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Research article

Green development level assessment and obstacle analysis of China's coal-resource-based regions

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A R T I C L E I N F O

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A B S T R A C T

Coal is the main source of energy in China, however, in the context of carbon neutrality, how coal-resource-based regions can not only undertake the national supply of terminal energy and industrial raw materials, but also achieve regional green development is an important issue. In this paper, first, we constructed a green development indicator system for coal-resource-based regions named the green development indicator system of coal-resource-based regions (GDISCR), which could coordinate the relationship among the economy, energy, and environment when evaluating the green development level. Second, we proposed a new evaluation model named dynamic spatial TOPSIS, which comprehensively considered the spatial differences of research subjects and the differences over time in the evaluation process. Third, we introduced the obstacle analysis model to find the obstacle factors preventing green development of coal-resource-based regions. Finally, we evaluated ten coal-resource-based provinces to evaluate their green growth levels and demonstrate the effectiveness of our methodology. The following were the major conclusions: (1) The average comprehensive evaluation value of the 10 coal-resource-based provinces was 0.3956, based on which the coal-resource-based provinces could be divided into two types, namely, provinces with better or worse green development levels. (2) The obstacles restricting the green development of provinces with coal resources were dynamic, but the importance of an obstacle factor for provinces was relatively fixed. (3) The greatest obstacle to the green development of provinces with coal resources was technological capacity in the economy, with an average obstacle degree of 27.48% in 2022, and they had similar difficulties in energy transition but different difficulties in environmental protection. On the basis of these findings, some feasible recommendations for the environmentally friendly growth of coal-resource-based provinces are discussed.

1. Introduction

One of the most serious problems confronting humanity is global climate change. After the United States, China is now the country with the most historical carbon dioxide emissions. China pledged at the 75th United Nations General Assembly that it will achieve carbon peaking by 2030 and carbon neutrality by 2060 in response to climate change and internal environmental challenges. China's major source of CO2 emissions is the production and use of coal. In 2020, China's total primary energy production was 146577607 terajoule, of which the coal supply accounted for 60.69% [1]. China has the resource characteristics of abundant coal, little oil,

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and little gas; these factors have led to coal dominating China's energy resources, and this will continue in the future [11]. As a coal production base, coal-resource-based regions are a significant part of the sustainable advancement of the national economy and the achievement of national carbon neutrality [24] [18]. However, long-term extensive development models have resulted in a slew of issues for coal-resource-based regions, including anomalous economic structures, a gravely harmed natural environment and undeveloped alternative sectors [16]. Hence, in the context of carbon neutrality, how coal-resource-based regions can not only undertake the national supply of terminal energy and industrial raw materials but also achieve regional green development is an important issue.

Due to the growing concern over carbon neutrality, there has been an increase in studies on the transition and green development of coal-resource-based regions. Tadeusz et al. explored transition stakeholders' beliefs and perceptions about political, economic, social, environmental and technological risks and opportunities for the coal-dependent region of Silesia (Poland) [17]. Hana et al. proposed an analytical framework with a combination of value chain analysis and energy sector analysis, by which they evaluated the strategy for the clean energy transition of the Slovakian region Upper Nitra [7]. Relying on social network analysis, Calvo-Gallardo et al. assessed how regional innovation systems support research and innovation smart specialization strategies in coal intensive regions [2]. Through soft-linking an energy system model with an input-output model and a regional macroeconomic model, Oei et al. examined the consequences of the planned coal phase-out in Germany. They found that support from federal policy was necessary to support structural change in these regions [15]. Nel et al. drew on international and South African evidence of the effects and responses to mine closure, regional resilience theory and evolutionary economic geography theory to analyze the implications and prospects for economic renewal as the coal industry winds down [13]. In China, the majority of current research focuses on the barriers to and determinants of the industrial transformation of cities with coal resources. Long et al. developed an evaluation index system that satisfied the requirements of green development in coal-resource-based cities by taking into consideration four dimensions: economic green development, social green development, resource green development, and environmental green development. They found that China's coal-dependent cities typically had poor levels of green development and that the rate of improvement was modest [11]. Using the Super-SBM model, Hou et al. examined the capacity of sustainable development for four typical coal cities in China from 2012 to 2016 [8]. A comprehensive GDL evaluation index system was created by Yang et al. from societal, economic, and environmental aspects. Based on the index system, they assessed the level of green development of cities dependent on mineral resources using the entropy technique and the AHP [23]. Zhai et al. used the environmental Kuznets curve (EKC) hypothesis, the vector autoregressive (VAR) model and time series data from Yulin city to investigate the relationship between socioeconomic development and industrial "three wastes" emissions [25].

