Research on Sustainable Coordinated Development of Mineral Resource Development and Ecological Environment Protection in Resource-Based Cities

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Abstract: *This paper establishes a Sustainable Coupling Coordination Degree Model (SCCDM) based on the concept of sustainable development, in order to increase the sustainability perspective of coordinated development and improve the traditional CCDM, and explore the relationship between mineral resource development and ecological environment protection in resource-based cities. The feasibility and superiority of SCCDM are verified using the 2010-2020 dataset of mineral resource development and ecological environment protection in resource-based cities, and analyze the coordinated development characteristics of different resource development stages and regions. The research results are as follows: 1. it is verified that the SCCDM is more in line with the coordination definition for evaluating the coordination relationship between two subsystems, proving that the SCCDM is an effective coordination evaluation method. 2. From 2011 to 2019, the average sustainable coupling coordination degree of various resource-based cities was greater than 0.6, and overall showed an upward trend; From 2010 to 2020, the development of mineral resources in different types of resource-based cities basically met their development trends, and the degree of sustainable coupling coordination showed an upward trend; There is significant growth in the southern coastal comprehensive economic zone and the southwestern comprehensive economic zone, while the downward trend in the northeast comprehensive economic zone and the eastern coastal comprehensive economic zone is prominent. In sum, The SCCDM is more effective, comprehensive, and objective in coordination relationships compared to CCDM. It is more sensitive to changes in the coordination relationship between the two systems. The sustainable coordination degree is steadily improving, and the coordination relationship between mineral resource development and ecological environment protection is also constantly improving.*

Keywords: Mineral resource development; Ecological environment protection; Coordinate relationships; Resource-basic cities; Sustainable development

Ⅰ. INTRODUCTION

The Global Environment Outlook CEO-6 clearly points out that negative human health issues are also related to mining and ore processing. Mining waste is one of the largest waste streams in the world by volume, and mining activities have an impact on ecosystems and lead to soil pollution[1]. The development of mineral resources can also cause environmental problems such as ecological disturbance, damage to natural flora and fauna, air, land, and water pollution, instability of soil and rocks, landscape degradation, and radiation hazards[2]. China's industrialization process is advancing rapidly, and the conflict between development and environment is becoming increasingly severe. Ecological pressure is high. As of 2022, the total production of general industrial solid waste in China is 4.11 billion tons, and the total production of disposable energy is 4.66 billion tons of standard coal, an increase of 9.2% compared to 2021[3]. With the indiscriminate development of various mineral resources in China, problems such as mineral resource depletion, ecological environment damage, and socio-economic recession have gradually emerged. As a high energy consuming and polluting industry, the extensive development model of the mining industry mainly brings about ecological damage and environmental pollution.. The National Sustainable Development Plan for Resource-based Cities (2013-2020) proposes to promote the sustainable development of resource-based cities, accelerate the transformation and development of resource depleted cities, and promote the coordinated development of resource rich areas[4]. The Sustainable Development Goals Report-2023 indicates that the world continues to move towards sustainable energy goals, but the pace is not fast enough. At current rates, by 2030, approximately 660 million people will still have no access to electricity, and nearly 2 billion people will still rely on polluting fuels[5]. The Tracking SDG7: The Energy Progress Report also states that unless the pace accelerates, the share of renewable energy in the total final energy consumption (TFEC) will continue to be sluggish[6]. And among the various influencing factors on the transformation of resource-based cities, environmental factors have the most significant impact[7]. Therefore, exploring the coordinated development relationship between mineral resource development and ecological environment protection is of great significance for maintaining national energy and resource security, promoting new industrialization and urbanization, promoting social harmony and stability, national unity, and building a resource saving and environmentally friendly society.

Ⅱ. RESEARCH OBJECTS

As a source of basic energy and important raw materials, resource-based cities have made outstanding contributions to China's economic and social development. Large scale mineral mining requires a significant amount of resources, but at the same time, these mining activities often cause irreversible damage to the ecological environment. The technology and management level of mineral resource development are relatively lagging, and environmental awareness and technical means are insufficient. This has led to inadequate environmental protection measures during the mining process, resulting in environmental pollution and ecological damage.

