure was 0.0755, which far exceeded the other factors, and it can be concluded that there was heterogeneity in the economic development of different mining areas, which affected the RECC of mining areas.

4. Discussion

China's rare earth resources are widely distributed, divided by rare earth ore formulations, Bayan Obo, Mianning and Weishan are light rare earths, Longnan, Pingyuan and Chongzuo are medium and heavy rare earths, with different resource endowment phases in each mining area[67]. Light rare earths are mainly in the northern region, and most of them can be mined on a large scale, but the mining and smelting process has a large impact on the environment and the extraction cost is high[68]. The order of ecological damage loss was Longnan > Pingyuan > Mianning, and Weishan had the least loss. In terms of rare earth ore types, heap leaching and pool leaching processes were mainly used for medium and heavy rare earth development in the past[69]. Both processes include topsoil stripping and ore body mining, thus causing more damage to the ecological environment; after switching to in-situ leaching, the vegetation of the ore body is not destroyed and no topsoil is stripped, thus causing less damage to the ecological environment[70]. The government should consider a reasonable layout of mines, especially in the medium and heavy rare earth areas in the south, and all mineral resources in the key exploration planning areas should undergo ecological and environmental assessment and economic benefit assessment before development and determine the suitability of mining operations based on the results. It is worth noting that the Weishan Mine is currently mined underground and the mine has been using the shallow hole retention mining method for many years, with the tailings filling the void area afterwards, so the ecological damage loss here is small.

The size of environmental pollution loss of rare earth smelting was related to the characteristics of rare earth ore resources, production process and production scale; in the order of environmental treatment cost, Bayan Obo > Mianning > Longnan > Weishan > Chongzuo > Pingyuan, northern rare earth mines are mainly dominated by atmospheric and radioactive contamination[71], medium and heavy rare earth mines are dominated by water pollution and agricultural soils[72,73]. Northern light rare earths are mostly polymetallic co-associated ores, with complex composition, large tailings and serious pollution, of which radioactive pollution is particularly important, due to its natural decay characteristics, thorium in the classification of radioactive toxicity belongs to the highly toxic category, insoluble thorium in the form of dust into the human body, radioactive compounds in the lungs gradually accumulate, directly damage the lungs[71]. The environmental pollution loss of southern medium and heavy rare earth mines is mainly water pollution and farmland soil pollution, due to its poor endowment conditions, scattered distribution, low abundance, difficult to scale up production, the use of ammonium sulfate in situ leaching method, will produce a large amount of high concentration of ammonia nitrogen wastewater, causing serious pollution to local water resources[74].

National policies related to rare earths are important indicators that influence the index of each mining area. Since the 21st century, China has taken an absolute share in the supply side of the rare earth market. However, due to the large number of domestic production enterprises, the competition among enterprises is fierce, blind production, there are also very serious illegal mining of rare earths, theft phenomenon, informal mining methods not only seriously pollute the environment, but also disrupt the market order. The international rare earth market has been in a state of oversupply, which has been the biggest problem facing the rare earth market. The result is that China supplies most of the rare earths to the world, consumes a large amount of resources, and bears huge environmental costs without reaping the corresponding economic benefits. In response to these problems, the state should take measures to guide the domestic market. First, we should raise the market access threshold to curb low-end excess capacity[75]; The management of rare earth resources reserves can be refined, from general management by light and heavy mining areas to management by rare earth allocation, detailed to the elements. Second, increase the application of rare earth research, expand consumer demand, and fundamentally solve the problem of supply exceeding demand in the market. Finally, it is necessary to implement the minimum required indicators for the development and utilization of rare earth resources, and to implement differentiated environmental management policies and establish an ecological civilization evaluation mechanism; introduce a GEP accounting system and incorporate ecological benefits into the evaluation system.