Although regional green development level assessments have become the main focus of the current research on coal-resource-based regions, these regions are mostly cities, and their research areas are too small to be representative. In the early stages of achieving carbon neutrality, we must pay closer attention to the degree of green growth in larger regions with coal resources. Furthermore, because the implementation of green development in coal-resource-based areas involves a complex dynamic system made up of economic, resource, environmental, social, and other subsystems, we need to consider both the variety of the subsystems as well as how they interact. Finally, current research primarily assesses and analyzes the low-carbon development status of regions based on coal resources without further studying the obstacles that hinder the level of green development of regions. Hence, it is difficult to provide focused optimization measures for coal-resource-based regions to encourage green development.

In this paper, we regard coal production-intensive regions as coal-resource-based regions, and the primary contributions are as follows. First, by suggesting a complete index system that incorporates the economy, energy, and environment, we focused on the balanced evaluation of the green development of coal-resource-based regions rather than considering emissions reduction as the evaluation aim. Second, we proposed a brand-new evaluation model called dynamic spatial TOPSIS that took into account the spatial disparities between research subjects and the variations over time in the evaluation procedure. Third, we established an obstacle analysis model to identify the obstacles preventing the green growth of coal-resource-based areas from numerous angles, which may optimize the structural arrangement of each subsystem throughout the transformation of coal-resource-based regions. Finally, we chose ten representative coal-resource-based provinces in China as examples and assessed them using the same index system, which was useful in identifying the advantages and disadvantages of green development in various coal-resource-based regions. Our comprehensive findings are anticipated to further the study of numerous issues that major regions with coal resources confront while pursuing low-carbon development and to serve as an invaluable resource for policy-makers.

The structure of the paper is as follows. In Section 2, we review related works of our research. In Section 3, we construct a green development indicator system for coal-resource-based regions. In Section 4, we introduce the research methods and propose a dynamic spatial TOPSIS method. In Section 5, we describe and discuss the main evaluation results of selected coal-resource-based regions. In Section 6, we provide a quick summary of this paper's conclusions and ideas for how to raise the degree of green development in areas with coal resources in light of the findings.

2. Literature review

TOPSIS is a technique to evaluate the performance of alternatives by examining their similarity with the ideal solution, and it has been widely used in social economy, engineering technology, and other fields [14]. Because it is not significantly affected by its parameters, the TOPSIS method is one of the most commonly used methods in evaluating the green development of regions. Wang et al. constructed a framework for evaluating the green transformation performance (GTP) of resource-based cities in China and measured the GTP of 115 prefecture-level and above resource-based cities in China using the entropy weight-TOPSIS model [20]. Huang et al. described the industrial transformation process of coal-energy cities and developed an assessment model for the

Table 1
Limitations of Exist Methods.