Due to the complexity of mineral resource development and ecological environment protection systems, it is difficult to have a single indicator to measure their development level. Therefore, this article collects data from the following three aspects, involving mineral mining data, such as proven reserves of ore, annual mining output of ore, and employment in the mining industry; Environmental protection data, such as annual emissions of industrial wastewater, annual emissions of industrial carbon dioxide, annual emissions of industrial smoke and dust, harmless treatment rate of household waste, and centralized treatment rate of sewage treatment plants, urban statistical data, such as annual added value of mining industry, industrial annual added value, green coverage rate, etc. Among them, the proven reserves of ore mainly come from the official website of the city government or Baidu Baike; The annual mining output and industrial added value of the mining industry mainly come from the "Statistical Yearbook" and "Statistical Bulletin of National Economic and Social Development" of various cities; The number of employment in the mining industry, annual emissions of industrial wastewater, annual emissions of industrial carbon dioxide, annual emissions of industrial smoke and dust, harmless treatment rate of household waste, and centralized treatment rate of sewage treatment plants are mainly from the "China Urban Statistical Yearbook". The green coverage rate is mainly from the "Land and Resources Statistical Yearbook". A total of 27 cities from 2010 to 2020 were collected in the "National Economic and Social Development Statistical Bulletin" for a total of 11 years Statistical Yearbook, final calculation and statistics of 2970 indicator data.

III. RESEARCH METHODS

By combining multiple evaluation indicators or multi-dimensional evaluation indicators using a comprehensive evaluation model, each indicator is weighted and normalized to comprehensively evaluate different aspects of problems or objects. This article is based on the MREE theoretical model, starting from the two dimensions of mineral resource development efficiency and ecological environment protection quality, and constructing indicator systems to evaluate the level of mineral resource development and ecological environment protection in resource-based cities:

$$F_1 = \sum_{i=1}^{p} w_i x_i \quad (1)$$

$$F_2 = \sum_{j=1}^{q} w_j x_j \quad (2)$$

Where x_i and x_j represents the standardized values of mineral resource development efficiency and ecological environment protection quality, w_i and w_j is the weight of each indicator calculated using the entropy weight method based on standardized values.

A CCDM

The Traditional Coupled Coordination Model (CCDM) is a mathematical model used to study the interactions and coordination relationships between different subsystems within a system. It aims to optimize decisions for multiple related variables simultaneously by considering the interdependence and interaction effects between different subsystems. Liao Zhongbin first merged coupling and coordination degree into a coupling coordination degree model, determining the degree of coupling coordination within or between different systems, and further dividing the level of coupling coordination degree.

$$C = 2 \times \left[\frac{F_1 \cdot F_2}{(F_1+F_2)^2}\right]^{\frac{1}{2}} \quad (3)$$

$$T = \alpha \cdot F_1 + \beta \cdot F_2 \quad (4)$$

$$D = \sqrt{C \cdot T} \quad (5)$$

In the formula, C is the coupling degree, T is the coordination degree, D is the coupling co scheduling, and F_1 and F_2 represents the development level of the two systems, α and β Are the weights taken by the two systems respectively, and $\alpha + \beta = 1$. Usually assigned by scholars α and β 0.5 and 0.5 respectively; It can be seen that the coupling degree C, development degree T, and coordination degree D all depend only on the size of F_1 and F_2 which makes it difficult to consider the changing trend of the system in the time dimension.

For example, there is at a certain point in time $F_1' = F_1$ and $F_2' = F_2$, and F_1 and F_2 Both are showing a rapid upward trend, while F_1' and F_2' shows a rapid decline and decline trend, but the value of co scheduling D calculated by the CCDM is the same. Therefore, the comprehensive evaluation of the coordination degree of the two systems by this model is not comprehensive, and it is difficult to reflect the complex coordinated development situation. Based on the definition of coordination, coordinated development is a development aggregation that emphasizes holism, comprehensiveness, and internality. It is not a "growth" of a single system or element, but a comprehensive development under the beneficial constraints and regulations of multiple systems or elements in coordination.