5. Conclusion

This paper studies the status of the RECC of major rare earth mining areas in China in 2019 by coupling the support index and the pressure index. In addition, this paper studies the dynamics of the RECC for each mining area from 2012 to 2019. Finally, a comparative analysis of the main obstacles supporting the improvement of the index for each mining area in 2012 and 2019 is presented. The main conclusions are, first, in terms of weights, the combined weight of ecological damage loss was the largest in the pressure system and the smallest in the social pressure. The combined weight of climatic conditions in the support system was the largest and the economic development was the smallest. Second, Bayan Obo was overloaded, and the pressure of human and social activities had exceeded the capacity of local resources and environmental services to support it. the RECCs at Longnan and Mianning were very close to the alert level. All other mining areas had surplus RECCs. Third, from 2012–2019, the average RECC index for the six mining districts is trending upward, with an inverted V-shaped change in the average pressure and support indices. The increased rate of the pressure index has slowed down, but the decrease of the support index was larger. Fourth, the environmental pollution control investment to GDP ratio is the most common problem that most mining communities face in improving their support index. Among all rare earth mining areas, the environmental pollution loss in light rare earth mining areas was greater than that in medium and heavy rare earth mining areas, and the ecological damage loss in medium and heavy rare earth mining areas was greater than that in light rare earth mining areas.