Methods	Limitations
The entropy weight-TOPSIS model [20]	It did not take into account trend characteristics of alternatives when calculating relative distances
The upgraded TOPSIS [9]	It did not take into account trend characteristics of alternatives when calculating relative distances
The improved TOPSIS method [10]	It set the ideal value artificially which lacked a quantitative basis
The improved TOPSIS method [5]	It could not take into account the time characteristic factor

economic transformation of upgraded TOPSIS coal-based energy cities based on the entropy weight [9]. However, the traditional TOPSIS method does not take into account trend characteristics of alternatives with the ideal solutions when calculating relative distances of an alternative from the positive ideal solution (PIS) and the negative ideal solution (NIS) using the Euclidean distance [19]. The entropy weight-TOPSIS model [20] and upgraded TOPSIS [9] improved the weighting step but did not solve the relative distance problem in the calculation steps. Liu et al. proposed an improved TOPSIS method and comprehensive index system incorporating the economy, society and environment to evaluate the transformation level of 81 resource-based cities in China [10]. The improved TOPSIS method [10] tried to solve the relative distance problem by artificially setting the ideal value; however, it lacked a quantitative basis. Chun et al. introduced an improved TOPSIS approach that created spatial feature vectors and determined the cosine of the included angle of the vectors to determine the degree of correlation between the vectors. They converted the algebraic distance of alternatives from the PIS and NIS into geometric similarity and improved the refection of the real situation by combining the Euclidean distance and cosince similarity [5]. The improved TOPSIS, however, could not take into account the time characteristic factor and could only perform static thorough evaluations of cross-sectional data without taking into account the overall dynamic changes [4] [11]. The limiations of related methods were summarized as Table 1. In this paper, we comprehensively considered the spatial differences of research subjects and the differences over time in the evaluation process and proposed a dynamic spatial TOPSIS method.

The research on the comprehensive balance and coordinated development of the three subsystems in the social development system, as well as the interaction between subsystems, is primarily covered by the 3E system, which stands for economy, energy, and environment and is a comprehensive development index system that has gained popularity worldwide [26]. To provide decision-makers with specific information on the accomplishment of sustainable development goals, Yan et al. created a 3E efficiency indicator [22]. To discover green transformation and sustainable development, Mu et al. employed multi-criteria decision making (MCDM) methodologies to explore the correlation and synergy of the urban 3E system [12]. Chun et al. created the CNCIS, a novel approach for evaluating carbon neutrality capability that can dynamically represent the balance between the economy, the environment, and energy in the process of lowering carbon dioxide emissions [5]. Zuo et al. used system dynamics to develop models of a 3E system's sustainable evolution that not only emphasized the 3E system's operation but also made clear the complex logical relationships between its components [27]. Hence, we know that the 3E system has a specific structural relationship and is most frequently used to build decision models. Coordinating the interaction between the economy, energy, and environment and investigating their impact on the sustainable development of coal-resource-based regions is a significant issue in the context of carbon neutrality.

3. Green development indicator system

The interaction between energy, economy and environment is mutually influenced and dynamically balanced for coal-resource-based regions. The most fundamental forces behind the creation and use of energy are economic development and technical advancement. The availability of energy underpins the economy; hence, ensuring its security is essential to the economy's efficient operation. Since the economy and energy depend on and are carried by the environment, these activities also have an impact on it. We presented a green development indicator system for coal-resource-based regions based on this theoretical supposition.

In accordance with the analysis of coal-resource-based regions and the 3E system, screening of the influencing factors is performed based on a review of the literature, expert knowledge and experience. We established the green development indicator system of coal-resource-based regions (GDISCR), which consists of three parts, namely, the economy system: relevant indicators representing the economic development and technological progress of a region; the energy system: relevant indicators representing the level of low carbon and security of energy supply; and the environmental system: relevant indicators of carrying capacity and pollution in response to economic and energy actions. The GDISCR contains 3 layers and 18 specific indicators, which are shown in Table 2.

(1) Economy: To accomplish the sustainable development of regions with coal resources, it is vital to strike a balance between the rate and quality of economic growth. To fulfill the dual objectives of economic growth and environmental reform, regions with a heavy reliance on coal resources should aggressively stimulate industrial restructuring, raise investment in clean energy, and foster technical innovation. In this study, the green development level in the economic aspect was measured via six indicators: population, proportion of tertiary industry, per capita GDP, technology market transactions, full-time equivalent of R&D personnel of industrial enterprises above designated size, and proportion of investment in clean electricity generation. The following is a sample indicator definition and calculation formula.