B SCCDM

Steon first proposed the concept of the SDM model (Scissor Difference Model) to describe the price gap advantage between industrial and agricultural products[8], which is currently widely used in various economic, environmental and other studies to measure the differences in development trends between systems:

$$\alpha = arc\ cos \frac{1+V_{f_1} \cdot V_{f_2}}{\sqrt{\left(1+V_{f_1}^2\right)\left(1+V_{f_2}^2\right)}} (0 \le \alpha \le \pi) \quad (6)$$

Among them, f_1 and f_2 represents the development level of the two systems, V_{f_1} and V_{f_2} represents the development speed at time t, respectively, α Represent at time t that The angle of f_1 and f_2, which can reflect the difference in the development trends of the two systems at time t.

Li Chongming established a coordinated development evaluation model based on system science theory to analyze the evolution of small town resource environment system and socio-economic system[9], and established system evolution equations A and B, respectively, to represent the evolution states of the two subsystems affected by external factors:

$$A = \frac{df_1}{dt} = \alpha_1 \cdot f_1 + \alpha_2 \cdot f_2 \quad (7)$$

$$B = \frac{df_2}{dt} = \beta_1 \cdot f_1 + \beta_2 \cdot f_2 \quad (8)$$

Among them, f_1 and f_2 represents the development level of the two subsystems, α and β The coefficients of A and B affected by the two subsystems are and are calculated by calculating the evolution speed of the two systems V_A and V_B will analyze its coordination relationship and establish its development mechanism, such as: $\gamma = arc\ tan \frac{V_A}{V_B}$, γ The angle between the development of A and B reflects their degree of coordination.

Therefore, based on the traditional coupling coordination degree model and the concept of analyzing the coordination degree model between systems mentioned above, the development speed measurement system is introduced to measure the development trend at a certain moment. When analyzing the coordination development degree between systems, not only the development level between systems is considered, but also the sustainability of their coordinated development in the time dimension is considered, and the coordination degree between systems is comprehensively evaluated, Meet the requirements of coordinated development concept:

The model based on the coupling degree and development degree in the traditional coupling coordination degree model remains unchanged, as shown in equations (3) and (4). Additionally, f_1 and f_2. Perform nonlinear fitting and calculate the development speed V at different time t separately V_{f_1} and V_{f_2}:

$$C = e^{-\theta_1 \times \left(arc\cos \frac{1+V_{f_1} \cdot V_{f_2}}{\sqrt{\left(1+V_{f_1}^2\right)\left(1+V_{f_2}^2\right)}} \right)} \tag{9}$$

$$ST = e^{\theta_2 \times (\alpha \cdot V_{f_1} + \beta \cdot V_{f_2}) - \delta} \tag{10}$$

$$SD = \sqrt[4]{C \cdot T \cdot SC \cdot ST} \tag{11}$$

In the formula, SC represents the sustainable coupling degree, ST represents the sustainable development degree, and SD represents the sustainable coupling co scheduling, θ_1 and θ_2 are the adjustment coefficients for SC and ST, respectively. The purpose is to use the exponential function $f(x) = e^x$ to normalize the angle value, which can reasonably regulate the size of the value. Moreover, both SC and ST use the exponential function to eliminate dimensional inconsistency, making the evaluation results comparable and ensuring the rationality of SD value calculation. Among them, $arc\cos \frac{1+V_{f_1} \cdot V_{f_2}}{\sqrt{\left(1+V_{f_1}^2\right)\left(1+V_{f_2}^2\right)}} \in [0, \pi]$, $\theta_1 \in [0, +\infty)$, so $SC \in [0,1]$, due to $V_{f_1}, V_{f_2} \in (-\infty, +\infty)$, by assigning values θ_2 and δ Ensure $ST \in [0,1]$, and $\theta_2, \delta \in [0, +\infty)$, therefore the sustainable coupling coordination degree $SD \in [0,1]$.