6. Declarations

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Figures

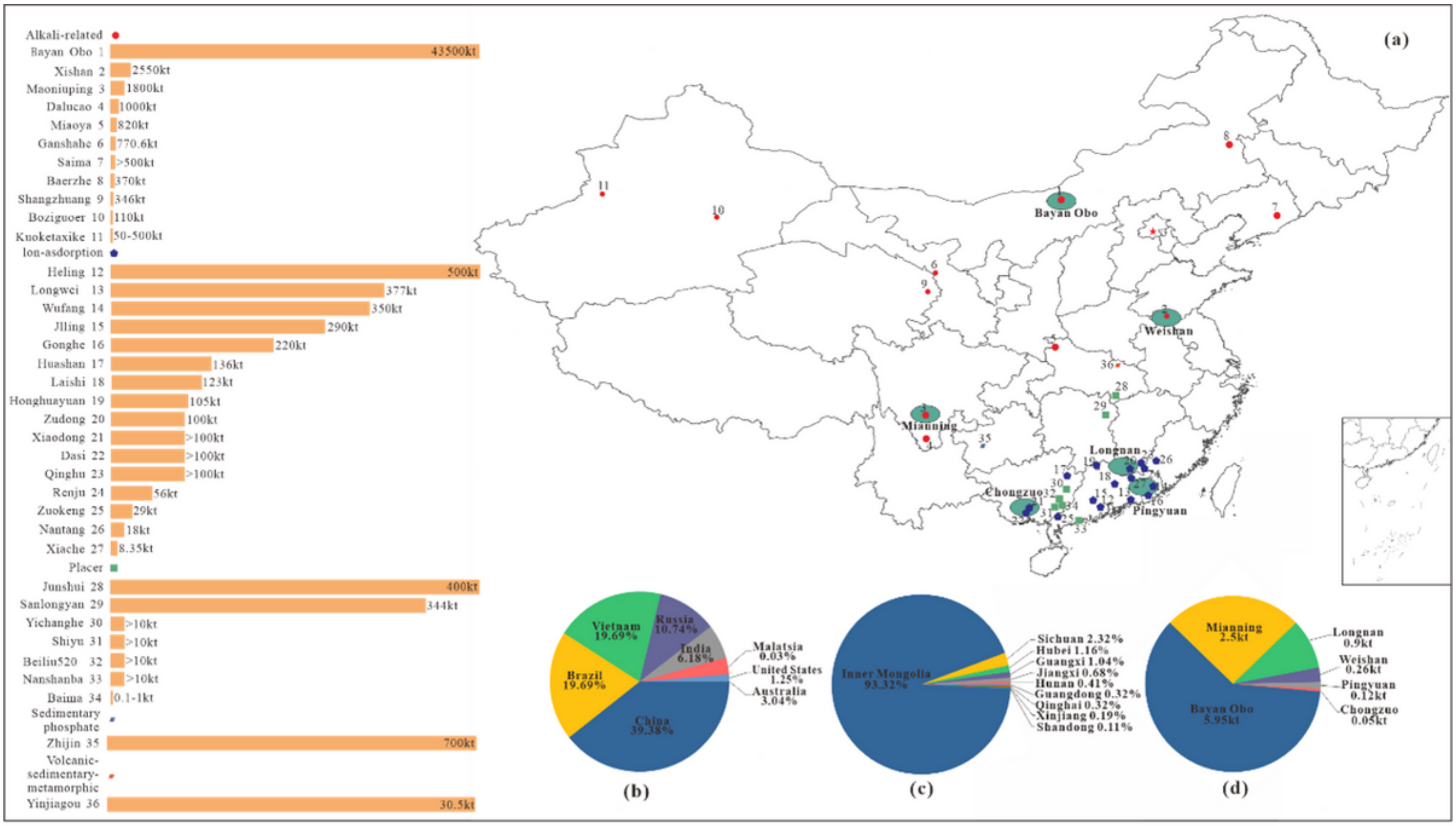

Figure 1

Distribution of rare earth mines in China. (a) 36 rare earth mine types and reserves; (b) reserves of rare earths in major countries in the world; (c) reserves of rare earths in major provinces in China; (d) annual mining capacity of rare earths in major mining areas in China.