The proportion of investment in clean electricity generation reflects the development level of the regional clean power supply, which is calculated by formula (1).

Table 2
Green development indicator system of coal-resource-based regions.

First Layer	Second Layer	Third Layer	Type
Economy	Economy development	X1:Population	Positive
		X2:Proportion of tertiary industry	Positive
		X3:Per capita GDP	Positive
	Technology	X4:Technology market transactions	Positive
		X5:Full-time equivalent of R&D personnel of industrial enterprises above designated size	Positive
		X6:Proportion of investment in clean electricity generation	Positive
Energy	Low carbon	X7:Proportion of electricity from thermal power generation	Negative
		X8:Average wind power density at 70 m	Positive
		X9:Average horizontal radiation	Positive
	Security	X10:Elasticity coefficient of energy production	Positive
		X11:Regional electricity redundancy	Positive
		X12:Degree of self-sufficiency in raw coal	Positive
Environment	Environmental carrying capacity	X13:Afforestation area	Positive
		X14:Per capita water resources	Positive
		X15:Greening rate of built-up area	Positive
	Environmental pollution	X16:Per capita carbon dioxide emissions	Negative
		X17:Carbon emission intensity	Negative
		X18:SO2 emissions	Negative

$$Proportion\ of\ investment\ in\ clean\ electricity\ generation = \frac{investment\ in\ electricity\ generation - investment\ in\ thermal\ power\ generation}{investment\ in\ electricity\ generation} \tag{1}$$

(2) Energy: For coal-resource-based regions, on the one hand, the efficient development of fossil energy represented by coal is an inherent requirement for ensuring national energy security in the current energy structure of China. On the other hand, increasing the proportion of clean energy supply is a necessary path for regional sustainable development and low-carbon transformation. Hence, it is essential to balance energy security and low carbon development. In this study, the green development level in the energy aspect was measured via six indicators: proportion of electricity from thermal power generation, average wind power density at 70 m, average horizontal radiation, elasticity coefficient of energy production, regional electricity redundancy, and degree of self-sufficiency in raw coal. The following is a sample indicator definition and calculation formula.

Regional electricity redundancy reflects regional energy security capacity, which is calculated by formula (2).

$$Regional\ electricity\ redundancy = \frac{net\ transfer\ capacity\ of\ electricity}{electricity\ consumption\ of\ the\ region} \tag{2}$$

(3) Environment: The environment is the basis of economic growth and resource development. However, economic and energy activities cause pollution and have become an important factor hindering regional development. Therefore, it is necessary to improve the carrying capacity of the environment and reduce environmental pollution. In this study, the green development level in the environmental aspect was measured via six indicators: afforestation area, per capita water resources, greening rate of built-up area, per capita carbon dioxide emissions, carbon emission intensity, and SO2 emissions. The following is a sample indicator definition and calculation formula.

The correlation between a region's economy and carbon dioxide emissions is measured using carbon emission intensity, which is calculated by formula (3).

$$Carbon\ emission\ intensity = \frac{carbon\ dioxide\ emissions}{GDP} \tag{3}$$

4. Research methods

Within the context of this study, the research methods are outlined in Fig. 1. First, we used the entropy method to compute the objective criteria weights based on the GDISCR. Second, we took the weights as input to the improved TOPSIS and identified the green development level of coal-resource-based regions to be evaluated. Third, we conducted obstacle analysis based on the weights to obtain obstacle factors and the degree of obstacles that restrict the green development of coal-resource-based regions to provide a targeted decision-making basis. Finally, combined with the results of comprehensive evaluation and obstacle analysis, we proposed corresponding suggestions.

4.1. Entropy weight method

The effective information and indicator weight included in the known data are calculated using the entropy weight technique [3]. The practical importance coefficient of the indicator is not indicated by the entropy weight, which only indicates the relative importance coefficient of each indicator in the competition under the conditions of a particular evaluation object and evaluation index when formulating a decision or evaluation plan.