Ⅳ. RESULT AND ANALYSIS

A Model parameter analysis

In the sustainable coupling coordination model constructed in this study, there are two adjustment parameters θ_1 and θ_2. Capable of controlling the fluctuation range and data distribution of SC and ST to a certain extent, without affecting the overall data development trend, and adjusting parameters reasonably θ_1 and θ_2 Able to highlight data features without distortion. In Figure 1, it represents different adjustment parameters θ_1 and θ_2 The distribution of data at value, showing the central trend and degree of dispersion of the data, and comparing the fluctuation of its development trend, $\theta_1 = 1$ and $\theta_2 = 1$, the data distribution is very concentrated, the development trend is not obvious, and the average value is almost at the same level; When $\theta_1 = 25$ and $\theta_2 = 25$, the data distribution is very discrete, with significant fluctuations, but significant data distortion; $\theta_1 = 5$ and $\theta_2 = 5$, the data distribution is reasonable and the development trend is obvious. Therefore, this study adopts $\theta_1 = 5$ and $\theta_2 = 5$ reflects the sustainable development level of mineral resource development efficiency and ecological environment protection quality, and to ensure $SD \in [0,1]$ $\delta = \sqrt{2}$ Translate the data to a value greater than 0. In summary, although adjusting the parameters θ_1 and θ_2 has a significant impact on the degree of data dispersion and size, but its development trend is almost consistent. Therefore, only reasonable adjustment parameters need to be used to express data features while ensuring that the data is not distorted.

At the same time, it was found that the data of 2010 and 2020 had a high degree of dispersion and volatility. The reason for this is that the polynomial fitting method was used to calculate the curvature of mineral resource development efficiency and the curvature of ecological environment protection quality, which resulted in a large or small fitting curvature at the endpoints, resulting in data distortion during this period. Therefore, in subsequent research, this article only analyzes the sustainable coupling coordination degree from 2011 to 2019, To ensure the accuracy of the analysis results.

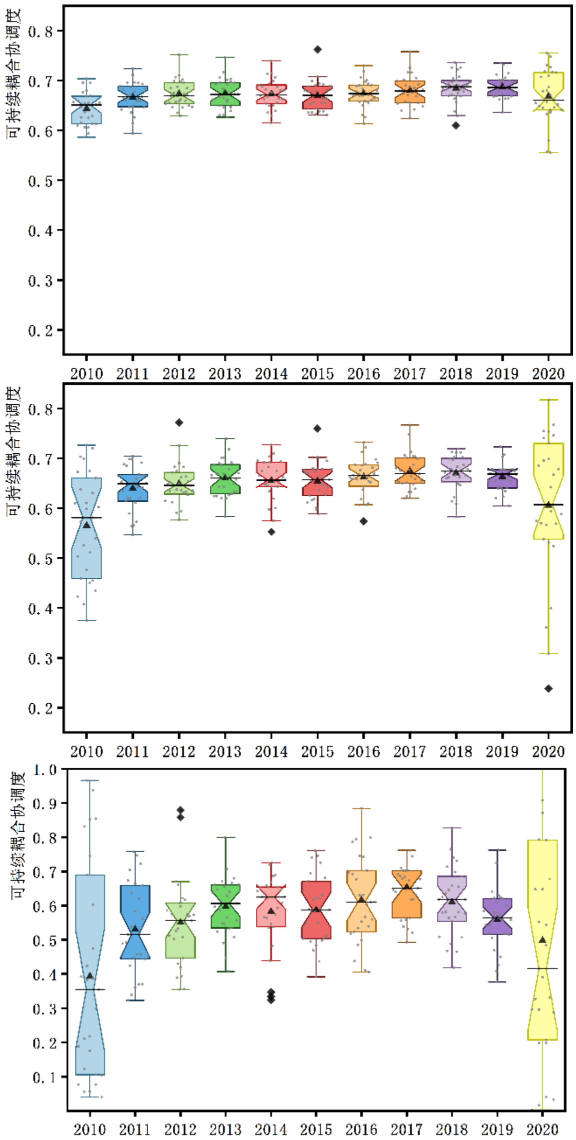


Fig.1 *Data distribution of sustainable coupling coordination between mineral resource development and ecological environment protection in resource-based cities, 2010-2020*