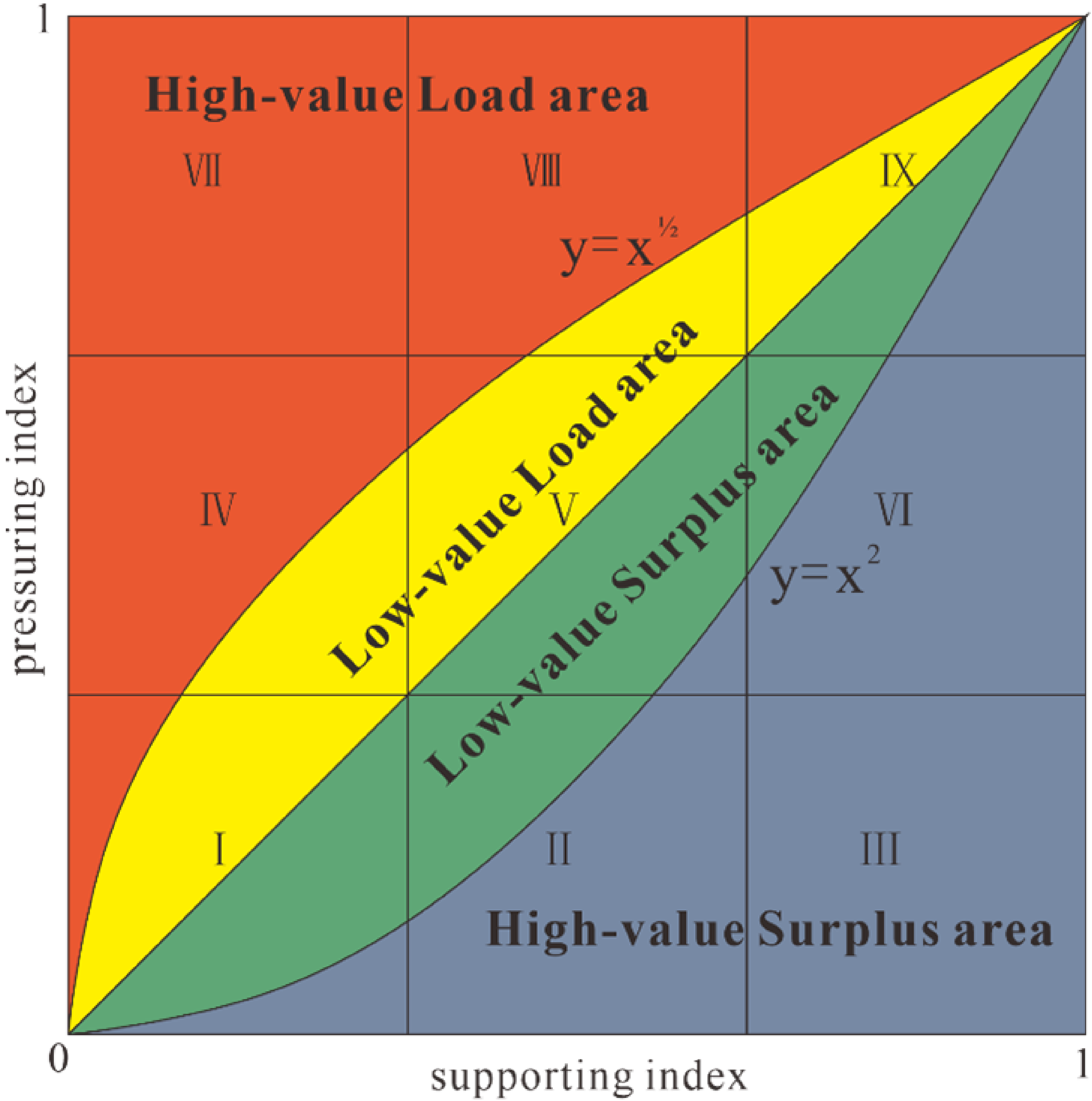

Figure 2

Schematic diagram of support index and pressure index zoned states and coupling curves.

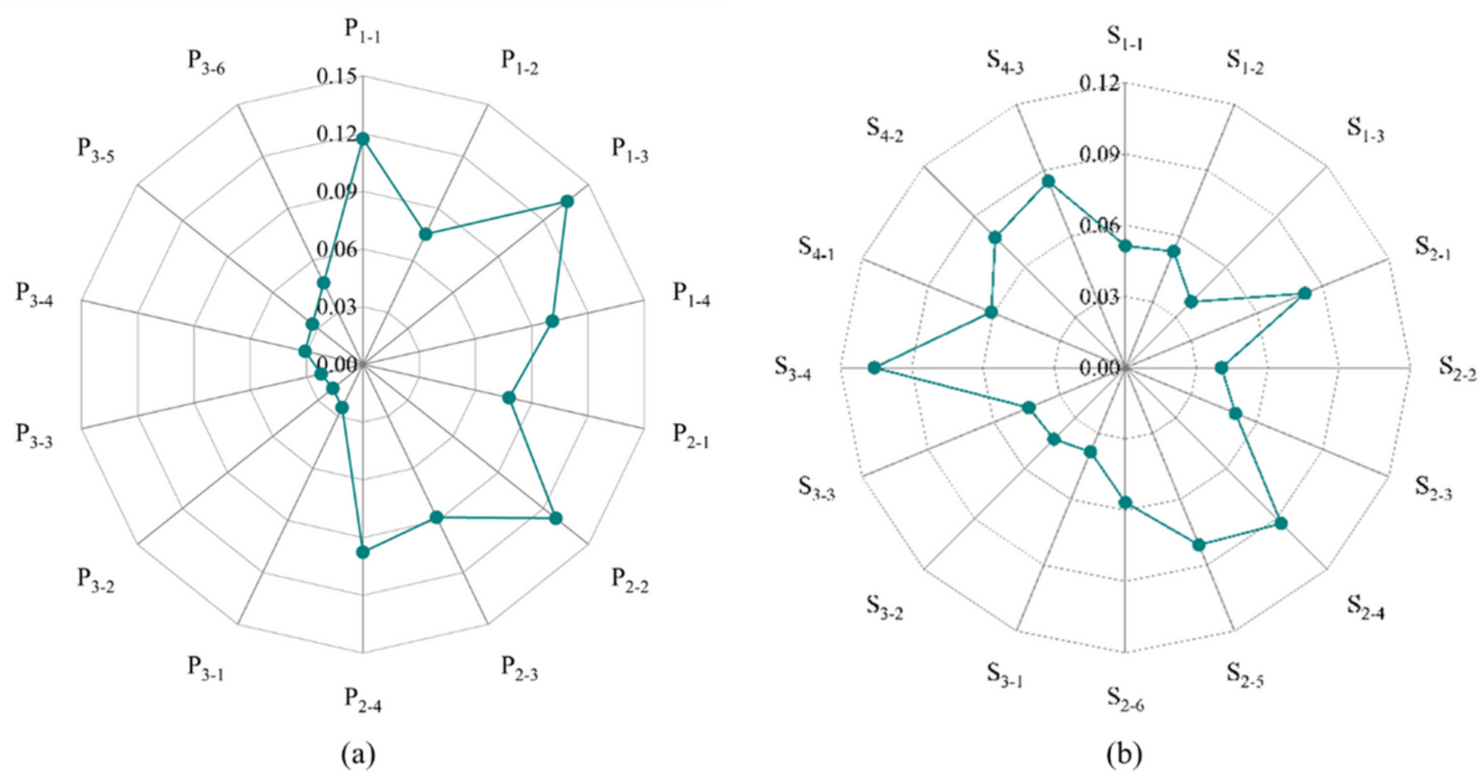

Figure 3

Comprehensive weights of evaluation indicators. (a) Pressure indicators weights; (b)Support indicators weights.

