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Study on coupling between mineral resources exploitation and the mining ecological environment in Shanxi Province

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Abstract

Due to rapid socioeconomic development, seeking the coordination of resources exploitation and the ecological environment has become an objective requirement for the healthy and sustainable development of the mining industry. This paper selects 23 indicators with which to construct an evaluation index system for mineral resources exploitation and the mining geological ecological environment of Shanxi Province from 2003 to 2015. It then establishes a development index model, a coupling degree model and a coupling coordination degree model. Using a time-series analysis, the comprehensive development level, coupling status and coupling coordination degree of the two systems are analyzed. The results are threefold. (1) The overall level of mineral resources exploitation improved, but, after 2012, the level dropped significantly. The ecological environment in the mining area has improved as a whole, but, due to the ecological fragility caused by long-term extensive mining and acute treatment, the state of the ecological environment fluctuates greatly. (2) The coupling degree between mineral resources exploitation and the mining ecological environment is stable, and it has been in the antagonistic stage for a long time. Although the degree of coupling coordination has improved, it remains at a low level. (3) Further improvement in the coordination between mining exploitation and the mining ecological environment in Shanxi Province has been restricted due to several indicators with greater weights. Recommendations to be considered by policy makers include insufficient sustainable development concepts, outstanding historical issues and the lack of guarantees for environmental protection funds.

Keywords Mineral resources exploitation · Mining ecological environment · Coupling coordination degree model · Shanxi Province

1 Introduction

Mineral resources are the basis for human production and living materials. Positively and beneficially, mining activities can provide opportunities for economic growth, poverty reduction and increased integration with the global economy (Yang et al. 2019;

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Lagos and Edgar 2010; Hajkowicz et al. 2011). In contrast, because the economy is increasing, the contradiction continues to intensify between resource development and the ecological environment. Unreasonable resource development is bound to have a negative impact on the ecological environment. The mining industry in China, particularly coal mining, is regarded as a driving force of the nation's economy (Yang et al. 2019), and it has pros and cons, especially in regional areas (Ge and Lei 2013; Lei et al. 2013). Conversely, others have pointed to environmental problems, such as wastewater, air pollution, hydrological disturbance and waste rock or waste residue (Bian et al. 2010). In the process of realizing regional sustainable development, we must consider the coordinated development of resources exploitation and the ecological environment while meeting the needs of both social and economic development.

At present, the researches on coupling relationships mainly focus on the ecological environment in combination with urbanization (Liu et al. 2018a; Wang et al. 2019; Cui et al. 2019; Hou et al. 2019), the economy (society) (Fan et al. 2019; Fischer et al. 2015; Guan et al. 2011) and the sustainable development of resources (Fang et al. 2019; Xing et al. 2019a, b; Xie et al. 2016). Li et al. (2012) constructed an evaluation index system for the urbanization level that included demographic, economic, social and spatial urbanization as well as an environmental index system that included environmental pressure, level and control. A coupling coordination degree model between urbanization and the environment was established based on panel data. Gu and Wang (2018) constructed a coupling degree model of economic development and the ecological environment in northeast China based on the gray correlation degree, revealed the spatiotemporal evolutionary law of regional coupling relations and predicted future development. Liu et al. (2018b) adopted the water ecological footprint model to analyze the evolutionary law of the water ecological footprint from 2006 to 2015. A coupling and coordination index system for water ecological sustainability was formed by including water resources, society, the economy and the ecological environment system, and an evaluation model of water ecological sustainability was further constructed. Based on the life-cycle theory of the mining area, Cui et al. (2018) constructed a coupling model for benefit systems based on the analysis of the coupling mechanism of land use socioeconomic benefits and ecological benefits to judge effectively the coordination and sustainability of land use in mining areas. Yan et al. (2015) adopted a qualitative research method to study systematically and comprehensively the impact of mineral resources development on the ecological environment in accordance with the three dimensions of mineral species, time and space to put forward the concept of mining transformation and upgrading from the system, technology and participation perspectives. Wang et al. (2017a, b) used a subjective and objective weighting method, a comprehensive evaluation method and a coupling coordination model to evaluate the coupling coordination degree of resources and the environmental carrying capacity in a mining economic zone in China, while summarizing the existing problems and proposed countermeasures. Liang (2009) explored the feedback mechanism of ecosystems on mineral resources exploitation based on an in-depth analysis of the impact of mineral resources exploitation on ecosystems and proposed further policy recommendations. In particular, the research scope and scale are also the focus of scholars in the field of coupling between mining and the ecological environment. Yang et al. (2019) presented the social, economic and environmental impact of mining at the (rural) community level in China based on the four indicators of employment opportunities, environmental pollution, land expropriation and land subsidence as well as associated resettlement, which provide a critical contribution to the impact of mining on the perspective of rural China. Moreover, large-scale underground mining and surface ecological environment protection in arid regions (Liu et al. 2019a; Zhang et al. 2009) or frail ecological areas (Yang et al. 2018) is a research and development focus.

Since 1992, China has made sustainable development a state policy. However, environmental pollution and ecological degradation remain serious problems in China, causing great damage to the economy and to production activities (Zhang and Wen 2008). Traditional mining is in a resource waste and economical extensive development mode that ignores the coordination between resources, social development and environmental construction. This situation results in the lack of an effective use of resources and a huge cost to the ecological environment. The direct result is that resources cannot be utilized effectively, and the cost of ecological environmental management is high. Sustainable development goals require sustainable and healthy mining development models. Mining cities have their own advantages in resources, technology and industry that help them face the obstacles of resources, the poor stability of the economic system, the fragile ecosystem and other problems. These advantages help the cities ensure they achieve sustainable development by employing a proper mining mode transformation strategy and strengthening ecological coupling. Based on the concept of ecological civilization and sustainable development, scholars have also analyzed the changing trend and evolutionary path of ecological environment coupled with social and economic development. Among them, Zhang and Wen (2008) identified how to coordinate the relationship better between the environment and the economy by examining the experience of China's environmental policies to improve the sustainability of industrial development, resources and the environment. Sauvé et al. (2016) examined the conceptual connotation and connection between environmental science and sustainable development from the perspective of the circular economy to deal with environmental challenges more generally. In particular, the circular economy proposes environmental sustainability. Chen et al. (2016) analyzed social sustainable development and the pathway toward low carbon transition from the perspective of a climate change scenario and an energy system to lay a technological foundation for sustainable resources, the economy and ecology. Xu (2015) took as his perspective the construction of ecological civilization, and his goal was the sustainable utilization of mineral resources. Then, he studied the contradiction between mineral resources exploitation and ecological environmental protection and its causes. Finally, he put forward countermeasures for changing the concept of economic development and optimizing the government management system of mineral resources exploitation.