B Comparative analysis between two models

Using data from Hechi City for statistical analysis, we first obtain information on various indicators based on its basic data, and then calculate the efficiency of mineral resource development and the level of ecological environment protection quality development from 2010 to 2020. We use nonlinear fitting methods (this study uses multiple functions to ultimately select polynomials for fitting) to obtain the fitting curve equation and fitting curve rate, and obtain F_1、F_2、V_{F_1} and V_{F_2}, the results were calculated using the CCDM and the SCCDM, respectively:

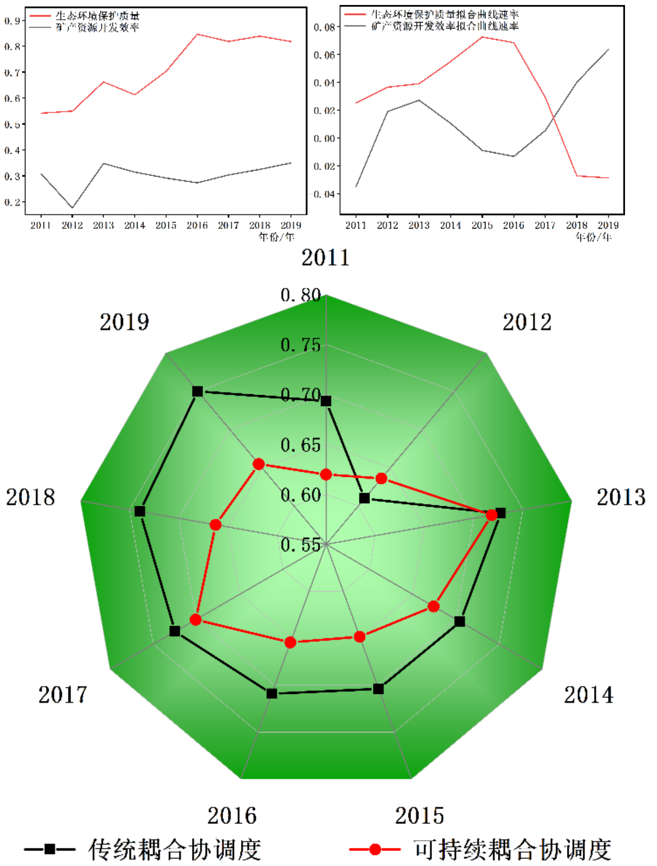
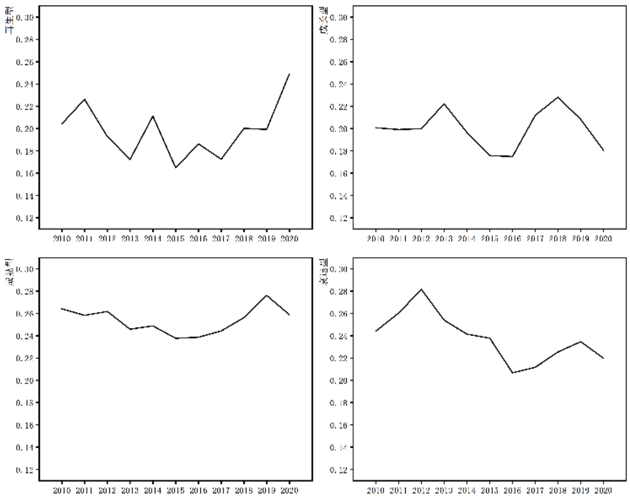


Fig.2 *Comparative analysis of two coordination models for mineral resource development and ecological environment protection in resource-based cities, 2011-2019*