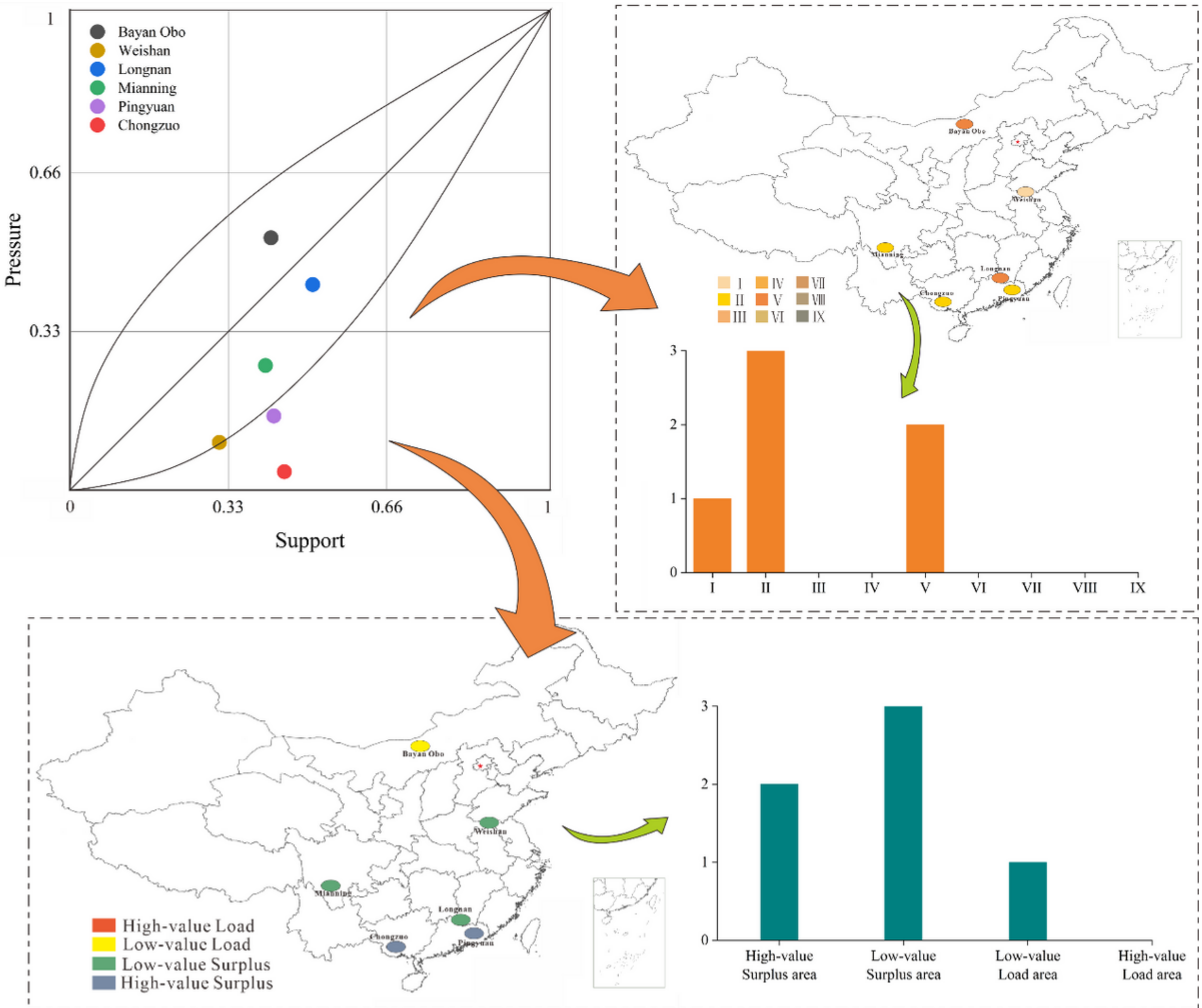

Figure 4

Schematic diagram of the classification of RECC in mining areas.