Research on the coordinated development of coupling mainly focuses on the coupled coordination evaluation model and empirical research. Firstly, based on system theory, a system dynamics (SD) model is established to analyze the coupling relationship between the systems. Zuo et al. (2014) combined the "water quantity-water quality-ecology" model with the "socioeconomic" model to establish a dynamic model of the coupled system. Based on the principle of SD, Xing et al. (2019a, b) established a dynamic model called the economy, resources and the environment (ERE) system. In addition, they established a coupling coordination degree model with ERE system coordination as the core and simulated four classical scenes—current, the economy, resources and the environment—through an SD model. Secondly, a benefit index or a data-envelopment analysis (DEA) model measurement is developed based on input–output thinking, energy input and value output to reflect the coupling relationship between systems, such as using an input–output model. Bastianoni et al. (2016) used the general input-status-output model to express the relationship and dynamics among the environment, the society and the economy (ESE). The integrated ESE development indices of the world's major countries were calculated using different time-series indicators, and the coordinated development degree of ESE was further assessed. Xu and Wu (2010) used the DEA method to study the comprehensive efficiency and influencing factors of the coordinated development level of various regions in China under environmental constraints. Thirdly, an econometric model has been used to analyze the coupling relationship between the systems. Usually, the coupling coordination degree model is the main coupling evaluation method used. Tretyakova (2014) used Russia as the research object and applied the coupled dynamic method to analyze the coordinated development between Russia's resource, economic and environmental systems from 1995 to 2012. We combine the above three different types of evaluation methods. In the coupling coordination degree model used in econometrics, the relative change speed of the system is usually expressed in the form of differential equations, and the degree of coordination is defined by the deviation between the development speed of each subsystem and the overall development speed of the system. This method can more accurately reflect the true connotation of system coordination and ensure the scientific nature and accuracy of the system-coordination analysis. In addition, the model is a dynamic evaluation model based on time parameters, which is suitable for the comparison of systematic evaluations in different periods.

Considering these limitations, to fill the research gaps, this paper specifically analyzed coupling between mining exploitation and ecological environmental development at the regional perspective (Shanxi Province of China), applying a time-series analysis, the comprehensive development level, the coupling status and the coupling coordination degree of the two systems based on 23 indicators from 2003 to 2015. The term "ecological environment" in this paper refers to the geological and ecological environments of mining areas, while the mining industry in Shanxi Province is dominated by coal, so the mining area usually refers to the surface mining area (the geological environment caused by a surface coal mine is more serious than that by an underground coal mine). Based on the concepts of ecological civilization and sustainable development, this paper further analyzes the reasons for the improvement in the coordination degree. It also provides suggestions for policy makers to improve the coordinated development level of mineral resources development and the ecological environment in mining areas. Doing so provides a path for operation specification for mining activities, orderly development for economic construction and sustainable metabolism for the ecological environment.

The remainder of this paper is organized as follows: Sect. 2 introduces the basic situation of Shanxi Province. Section 3 presents the development index model and the evaluation model, which include both the coupling degree model and the coupling coordination degree model, as well as data sources. Section 4 describes the empirical analysis and results. The conclusions and policy recommendations are summarized in Sect. 5.

2 Study area and background

Shanxi Province, located between the middle reaches of the Yellow River Valley and Taihang Mountain, is part of the Loess Plateau in China. According to the Shanxi Statistical Yearbook (Shanxi Bureau of Statistics 2017), the province covers 156,700 square kilometers, accounting for 1.6% of China's area. This province has 11 prefecture-level cities and 118 county-level administrative units, with a permanent residential population of 37.0235 million. In the past five years, among the 11 prefecture-level cities, the mining production of *Shuozhou* has been 19.57 million tons, ranking first in Shanxi Province.

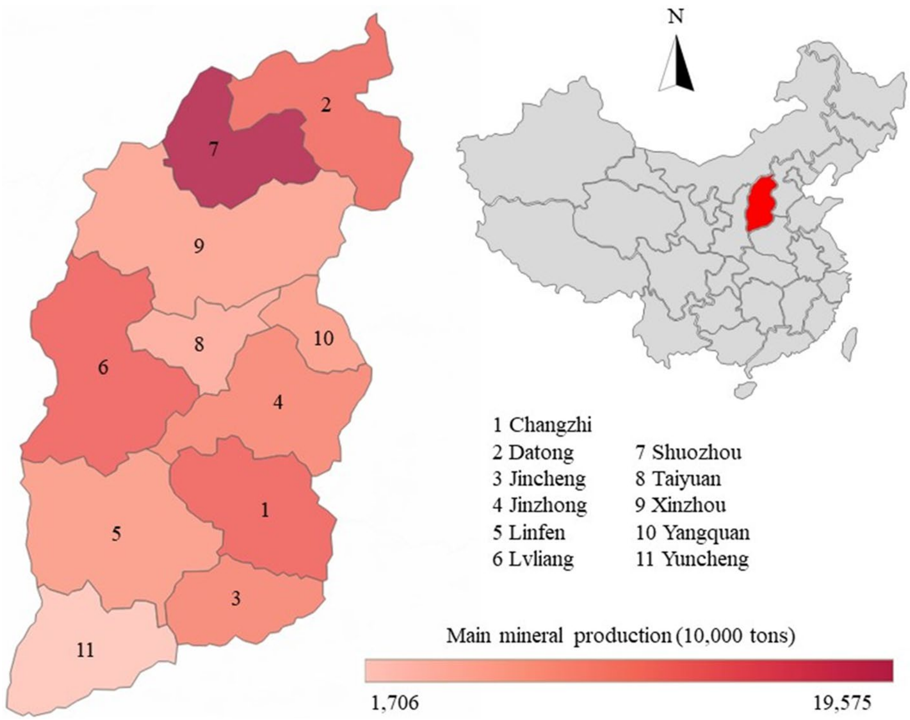

Fig.1 Location and distribution of mining production in Shanxi Province in China

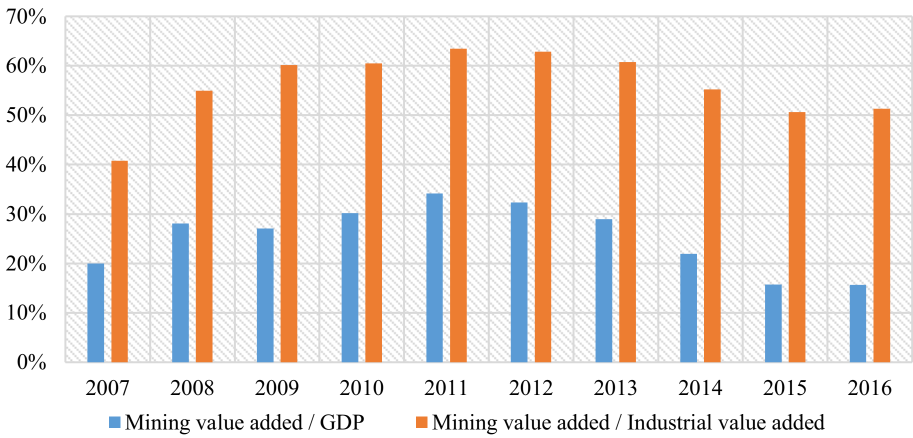

Fig.2 Proportion of mining value added to GDP and industrial value added in Shanxi Province

Mining output in *Shuozhou*, *Luliang*, *Changzhi* and *Datong* exceeded the provincial average of 89.62 million tons. *Yuncheng* produced the least at 17.061 million tons (Fig. 1).