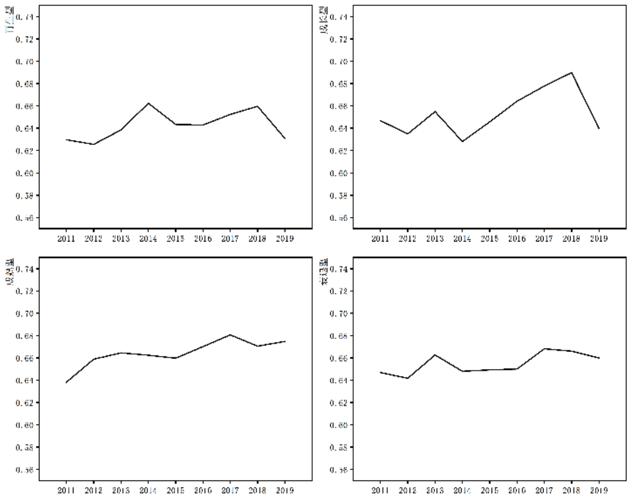
Compared with the CCDM and the SCCDM, the former has a significantly higher overall value than the latter. This is because the trend of changes in mineral resource development efficiency and ecological environment protection quality from 2011 to 2019 is not significant, resulting in a smaller fitting curvature. Although the overall coordinated development trend of the two is the same, it is quite different in some years. The traditional coupling coordination degree shows a trend of first decreasing and then continuously increasing, and dropped to its lowest point in 2012. This is mainly due to the cliff like decline in mineral resource development efficiency from 2011 to 2012, while the sustainable coupling coordination degree shows a fluctuating upward trend. The reason for this is that in 2011, the decline in mineral resource development efficiency was more obvious, As a result, its sustainable development degree ST is relatively low, while in 2012, both showed a warming trend with a positive fitting rate, resulting in only a gradual upward trend. In 2017, the sustainable coupling coordination degree reached its highest value. On the one hand, the development efficiency of mineral resources and the quality of ecological environment protection were relatively high, and on the other hand, the development trend of both was the same, with equal fitting curvature, resulting in a higher sustainable coupling degree SC; The downward trend from 2018 to 2019 is due to fluctuations in the quality of ecological environment protection, resulting in a negative fitting curvature, resulting in a lower degree of sustainable coupling and sustainable development. Overall, the sustainable coupling coordination degree is more objective and comprehensive in reflecting the coordination relationship between the two, not only reflecting their development level relationship, but also reflecting the coordination relationship of their future development trends. It is more sensitive to subtle changes in the two and can reflect more comprehensive and accurate information about the coordination relationship between the two to readers.

C Analysis of different types of features

Based on the comprehensive classification of resource-based cities in the National Plan for Sustainable Development of Resource-based Cities (2013-2020), which includes regenerative cities, growth cities, mature cities, and declining cities, this study analyzes the mineral resource development efficiency and sustainable coupling coordination degree of 27 different types of resource-based cities based on the differences in resource guarantee capacity and sustainable development capacity. From the development trend of mineral resource development efficiency in different types of cities, it can be seen that it is basically in line with the judgment of the planning on the development direction of each city from 2013 to 2020. The overall development level of regenerative and growth cities is relatively low, while the overall development level of mature and declining cities is relatively high. Moreover, the overall development trend of regenerative cities is decreasing first and then increasing, indicating that they will basically break away from resource dependence and enter a benign development stage from 2014 to 2015; Growth oriented cities have shown a fluctuating upward trend, with a relatively low development level from 2015 to 2016, but maintaining high-speed development from 2017 to 2019, indicating their great potential for resource security; Mature cities tend to be in a high-level development stage as a whole, with relatively flat fluctuations; Declining cities have shown an overall downward trend, reaching a peak in 2012 and continuing to decline, with their resources tending to be estimated and overall development lagging behind; And it is easy to find that all four resource-based cities have reached a turning point of decline before and after 2015. In "China's Mineral Resources Including 2015", it is also proposed that China's mining development has entered a period of adjustment. The Chinese government promotes the transformation and upgrading of mining by strengthening mineral resource exploration, improving the level of mineral resource conservation and comprehensive utilization. The trend of sustainable coupling and coordinated development in different types of cities shows that all four types of cities are showing an upward trend. Among them, regenerative cities show fluctuating growth, growth cities have the fastest and most fluctuating growth rate, mature cities continue to grow and are relatively flat, and declining cities have the slowest and lowest growth value. This is mainly due to the steady improvement of ecological environment protection quality, indicating the smooth transformation of China's mining development.