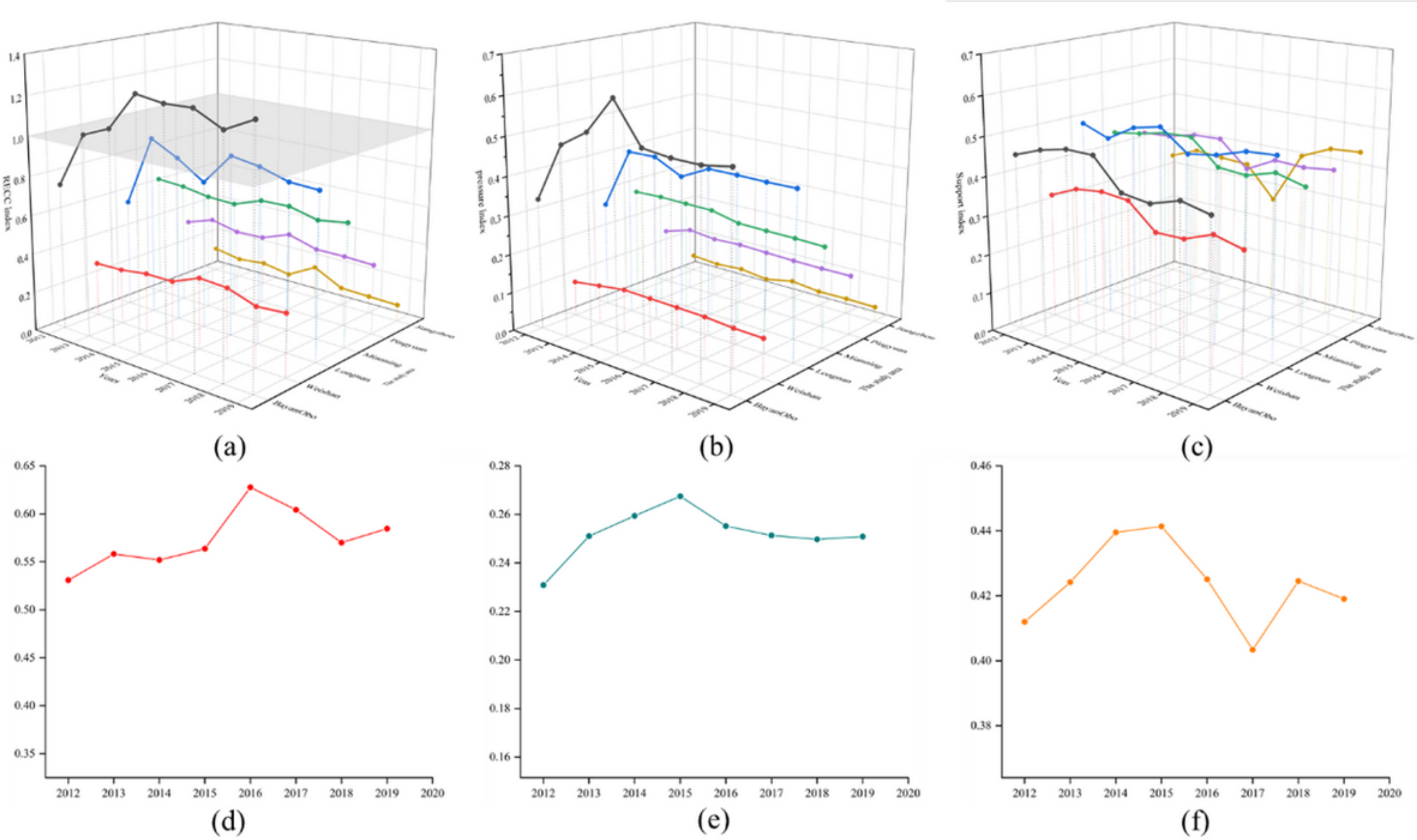

Figure 5

Changes in RECCs for each mine. (a) The trend of the RECC index in the mining area; (b) The trend of the pressuring index in the mining area; (c) The trend of the supporting index in the mining area; (d) The trend of average RECC index; (e) The trend of average pressuring index; (f) The trend of average supporting index.