According to the China Land and Resources Statistical Yearbook (Ministry of Natural Resources of the People's Republic of China 2016), as shown in Fig. 2, in the past ten years, the value added of the mining industry in Shanxi Province accounted for 56.05% of industrial value added. At its highest, it was 63.44%. Moreover, the province's mining industry accounted for 25.04% of the province's GDP, and, at its highest, it was 34.2%. Mining employment has accounted for more than 30% of industrial employment for a long time; however, mining employment began to decline in 2016 (see Fig. 3). Therefore, the mineral resources industry in Shanxi Province holds an important position in the national economic system.

On the one hand, Shanxi Province has continuously strengthened the construction of the national new comprehensive energy base, accelerated the pace of transformation and upgrading, made the industrial structure more reasonable, and gained strong momentum in subsequent development. On the other hand, mining has caused damage to the ecological environment in the process of promoting social economic development. The problem of the mine geological environments in Shanxi Province has become increasingly prominent, and the ecological carrying capacity has gradually declined.

Overall, seeking coordinated development between the exploitation of mineral resources and the ecological environment of the mining area has become an objective requirement for the healthy and sustainable development of the mining industry in Shanxi Province. Therefore, based on sustainable development theory, this study uses the coupling coordination degree model to explore the coupling relationship and the coordination degree between mineral resources exploitation and the mining ecological environment in Shanxi Province, laying an important foundation for the comprehensive, coordinated and sustainable economic increase and the ecological environment.

3 Methods and data sources

3.1 Data sources

This paper uses statistical data on Shanxi Province from 2003 to 2015 for an analysis and the research. The data were obtained from the China Land and Resources Statistical Yearbook (Ministry of Natural Resources of the People's Republic of China 2016), the Shanxi

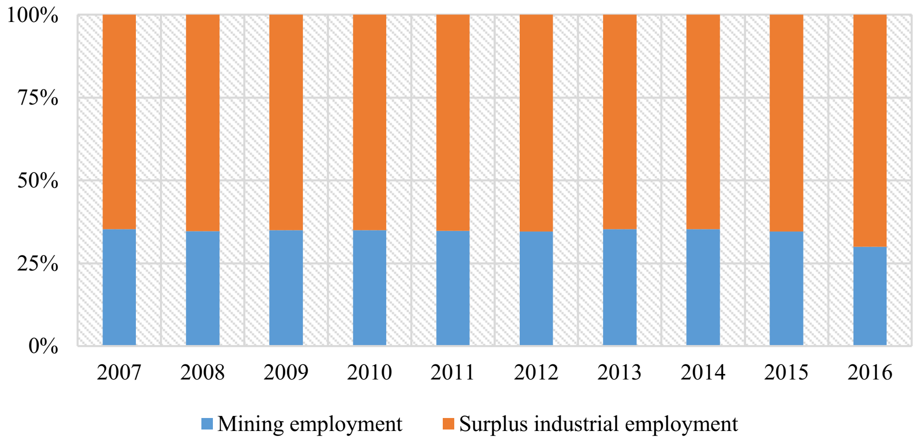

Fig.3 Proportion of mining employment to industrial employment in Shanxi Province

Statistical Yearbook (Shanxi Bureau of Statistics 2016) and the China Statistical Yearbook on the Environment (National Bureau of Statistics and Ministry of Environmental Protection 2016). In accordance with the indicator system, X_1–X_5 and Y_{11}–Y_{14} data were obtained from the China Land and Resources Statistical Yearbook, X_6–X_9 data were obtained from the Shanxi Statistical Yearbook, and Y_1–Y_{10} data were obtained from the China Statistical Yearbook on the Environment.

3.2 Index system

The coupling between the mineral resource development system (*M*) and the mining ecological environmental system (*E*) in Shanxi Province is an objective state in which the elements of the system promote and restrict each other. The development of mineral resources is inseparable from the support of the ecological environment of a good mining area. At the same time, the economic benefits generated by the moderate exploitation of mineral resources can promote the healthy development of the ecological environment of the mining area. However, excessive exploitation will damage the limited supply capacity of the ecological environment and the ability to resist external interference. The ecological environmental system will restrict the development of mineral resources through environmental pollution, ecological damage and natural disasters. In this study, mineral resources exploitation and the mining ecological environment in Shanxi Province are considered as two coupling systems. The evolutionary process, coupling state and coordination degree of the two systems are evaluated through a time-series analysis.

3.2.1 Index selection

The mining development system and the ecological environmental system for a mining area are regarded as the index system. Mining resources exploitation is an important way to promote the sustainable development of the regional economy, mainly from the aspects of the mining economy, employees and industrial benefits. However, mining activities always damage the ecological environment to some extent, resulting in the overall imbalance of coupling and coordination. Firstly, environmental degradation is used to assess the environmental impact caused by mining practices, i.e., the severity of exhaust, wastewater and solid waste (Yang et al. 2019). Secondly, land occupation is used to assess the loss of land caused by mineral exploitation and the recovery effect against the loss (Yang et al. 2019).

Therefore, we refer to the understanding of indicators in Yang et al. (2019). Moreover, we base our work on sustainable development theory and follow systematic, scientific, comprehensive and typical principles (Yao and Xiao 2015). We use these methods to create an index system for the coordinated development of mineral resources exploitation and the mining ecological environment. This index system considers the actual characteristics of Shanxi Province (Wang and Zou 2015; Ma and Yue 2018) and is shown in Table 1.

3.2.2 Weight determination

The entropy method is used to calculate the weight of each index (Wu and Zhang 2008). First, each index is standardized, and then, the information entropy is obtained. Finally, the weight of each index is calculated according to the information entropy. When the information entropy of the index is lower, the index varies more, and its weight is greater, and vice versa.