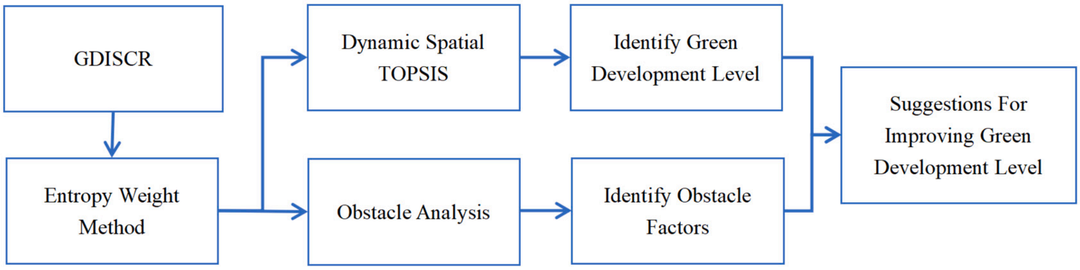

Fig. 1. The Workflow Diagram of This Research.

To build the initial data matrix of the entropy weight evaluation system X, set the performance of n evaluation objects in relation to m evaluation indicators as formula (4).

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \tag{4}$$

where $i = 1, 2, \ldots, n; j = 1, 2, \ldots, m$.

Normalization of each decision matrix criterion to achieve comparable and dimension-less performance measurements. Determine the p_{ij} fraction of the jth indicator ith evaluation alternative x_{ij} as formula (5).

$$p_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \tag{5}$$

The e_jth indicator's entropy is determined as formula (6). When e_j is larger, it indicates that the information is more helpful and that this indication has a stronger influence on the goal in the overall evaluation.

$$e_j = -\frac{1}{\ln(n)} \sum_{i=1}^{n} p_{ij} \ln(p_{ij}) \tag{6}$$

Normalizing the information entropy e_j yields the initial goal weights $w_j (0 < w_j < 1)$ as formula (7).

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{m} 1 - e_j} \tag{7}$$

4.2. Dynamic spatial TOPSIS method

The basic steps of the dynamic spatial TOPSIS method are as follows.

Build a weighted normalized decision matrix as formula (8).

$$V = YW = \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1m} \\ y_{21} & y_{22} & \cdots & y_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ y_{n1} & y_{n2} & \cdots & y_{nm} \end{bmatrix} \begin{bmatrix} w_{11} & 0 & \cdots & 0 \\ 0 & w_{22} & \cdots & x_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & w_{nm} \end{bmatrix} = \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1m} \\ v_{21} & v_{22} & \cdots & v_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ v_{n1} & v_{n2} & \cdots & v_{nm} \end{bmatrix} \tag{8}$$

Different indication directions should be homogenized. When TOPSIS calculates the distance measure of the objects, we should convert the objects v_j of negative indicators j to positive indicators using $v_j{}^* = 1/v_j$.

Determine the positive ideal solution (PIS) and negative ideal solution (NIS) as formula (9).

$$\begin{aligned} V^+ &= \{\max v_{ij} | j = 1, 2, \ldots, n\} = \{v_1{}^+, v_2{}^+, \ldots, v_q{}^+\} \\ V^- &= \{\min v_{ij} | j = 1, 2, \ldots, n\} = \{v_1{}^-, v_2{}^-, \ldots, v_q{}^-\} \end{aligned} \tag{9}$$

where $v_1{}^+, v_2{}^+, \ldots, v_q{}^+$ represent the index value of the positive ideal alternative and $v_1{}^-, v_2{}^-, \ldots, v_q{}^-$ represent the index value of the negative ideal alternative.