(a) Development of Mineral Resources in Different Types of Cities



(b) Sustainable coupling and coordination of different types of cities

Fig.3 *Analysis of the characteristics of different coordination types in resource-based cities, 2010-2020*

D Aggregation Analysis of Eight Major Economic Zones

The Development Research Center of the State Council issued a report stating that the method of dividing the East, Central, and West regions followed by China is no longer appropriate. To this end, the report proposes the specific concept of dividing the mainland into four major sectors during the 11th Five Year Plan period: the eastern, central, western, and northeastern regions, and dividing the four sectors into eight comprehensive economic zones: the northern coastal comprehensive economic zone, the northeastern comprehensive economic zone, the eastern coastal comprehensive economic zone, the middle reaches of the Yellow River comprehensive economic zone, the southern coastal comprehensive economic zone, and the northwest comprehensive economic zone Southwest Comprehensive Economic Zone and Middle Yangtze River Comprehensive Economic Zone. By mapping the coordinated development of 27 resource-based cities in various comprehensive economic zones, this article further presents the sustainable coupling and coordinated development differences between mineral resource development efficiency and ecological environment protection quality in various regions of the country. Overall, the sustainable coupling and coordinated development situation in various regions has little fluctuation, with fluctuations ranging from 0.6 to 0.7. Overall, there is an upward trend in the time dimension, with only the Eastern Coastal Comprehensive Economic Zone and the Northeast Comprehensive Economic Zone showing a downward trend. Due to rapid economic development, especially in the manufacturing and internet industries, the development of mining in the Eastern Coastal Area is also due to resources, environment Policies and other reasons gradually withdrew from the stage; However, most resource-based cities in Northeast China are gradually entering the stage of middle-aged and elderly development, facing problems such as resource scarcity, high ecological pressure, and talent loss, leading to a decline in their sustainable development coupling coordination; In other regions, especially the southern coastal and southwestern regions, the degree of sustainable coupling and coordinated development steadily increased between 2011 and 2019. On the one hand, with the development of technology and the improvement of personnel quality, the efficiency of mineral resource development has been improved to a certain extent; On the other hand, the concept of protecting the environment and ecology is being promoted nationwide, and the environmental quality of various cities is steadily improving.

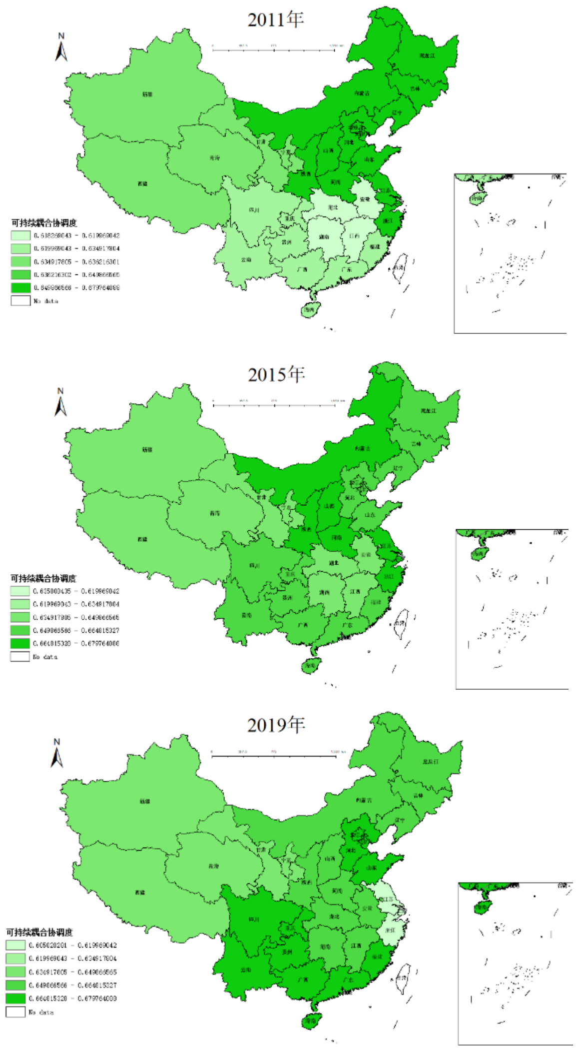


Fig.4 *Characteristics of Sustainable Coupling Coordination Degree in the Eight Comprehensive Economic Zones, 2011-2019*