Table 1 Index system of the coordinated development of mineral resources exploitation and the mining ecological environment

System	Specific indicator	Indicator direction	Unit	Weight
Mineral resources exploitation system	X_1 Mining production	Positive	Ten thousand tons	0.1540
	X_2 Total mining output value	Positive	Ten thousand yuan	0.0825
	X_3 Comprehensive utilization value	Positive	Ten thousand yuan	0.0774
	X_4 Mining enterprises	Positive	Number	0.1545
	X_5 Mining employees	Positive	Person	0.1614
	X_6 Average annual salary of on-the-job workers	Positive	Yuan	0.1151
	X_7 Total mining profits and taxes	Positive	Ten thousand yuan	0.0490
	X_8 Total investment in mining fixed assets	Positive	Ten thousand yuan	0.0715
	X_9 Mining output value as a share of GDP	Positive	%	0.1346
Mining ecological environment system	Y_1 Total discharge of mining wastewater	Negative	Ten thousand tons	0.0275
	Y_2 Mining wastewater treatment capacity	Positive	Ten thousand tons	0.0385
	Y_3 Wastewater treatment facilities	Positive	Set	0.0270
	Y_4 Total emissions of mining waste	Negative	Billion cubic meters	0.0477
	Y_5 Total sulfur dioxide emissions from mining	Negative	Ten thousand tons	0.0248
	Y_6 Mining smoke and dust emissions	Negative	Ten thousand tons	0.0311
	Y_7 Exhaust gas treatment facilities	Positive	Set	0.0386
	Y_8 Mining solid waste production	Negative	Ten thousand tons	0.0532
	Y_9 Solid waste comprehensive utilization	Positive	Ten thousand tons	0.0709
	Y_{10} Pollution control project completed investment	Positive	Ten thousand yuan	0.0530
	Y_{11} Occupied or damaged land area this year	Negative	Hectare	0.2053
	Y_{12} Capital investment in restoration of the mine environment	Positive	Ten thousand yuan	0.1501
	Y_{13} Mines restored and controlled this year	Positive	Number	0.1501
	Y_{14} Mine recovery area this year	Positive	Hectare	0.0822

Since the selected indicators have different sources, the units and orders of magnitude are different. To facilitate a comparison between the indicators, they are standardized.

Positive index: $X^{+} = \frac{X_{ij}-X_{\min}}{X_{\max}-X_{\min}}$; Negative index: $X^{-} = \frac{X_{\max}-X_{ij}}{X_{\max}-X_{\min}}$where X^{+} and X^{-} are the normalized values of the indexes, x_j is the actual value of the index, $x_{\max}$ is the maximum value of the index, and $x_{\min}$ is the minimum value of the index.

First, we calculate the proportion of the *i*-th evaluation object in the index under the *j*-th indicator through formula (1), that is, the contribution rate of the indicator.

$$y_{\mathrm{ij}}=\frac{x'_{\mathrm{ij}}}{\sum_{i=1}^{\mathrm{m}} x'_{\mathrm{ij}}}(0 \le y_{\mathrm{ij}} \le 1) \tag{1}$$

Then, we calculate entropy of information e_j through formula (2).

$$e_j = -\frac{1}{\ln m}\sum_{i=1}^{m} y_{ij}\ln y_{ij} \tag{2}$$

The weight of the *j*th index is denoted as w_j, and the weight of each evaluation index is calculated by formula (3).

$$w_j = \frac{1-e_j}{\sum_{j=1}^{\mathrm{n}} 1-e_j}(j = 1, 2, \dots, n) \tag{3}$$

3.3 Model construction

The coupling relationship refers to the dynamic association between two or more systems through interaction; the systems affect each other and eventually synergize. The coupling degree is used to measure the degree of synergy between the internal order parameters in the process of the system from disorder to order.

Therefore, this paper defines the degree of interaction and mutual influence between the two systems (mineral resources exploitation and the mining ecological environment) as the coupling degree of the "mineral resources exploitation and the mining ecological environment" systems through their coupling factors.

3.3.1 Development index model

Before calculating the coupling coordination, the comprehensive evaluation method is used to calculate the comprehensive index of each system (Wang et al. 2017a, b). To clarify the relationship between mineral resources exploitation and the ecological environment of the mining area, the system development index model is established through causality to analyze the state of the system (Xiong et al. 2015).

The two systems are both nonlinear, and the evolutionary equation is:

$$\frac{\mathrm{d}x(t)}{\mathrm{dt}} = f(x_i), \quad i = 1, 2, \dots, n \tag{4}$$

where x_i is the system influence factor and f is the nonlinear function of x_i.

According to Lyapunov's first method, the motion stability of a nonlinear system depends on the properties of the eigenvalues of the first approximation system, and the higher-order term X_i can be omitted to ensure the stability of the motion. Therefore, Eq. (4) can be expressed as an approximate linear system:

$$\frac{\mathrm{d}x(t)}{\mathrm{d}t} = \sum_{i=1}^{n} a_i x_i \quad i = 1, 2, \dots, n \tag{5}$$

Therefore, the development index model of the mineral resources exploitation system (M) and the mining ecological environment system (E) is established:

$$f(M) = \sum_{i=1}^{n} a_i x_i \quad i = 1, 2, \dots, n \tag{6}$$

$$f(E) = \sum_{i=1}^{n} b_i y_i \quad i = 1, 2, \dots, n \tag{7}$$

where x_i and y_i are components of the two systems, and a_i and b_i are the weights of each element.

3.3.2 Coupling degree model

Referring to the concept of capacity coupling and the coefficient model in physics, the coupling degree model of multi-system interaction can be generalized (Liu et al. 2005), namely:

$$C_{\mathrm{n}} = \left\{ \left(u_1, u_2, \dots, u_{\mathrm{m}}\right) / \left[\prod \left(u_i + u_j\right) \right] \right\}^{1/\mathrm{n}} \tag{8}$$

According to formula (8), the coupling degree model is established of the mineral resources development and the mining ecological environmental development systems in Shanxi Province:

$$\mathrm{C}_2 = \left\{ \frac{\mathrm{f\,(M)\,f(E)}}{[\mathrm{f\,(M) + f\,(E)}]^2} \right\}^{1/2} \tag{9}$$

Obviously, the degree of coupling $C \in [0,1]$. When $C = 0$, the degree of coupling is the smallest, the system is in an unrelated state, and it will gradually develop into disorder. When $C = 1$, the coupling degree is the largest; the system reaches a benign coupling state; and it will gradually move toward a new ordered structure. Generally, the system-coupling process can be divided into four stages: low-level coupling, the antagonistic period, the running-in period and high-level coupling (Song et al. 2008; Wang et al. 2017a, b; Fan et al. 2019). The specific judgment criteria are shown in Table 2.

3.3.3 Coupling coordination degree model

Coordination generally refers to the proper coordination of the various elements in the system during the evolution of the system. Since the coupling degree cannot fully reflect the level of the coordinated development of the mineral resources development system and the mining area ecological environment system, the coupling coordination degree model is introduced to analyze further the coordination degree of the two systems (Fan et al. 2019).