Based on the Euclidean distance and cosine distance, calculate the distance measure of the object to be evaluated from each option to positive and negative ideal points as formulas (10) and (11).

$$D_i^{euc+} = \sqrt{\sum_{j=1}^{n}(V_{ij} - V_j{}^{+})^2}$$
$$D_i^{euc-} = \sqrt{\sum_{j=1}^{n}(V_{ij} - V_j{}^{-})^2} \tag{10}$$

$$D_i^{cos+} = sim_i^{+}(V_i, V^{+}) = \cos_i^{+}\theta = \frac{V_i \times V^{+}}{\|V_i\| \times \|V^{+}\|}$$
$$D_i^{cos-} = sim_i^{-}(V_i, V^{-}) = \cos_i^{-}\theta = \frac{V_i \times V^{-}}{\|V_i\| \times \|V^{-}\|} \tag{11}$$

Compute the object's enhanced distance measure $D_i{}^{+}$ and $D_i{}^{-}$ from each alternative to positive and negative ideal points as formula (12).

$$D_i{}^{+} = \sqrt{D_i^{euc+} \times D_i^{cos+}}$$
$$D_i{}^{-} = \sqrt{D_i^{euc-} \times D_i^{cos-}} \tag{12}$$

Determine the degree of separation C_i between the current value of each index and the positive ideal solution as formula (13).

$$C_i = \frac{D_i{}^{-}}{D_i{}^{+} + D_i{}^{-}} \tag{13}$$

where $0 \leq C_i \leq 1$ and the greater the C_i is, the better the evaluation results are.

The significance of various moments can be measured using time weights. We assign time weights T to different years by solving the nonlinear programming problem as formula (14) [11].

$$\begin{cases} \max(-\sum_{j=1}^{q} T_j \ln T_j) \\ s.t. \lambda = \sum_{j=1}^{q} \frac{q-j}{q-1} T_j \\ \sum_{j=1}^{q} T_j = 1, 0 \leq T_j \leq 1 \end{cases} \tag{14}$$

where T_j represents the time weight in year j and q is the number of years. λ $(0 \leq \lambda \leq 1)$ indicates the importance of timing during the operator assembly process. The smaller λ, the more the evaluator focuses on the data that are closer to the evaluation time. Conversely, attention is given to data that are farther away from the evaluation time when λ is larger. A value of $\lambda = 0.1$ indicates extreme attention to recent data, while $\lambda = 0.9$ means that long-term data are of extreme importance.

Finally, we calculate the dynamic spatial comprehensive evaluation value as formula (15).

$$H_i = \sum_{j=1}^{q} T_j C_i \tag{15}$$

where the greater the H_i is, the better the evaluation results are.

4.3. Obstacle analysis method

We introduced the obstacle degree model to examine the obstacle indicators to determine the direction of enhancing green transformation to understand the influence of various indicators on green development. The obstacle degree model is a frequently used mathematical statistical model for a thorough assessment of ecological resources and the environment [21] [6]. The obstacle degree is calculated by formulas (16) and (17).

$$P_{ij} = 1 - Y_{ij} \tag{16}$$
$$O_{ij} = \frac{P_{ij} W_i}{\sum_{i=1}^{m} P_{ij} W_i} \tag{17}$$

where O_{ij} represents the obstacle degree of the ith indicator in year j, and P_{ij} represents the uncorrelation degree of indicator i in year j. W_i is the weight of a single factor to the overall goal calculated by the entropy model. On the basis of the obstacle degree model for individual indicators, we can calculate the obstacle degree on criterion layer A_n as formula (18).