Ⅴ. DISCUSS

Coordination is a benign interrelationship between two or more systems or system elements, which is a well coordinated, harmonious, and virtuous cycle relationship between systems or within system elements[10]. Since China proposed the "Sustainable Development Strategy" in the 1980s, the concept of sustainable development has been deeply rooted in people's hearts. Therefore, when evaluating and analyzing the coordination of two systems, it is also necessary to consider the sustainability of coordination, The new coordination should be a relationship between the system or its elements that is well coordinated, harmonious, consistent, virtuous, and mutually beneficial for a long time. This article establishes a SCCDM for the two systems of mineral development and ecological protection. Based on the fitted curve of the system development level, the sustainable coupling degree and sustainable development degree are proposed to comprehensively evaluate the sustainable coordination level of the two systems. This not only analyzes the coordination under the current development level, but also takes into account the coordination of the future development trends of the two systems. Taking the data from Hechi City from 2010 to 2020 as an example, compared with the CCDM, the SCCDM reflects the coordination relationship between the two systems more objectively and comprehensively, is more sensitive to the coordination relationship between the two systems, and is more effective and in line with the actual expression of sustainable coordination level.

This article takes 27 resource-based cities as the research object, involving mineral resources such as aluminum, iron, zinc, non-ferrous metals, coal, natural gas, and oil. The SCCDM is used to analyze the coordinated development characteristics of these cities from 2011 to 2019. The conclusions are as follows: 1. The coordinated development efficiency of mineral resources and ecological environment protection quality in various resource-based cities from 2011 to 2019 were good. The average sustainable development coordination degree of each city is greater than 0.6. From a time perspective, the overall trend shows an upward trend, reaching peaks of 0.660 and 0.675 in 2013 and 2017, respectively. It slightly decreased from 2013 to 2015, with a decrease of 0.88%. 2. The development of mineral resources in different types of resource-based cities basically met their development trends from 2010 to 2020, and the sustainable and coordinated development of different types of resource-based cities showed an upward trend from 2011 to 2019. The mining of mineral resources in regenerative cities first decreased and then increased, while sustainable coordination continued to rise, reaching its peak in 2014; The growth rate of mineral mining in growing cities is relatively small and showed a significant downward trend from 2014 to 2015, but the sustainable coordinated increase is significant; Mature cities maintain a high level of mineral exploitation while maintaining sustainable, coordinated and steady growth; Mineral mining in declining cities is showing a downward trend, but sustainable coordination is relatively stable. 3. Mapping the sustainable and coordinated development of the eight major comprehensive economic zones with resource-based cities across the country, the differences in coordinated development between different regions are not significant, and the overall trend is becoming increasingly coordinated. The growth in the southern coastal comprehensive economic zone and the southwestern comprehensive economic zone was more significant, while the decline in the northeast comprehensive economic zone and the eastern coastal comprehensive economic zone was prominent. However, the overall sustainable coordination range still fluctuated between 0.605 and 0.694.

Sustainable development is still the top priority of China's development, and the coordination relationship between mineral resource development and ecological environment protection plays an important role. The research on the coordination relationship between the two is still in the initial stage. Although this article is based on the MREE theory and combined with the CCDM, a SCCDM has been established, which can provide reference for further analysis of coordination relationships and development laws, But there are also many areas that need improvement. For example, selecting the fitting function for the development level of subsystems, selecting appropriate methods to calculate the parameters of the SCCDM, calculating the sustainable coupling coordination degree between multiple subsystems, and using more resource-based city data for calculation and verification will all provide value for this research.

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