Table 2 Judgment criteria of the coupling degree between mineral resources exploitation and the mining ecological environment

Coupling degree	Coupling phase	Coupling characteristics
$0 < C \leq 0.3$	Low-level coupling period	The level of mineral resources exploitation is low, and the bearing capacity of the mining ecological environment is strong. The ecological environment of the mining area has experienced some extremely limited damage, and this environment can fully carry and digest the negative impact of the development of the mining industry. The two systems are in a low-level symbiosis stage
$0.3 < C \leq 0.5$	Antagonistic period	The development of mineral resources has entered a period of rapid development, the load capacity of the mining ecological environment has declined, and the negative impact of mining exploitation cannot be fully absorbed. At the same time, the destruction of the ecological environment has restricted the development of the mining industry
$0.5 < C \leq 0.8$	Running-in period	Due to the constraints of the ecological environment damage, the mining enterprises have begun to pay attention to the ecological environment and have invested a large amount of development funds into the restoration of the mining ecological environment. The mining development and the ecological environment of the mining area have begun to couple positively
$0.8 < C \leq 1$	High-level coupling period	After a continuous running-in period, adjustment and reorganization, mineral resources exploitation and the mining ecological environment have begun to promote each other and have entered a high level of coupling

Comprehensive development index *T* of mining exploitation and the ecological environmental development is calculated, and the *T* value reflects the overall synergistic effect or contribution of the two systems (Yi and Fang 2014). The formula is as follows:

$$T = \alpha \mathrm{f}(M) + \beta \mathrm{f}(E) \tag{10}$$

where α and β are undetermined coefficients. Because the mineral resources exploitation system and the mining ecological environmental system play the same role in the whole system, let $\alpha = \beta = 0.5$.

The calculation formula of coordination degree *D* is as follows:

$$D = \sqrt{C \times T} \tag{11}$$

When we consider the value of *D*, combined with the experience summary of domestic scholars and the actual situation of Shanxi Province, the judgment standard of the coupling coordination degree is calculated (Li and Cui 2018; Deng 2018) and shown in Table 3.

When $f(M) > f(E)$, an ecological lag has occurred; when $f(M) < f(E)$, a mining lag has occurred; and when $f(M) = f(E)$, mining is synchronized with the ecology.

4 Results and discussion

4.1 Development index-timing analysis

Formulas (6–9) are used to calculate the development index values of mineral resources exploitation and the mining ecological environment in Shanxi Province from 2003 to 2015, as shown in Table 4. The evolution curve is shown in Fig. 4.

The comprehensive development index (see Table 4 and Fig. 4) shows a trend of first increasing and then decreasing, with the rising trend concentrated before 2012, and the decrease occurring after 2012. This result indicates that the comprehensive development level of mineral resources exploitation and the mining ecological environment of Shanxi Province declined after 2012. In addition, in most years of the study period, the ecological environment of the mining area lagged behind the development of mineral resources, and the degree of this lag can be judged by the value of $I(M)$-$I(E)$. After 2012, the degree of the ecological lag was relatively reduced, which indicates that, although the emphasis on the

Table 3 Classification of the coupling degree of the coordination between mineral resources exploitation and the mining ecological environment

Coordination level	Range of coordination degree	Type
Disorders of recession	$D < 0.1$	Serious disorder
	$0.1 \le D < 0.2$	Moderate disorder
	$0.2 \le D < 0.3$	Mild disorder
Low coordination	$0.3 \le D < 0.4$	Near disorder
	$0.4 \le D < 0.5$	Minimal coordination
	$0.5 \le D < 0.6$	Primary coordination
Moderate coordination	$0.6 \le D < 0.7$	Intermediate coordination
	$0.7 \le D < 0.8$	Good coordination
High coordination	$D \ge 0.8$	Perfect coordination

Table 4 Comprehensive development index of mineral resources exploitation and the mining ecological environment in Shanxi Province from 2003 to 2015

Year	Mineral resources exploitation index *I(M)*	Mining ecological environment index *I(E)*	Comprehensive development index *T*	*I(M)−I(E)*
2003	0.3159	0.2708	0.293362	0.0451
2004	0.2090	0.2782	0.243595	−0.0691
2005	0.1819	0.2920	0.236936	−0.1101
2006	0.3548	0.2330	0.293902	0.1218
2007	0.4377	0.6066	0.522183	−0.1689
2008	0.5833	0.5664	0.574836	0.0169
2009	0.4538	0.7498	0.601797	−0.2960
2010	0.5316	0.4651	0.498383	0.0665
2011	0.7328	0.4684	0.600626	0.2644
2012	0.7445	0.6531	0.698779	0.0914
2013	0.6781	0.6107	0.644416	0.0674
2014	0.6342	0.6202	0.62718	0.0140
2015	0.4750	0.5676	0.521271	−0.0926

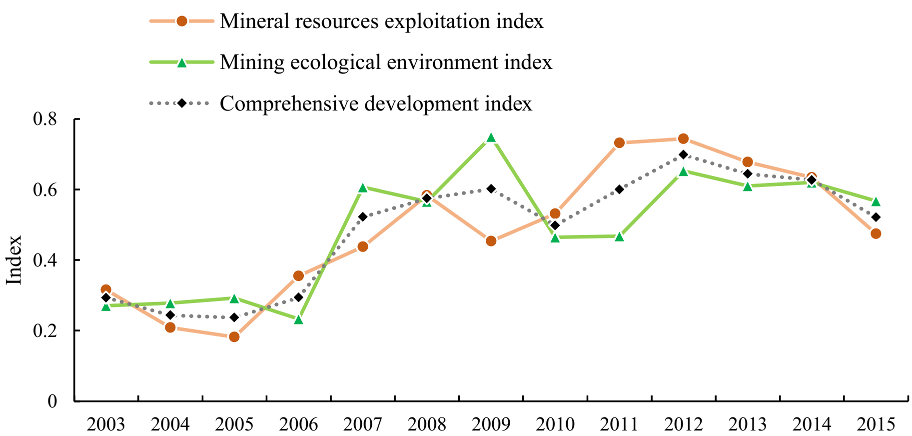

Fig.4 Comprehensive development trend of mineral resources exploitation and the mining ecological environment in Shanxi Province from 2003 to 2015

ecological environment of the mining area has been strengthened during the development of mineral resources in Shanxi Province, this emphasis remains insufficient. In general, the geological restoration has been undergoing.

4.1.1 Mineral resources exploitation index-timing analysis

According to the statistical data on mining exploitation in Shanxi Province over the past ten years (Shanxi Bureau of Statistics 2017), the annual average output value of coal resources is 36.3 billion (CNY), accounting for 94.77% of the output value of the mining industry in

Shanxi Province. Shanxi Province has many coal mines, and the change in the coal market has become the decisive factor in the fluctuation of the whole mining market. Therefore, this paper considers solely coal mines to analyze the status of mineral resources exploitation in Shanxi Province.