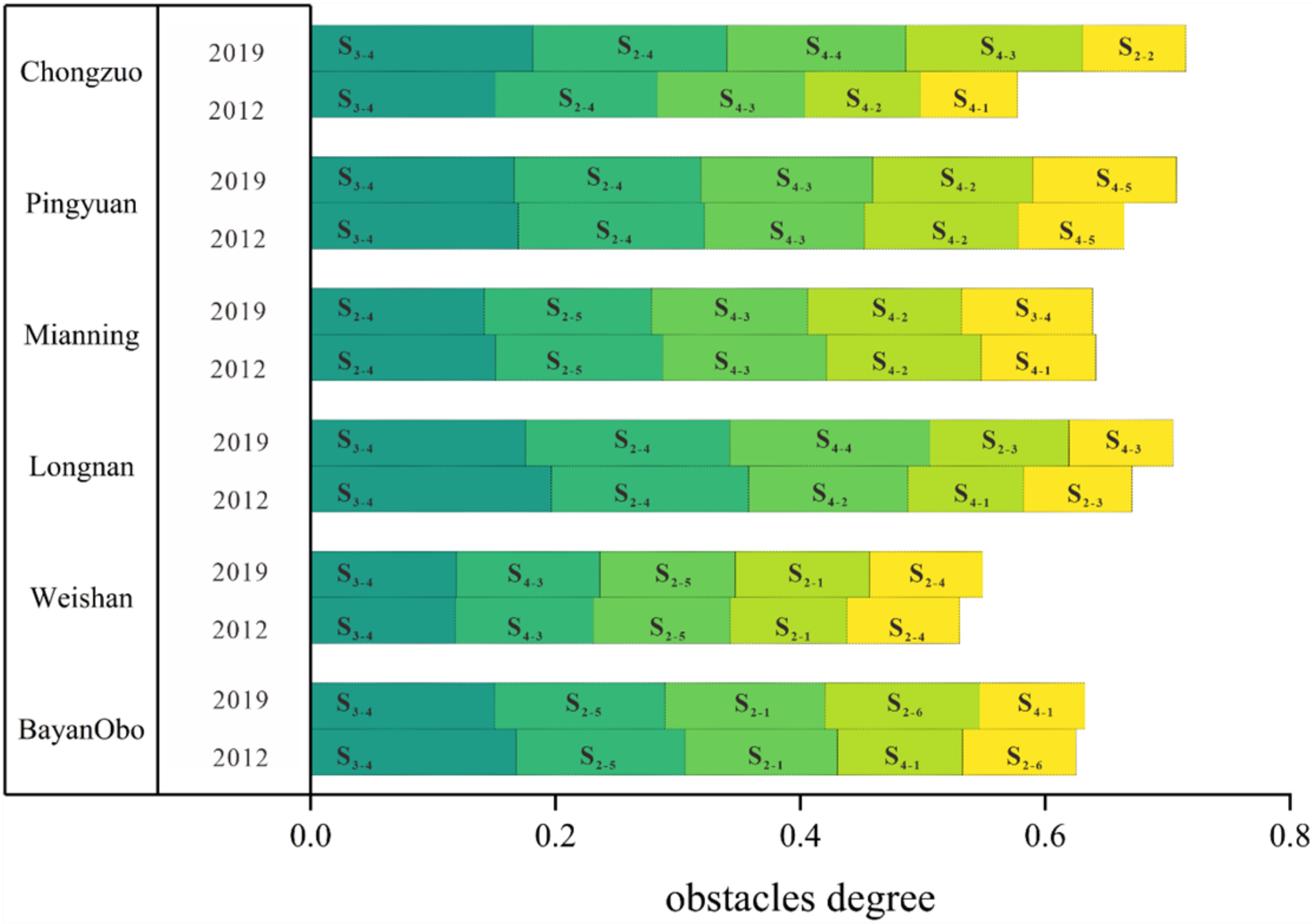

Figure 6

Top 5 Obstacle Indicators for the Support Index of the Mines.

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