Figure 4 shows that the mineral resources exploitation index is bounded by 2012, a trend of first rising and then declining. Before 2012, the increase fluctuated, and then a continuous decline occurred after 2012. Specifically, the index of mineral resources exploitation declined slightly in 2004 and 2005 and then continued to rise rapidly from 2006 to 2008. The index declined in 2009 and then recovered and reached its peak in 2012. After 2012, the index declined considerably.

The mineral resources exploitation index decreased in 2004 and 2005. Due to frequent mining accidents, Shanxi Province reformed coal property rights in 2004, which is known as "the watershed of industrial adjustment in the history of Shanxi coal production." In 2004, the province closed more than 4,000 illegal coal mines and shut down small coal mines with an annual output of less than 30,000 tons.

The level of mineral resources exploitation surged from 2006 to 2008. According to industrial statistics (State Administration of Coal Mine Safety 2016), the coal price increase in Shanxi Province was mainly concentrated between 2006 and 2008. In the past decade, coal prices reached a peak of 1100 yuan/ton in 2008, when the golden age of the coal industry arrived. A large number of enterprises entered the market, and the level of development of mineral resources continued to increase, reaching its first peak in 2008.

In 2009, the mineral resources exploitation index of Shanxi Province plummeted. In September 2008, a coal reform in Shanxi, which was promoted by the government and led by state-owned enterprises, officially began. The reform demanded mine closures within a limited period and forced consolidation. The government has successively issued various policy documents to constrain the standardized production management of the coal market and to close resource-exhausted coal mines. In addition to policy changes, the US subprime mortgage crisis in 2008 triggered a sharp decline in the trading prices of aluminum, copper, lead, zinc and other important mineral products on the international market. The impact of the financial crisis on the development of domestic mining led to a significant reduction in the level of mineral resources exploitation in Shanxi Province.

In the beginning of 2010, the two-year coal reform officially ended. Most of the private coal mines were merged into several large, state-owned enterprises, such as China Coal Group, Yangshuo Group, Jinmei Group and Tongmei Group. After the reorganization of Shanxi coal enterprises, industrial concentration and the technical level used in mining were greatly improved, and the sustainable development capability of the coal industry was significantly enhanced. The mineral resources development index experienced its second peak in 2012.

After 2012, the level of mineral resources development continued to decline. In the second half of 2012, the “Golden Decade” of the coal industry in Shanxi, which began in 2002, officially ended. Then, 2013 became a turning point for mining development. The world economy was weak due to its recovery, and the country faced a complex situation of shifts in the speed of economic growth, industrial restructuring and early stimulus policy adaptation. The Chinese economy entered a "new normal," marked by medium- and high-speed growth. New changes have occurred in the momentum of economic growth and in the industrial structure, and the coal industry is in a new development pattern. Due to problems such as "supply exceeds demand" and overcapacity, the characteristics of weak demand, high coal storage and business difficulties have always penetrated the Shanxi coal market. The price of coal has significantly decreased, and the level of mineral resources exploitation has continued to decline. By the end of 2015, the output of the coal mines in China was 5.7 billion tons, while the consumption of coal in that year was 3.75 billion tons. The country's coal overcapacity was nearly 2 billion tons. As "de-capacity" is a long and difficult process, the coal market in Shanxi still faces severe challenges.

4.1.2 Mining ecological environmental index-timing analysis

Compared with the development of mineral resources, the mining ecological environmental development index fluctuates greatly, indicating that the ecological environment of the mining area in Shanxi Province is unstable. The overall trend indicates that the index increased slightly, reflecting the improvement in the mining ecological status in Shanxi Province. Figure 4 shows that, before 2012, the trend of the ecological environmental development index was completely opposite that of the mining exploitation index; after 2012, both showed a trend of slow decline.

Before 2012, mineral resources exploitation and the mining ecological environment were negatively correlated. When the mining index increased, the ecological environment index decreased in the same year, and vice versa. This result indicates that the exploitation of mineral resources has been at the expense of the ecology for a long time and that an awareness of ecological environmental protection is seriously lacking.

However, 2007 was an exception, with a small increase in the level of mineral resources exploitation and a significant increase in the mining ecological environment. To ensure good air quality during the 2008 Beijing Olympic Games, in September 2007, the State Environmental Protection Administration and the government in Beijing led the development and implementation of the "Beijing Air Quality Assurance Measures for the 29th Olympic Games" in six provinces and cities, including Shanxi Province. The measures mainly included the regional linkage control of dust pollution, industrial pollution and coal pollution. Shanxi Province issued a series of documents, such as the "Notice on Strengthening Environmental Supervision during the Olympic Games" and the "Work Plan for Air Quality Assurance during the Olympic Games." The relevant measures mainly included restricting or stopping the production of high-energy-consumption and high-pollution enterprises such as steel and cement production as well as increasing the comprehensive management of coal gangue mountains. Therefore, the ecological environment of the mining area was significantly improved in 2007.

In 2008, the exploitation of mineral resources and the mining ecological environment, again, had a negative relationship. The mining index increased sharply, and the ecological environmental index of the mining area declined slightly. This result shows that the ecology of Shanxi Province is very fragile, and the attention paid to the ecological environment management of mining areas began to weaken after the ecological environment was significantly improved in 2007. As mine geological environment treatment is a systematic project, it requires long-term and continuous management. Meanwhile, the governance of the ecological environment of the mining area in Shanxi Province remains at only the emergency level. Therefore, the temporary ecological environmental treatment contributed to developing the ecological environment of the mining area in Shanxi Province in 2008.

After 2012, the mining ecological environmental curve and the mineral resources exploitation curve began to change in the same direction, and mining development had a positive impact on the mining ecological environment. In 2012, the 18th National Congress of the Communist Party of China (CPC) proposed the Five-in-One Strategy and called for "deeply promoting the construction of an ecological civilization." Subsequently issued was the “Opinions of the CPC Central Committee and the State Council on Accelerating the Construction of an Ecological Civilization,” demanding “the restoration and comprehensive treatment of the mine geological environment.” A new situation developed in which the central government attached great importance to the construction of an ecological civilization. The leaders of Shanxi Province fully understand the role of mine environmental restoration and treatment in the construction of an ecological civilization, and they strengthened the protection and treatment of the mine geological environment. However, the development of the ecological environment of mining areas in Shanxi Province faced a new practical problem: during the "golden decade," social capital was highly attracted to the coal industry. People began to dig for coal, which caused irreparable damage to the ecological environment. Due to industrial overcapacity, coal prices fell, and total industry profits fell sharply. Many mining enterprises were in an intermittent production state and, due to decreasing profitability, reduced their investment in environmental restoration and treatment. The work of mine environmental restoration and management is progressing slowly. In addition, a large number of mining enterprises have withdrawn from the market due to policy integration and the industry downturn. Responsible subjects are lacking who will undertake the restoration and treatment of the geological environment of mines. As a result, the problems left over from history have gradually become prominent.

4.2 Coupling degree and coupling coordination degree-timing analysis

The above steps can be used to calculate the coupling degree and the coordination degree of mineral resources exploitation and the mining ecological environment in Shanxi Province from 2003 to 2015.

Table 5 shows that the coupling degree of mining exploitation and the mining ecological environment of Shanxi Province was the lowest in 2009 at 0.4846 and the highest in 2014 at 0.5; the average value was 0.4946. This result shows that the degree of coupling remained stable from 2003–2015 with only small fluctuations. The coupling status has been in an antagonistic period throughout the study period, indicating that the two systems

Table 5 Coupling and the coordination degree of mineral resources exploitation and the mining ecological environment in Shanxi Province from 2003 to 2015

Year	Coupling degree C	Coordination degree D
2003	0.4985	0.3824
2004	0.4949	0.3472
2005	0.4863	0.3395
2006	0.4892	0.3792
2007	0.4934	0.5076
2008	0.4999	0.5361
2009	0.4846	0.5401
2010	0.4989	0.4986
2011	0.4877	0.5412
2012	0.4989	0.5905
2013	0.4993	0.5672
2014	0.5000	0.5600
2015	0.4980	0.5095

have been in a state of mutual restraint and restriction for a long time. The exploitation of mineral resources causes irreversible damage to the mining ecological environment. At the same time, the mining ecological environment has a restrictive effect on mineral resources exploitation through environmental protection policies. The contradiction between the two systems is notable.

The coordination curve in Fig. 5 shows that the coupling coordination degree tends to increase volatility as a whole, indicating that the coordinated development level has gradually increased. Considering the type of the coupling coordination degree, the coordination state has been in a low coordination phase for a long time. The coupling coordination degree from 2003 to 2006 was between 0.3 and 0.4, which is a stage of near disorder. The coupling coordination degree of 0.4986 in 2010 indicates minimal coordination, and, for the years after 2007, the degree was between 0.5 and 0.6, which is the primary coordination stage. The coupling coordination curve has two "peak" points and two "valley" points. Among these points, 2005 was the first "valley" point, at which time the coordination degree fell to its lowest value, which was 0.3395, for the first time. From 2006–2009, the coordination degree experienced an upward trend with a growth rate of 59.1%. The degree of coordination increased the fastest in 2007, when it was 22.18% higher than it was in 2006. After that, the upward trend of coordination was slightly slower. By 2009, coordination reached the first "peak" point of 0.5401. The coordination degree in 2010 was 0.4986, it was even lower than that in 2007, and the second "valley" point appeared. After 2010, the degree of coordination increased sharply, reaching 0.5905 in 2012. This result represents the second "peak" point and the most-coordinated year in the research period, which was close to the intermediate coordination stage. After 2012, the degree of coordination continued to decrease. By 2015, the coordination degree of mining development and the ecological environment in Shanxi Province fell to its lowest point in five years.

The coupling curve and the coupling coordination curve of mining exploitation and the ecological environment in Shanxi Province indicate that the coupling type of the two systems has been antagonized throughout the study period. Although the coupling coordination degree has improved, it remains at a low level and has a downward trend, which indicates that, with the development of mining, the ecological environmental carrying capacity of mining areas in Shanxi Province has gradually declined, and the negative impacts of mining development cannot be fully absorbed. At the same time, the destruction of the

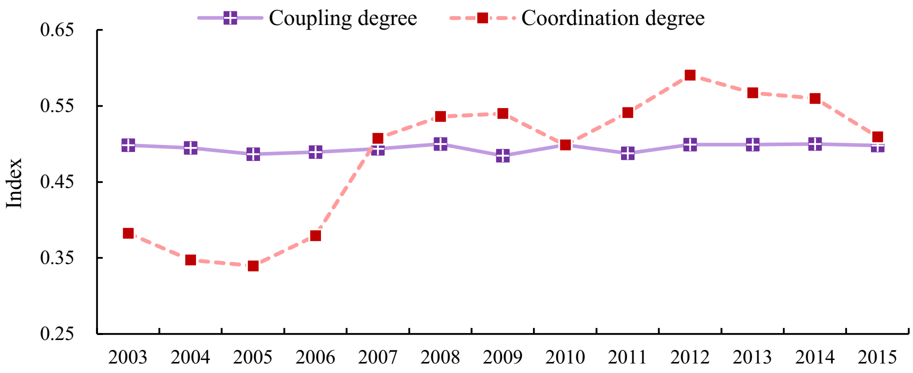

Fig. 5 Trends of the coupling and coordination degrees of mining exploitation and the mining ecological environment in Shanxi Province from 2003 to 2015

mining ecological environment limits the development of the mining industry. There are obstacles to the coordinated development of mineral resources exploitation and the ecological environment of the mining area.

4.3 Key index factor analysis

To find some factors restricting the coupling degree and the coupling coordination degree, the weight factor must be analyzed. Figure 6 rationally describes the degree of the indicators influence to explain the constraints with larger weights further.

The indices with greater weights are X_1 (*Mining production*), X_4 (*Mining enterprises*) and X_5 (*Mining employees*) in the mineral resources exploitation system. Employment growth in recent years has been steady, although the ratio is significant, which has no impact on the results. Therefore, mining and enterprise development are considered for explanations. On the one hand, the concept of the sustainable development of mining enterprises is a key problem. Affected by the misunderstanding of "rapid water flow," enterprises focus only on resource development in terms of the development of mineral resources and neglect ecological environmental protection and pollution control (Lv et al. 2019). They are generally concerned with abundance and eliminating poverty and have a weak awareness of environmental protection (Segerstedt and Abrahamsson 2019). On the other hand, the lack of learning ability of the management and technical staff leads to the improper use of enterprise management concepts and a weak innovation ability, which impedes the standardized and institutionalized transformation path. Policy makers should consider the acquisition and merger of enterprises to enhance comprehensive capacity in the future.

For the mining ecological environment system, indices Y_{11} (*Occupied or damaged land area this year*), Y_{12} (*Capital investment in restoration of the mine environment*) and Y_{13} (*Mines restored and controlled this year*) have higher weights. Firstly, some problems remain from the mining history. Shanxi has been seriously damaged by large-scale and extensive mining activities for a long time as a major mining province, leaving a very large historical debt for the restoration and treatment of the ecological environment. In recent

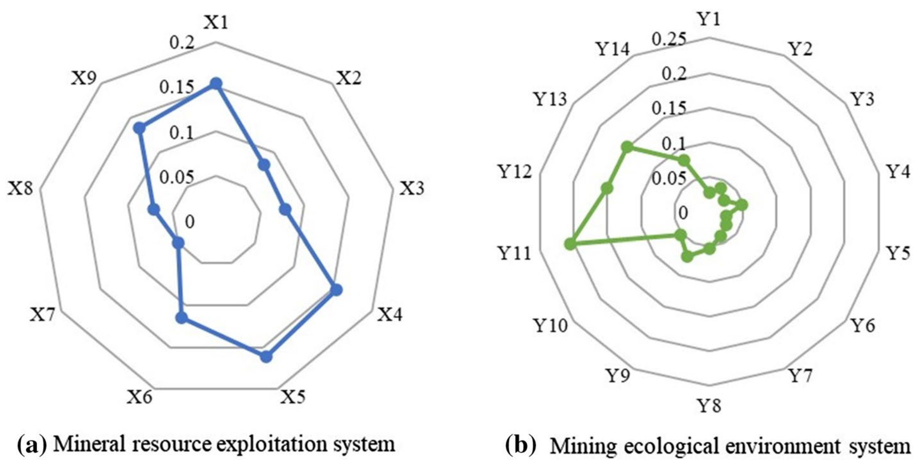

Fig. 6 Influence degree of indicators weight between mineral resources exploitation system (**a**) and the mining ecological environment system (**b**)

years, mining enterprises in Shanxi Province have continued to use outdated mining methods and mining technology for production, leading to an overall low standardization level of mining development and utilization. Waste rock tailings, piling chaos, wastewater, waste gas and solid waste comprehensive utilization rates are low. Subsidence, cracks and other geological environmental problems are becoming increasingly serious. In addition, land reclamation management has weak links, available land resources for mines have decreased and land waste has become a serious phenomenon (Mishra and Mishra 2017). The natural conditions of water shortages and other restrictions have further led to difficulties in vegetation restoration and management (Liu et al. 2019b). Secondly, the restoration and management of the geological environment is a systematic project with a relatively large cost, so the lack of funds becomes its biggest bottleneck. Governance has been lost subject to the geological environment of closed mines, abandoned mines and politically closed mines, resulting in no source of funds for the environmental governance left over from history. The mining market is currently depressed due to overcapacity, leading to a serious shortage of funds invested in recovery and management. In addition, local governments generally do not have budgets to address closed and abandoned mines, which minimizes the participation of social funds and lowers the enthusiasm of enterprises. Thus, the management function of the geological environmental restoration subject must be coordinated and a unified responsibility mechanism for restoration must be formed.

5 Conclusions and policy recommendations

5.1 Main conclusion

The exploitation of mineral resources and the ecological environment of mining areas involve systematic engineering. This study aimed to evaluate the coupling relationship between the two systems based on an analysis and by referring to relevant research results and theories. Firstly, the extreme value and entropy methods were applied to standardize the indexes of the system. Secondly, the development index of mineral resources exploitation and the ecological environment in the mining areas was analyzed. Thirdly, the degree of coordination was evaluated and analyzed between mining exploitation and the ecological environment in Shanxi Province from 2003 to 2015 through the calculation of the coupling coordination degree model. The research conclusions are as follows:

(1) The overall mineral resources exploitation index shows a trend of first rising and then falling. The year 2012 is a key turning point for mining development in Shanxi Province. Before 2012, the mining exploitation index rose in a volatile manner. After 2012, the index continued to decline, and the decline was significant. From 2003 to 2015, the exploitation level of mineral resources in Shanxi Province improved overall, but, after 2012, it decreased significantly. The index of the mining ecological environment increased, but the range of fluctuation was large. After 2012, the index tended to be stable with a slight decline, showing that the ecological environment of the mining area in Shanxi Province improved as a whole during the research period. However, due to the ecological fragility caused by long-term predatory mining and the acute management mode, the ecological condition of the mining area has been extremely unstable and has fluctuated greatly. Therefore, the mining ecological environment in Shanxi

Province requires continuous protection, long-term management and a high level of attention.

(2) The degree of coupling between the development of mineral resources and the ecological environment of the mining area in Shanxi Province indicates that, overall, the situation has been stable with small fluctuations. From 2003 to 2015, the coupling degree was between 0.48 and 0.5, and the coupling state was always in the antagonistic period, indicating that the two systems are mutually constrained and that contradictions appear. The degree of coupling coordination between mining exploitation and the ecological environment in Shanxi Province first increased and then decreased. Before 2012, the degree rose in a wave; after 2012, it decreased slowly. Overall, the degree of coupling coordination has increased, and the type of coordination has developed from near disorder to primary coordination, showing that the level of coordinated development in Shanxi Province has gradually improved but remains at a low level.

(3) By analyzing the indicators with larger weights, this paper determines the factors restricting the coupling degree and the coupling coordination degree and explains them by combining local policies and management. (i): The concept is insufficient of sustainable development of mining enterprises, and mining methods continue at the expense of the ecological environment. (ii): Geological environment problems, such as ground collapse caused by mining history, are increasingly serious. (iii): Geological recovery management funds are not guaranteed, and enterprises participate in them at a lower rate than is necessary.

5.2 Policy recommendations

Policy makers should consider the following suggestions according to the problems existing in the coordinated development of mining exploitation and the ecological environment in Shanxi Province:

(1) Establish and perfect an ecological compensation mechanism and standardize the mining development model. This policy should strengthen the comprehensive utilization of co-associated resources (Zhu 2017) under the constraint of ecological pollution. It should also effectively and gradually control ecological deterioration as it is implemented, aiding in the mining market's recovery. Responsible mine environmental protection and management should be implemented throughout the life cycle of mineral resources development. A new situation should be formed regarding the overall protection and treatment of both current production mines and those that have been closed and abandoned.

(2) Accelerate the construction of green mines. Mineral resources exploitation activities should be carried out within the scope of the ecological and environmental carrying capacity permit of the mining area (Yang et al. 2017). The economic benefits obtained should be rationally invested in the development of ecological environmental protection governance to form a virtuous cycle and to ensure the coordinated development of mining exploitation and the mining ecological environment. Mineral resources must be exploited to create "gold and silver mountains," which provide material and spiritual wealth to meet people's growing needs for a better life. Moreover, the government must protect the environment and create "green waters and green mountains," which provide high-quality ecological products to meet the growing needs of people for a beautiful ecological environment.

(3) Broaden funding channels to ensure adequate governance funds. Provincial financial subsidies and investments from local financial funds should be used to address problems related to historical mines, such as those abandoned or closed by policy. In accordance with the principle of "who mines and who controls," newly built and production mining enterprises should make their own investment. Preferential policies should be formulated to encourage investment governance for mines that can produce obvious economic benefits or that can be managed to become construction land. This policy is expected to attract social capital according to the principle of "who governs and who benefits."

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