$$A_n = \sum_{i=1}^{n} O_{ij} \tag{18}$$

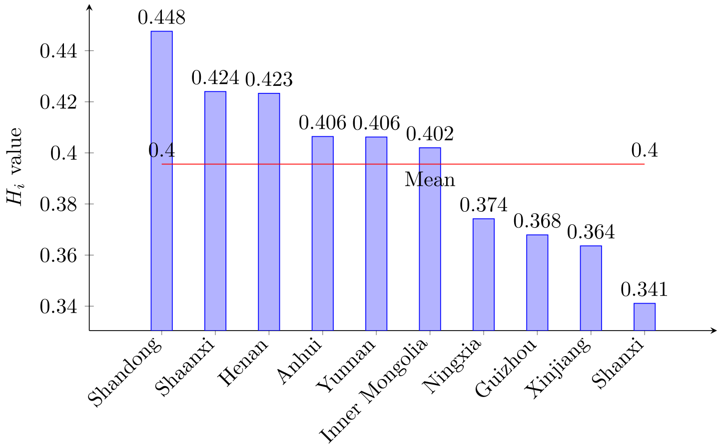

Fig. 2. Green Development Level of the Coal-resource-based Provinces.

5. Case study

5.1. Study area and data resources

We selected 10 provinces ranked among the top ten Chinese provinces in terms of raw coal production, namely Shanxi, Inner Mongolia, Anhui, Shandong, Henan, Guizhou, Yunnan, Shaanxi, Ningxia and Xinjiang. In recent years, the proportion of raw coal production of the regions accounting for China has continued to rise, from 88.18% in 2016 to 93.95% in 2021. Although these provinces are major exporting provinces of energy, traditional resource development models have not brought economic growth. In 2021, the total regional GDP of the ten provinces accounted for only 28.51% of the country's GDP. The ten provinces play important roles in China's energy security and economic development, and the low-carbon transformation of the provinces also determines whether China can achieve the synergistic promotion of energy security and sustainable economic development. Therefore, we selected ten provinces as the study area and provided important policy implications for the green development of coal-resource-based provinces.

The data of coal-resource-based provinces of China were obtained from the National Bureau of Statistics of China, the China Energy Statistical Yearbook, the China Electric Power Statistical Yearbook and the China Emission Accounts and Datasets (CEADs) from 2016 to 2022. Some missing data (such as technology market transactions in 2022) were calculated by the linear interpolation method based on the data of the past three years.

5.2. Results and discussion of dynamic evaluation

We used the entropy method to calculate the weight value of each indicator from 2016 to 2022, and then applied the dynamic spatial TOPSIS to obtain the evaluation values for different years. To facilitate the comparison between different attributes, a normalization method was used for dimensionless processing of the original data. The $\lambda = 0.2$ was determined by expert grading, and the time weights of 2016 to 2022 were $T_j = [0.0155, 0.0271, 0.0472, 0.0822, 0.1433, 0.2497, 0.4351]$. Based on the formula (15), we obtained the final dynamic spatial evaluation results of each province from 2016 to 2022.

As shown in the Fig. 2, the average comprehensive evaluation value of the 10 coal-resource-based provinces was 0.3956, based on which we could roughly divide the coal-resource-based provinces into two types, namely provinces with better or worse green development levels. The Shandong, Shaanxi, Henan, Anhui, Yunnan and Inner Mongolia belonged to better green development provinces, among which Shandong was higher than other provinces. From 2016 to 2022, the GDP of Shandong ranked third in China, far exceeding that of other coal-resource-based provinces. The proportion of tertiary industry (X2) showed an uptrend, which indicated that its industrial structure model continued to be optimized and upgraded. At the same time, technology capacity represented by technology market transactions (X4) and the full-time equivalent of R&D personnel of industrial enterprises above designated size (X5) is higher than that of other provinces, indicating that economic development and technology are important factors in improving the level of green development.

Shaanxi also had a better green development level. In terms of energy, the regional electricity redundancy continued to increase with the proportion of electricity from thermal power generation continuously decreasing, which reflected low-carbon development of the energy supply structure while taking into account the energy security. In terms of the environment, the level of environmental pollution such as carbon emissions intensity (X17) and SO2 emissions (X18) continued to decrease, along with the continuous enhancement of environmental carrying capacity. However, the indicators of economic development and technology represented by population (X1), proportion of tertiary industry (X2) and proportion of investment in clean electricity generation (X6) were relatively poor, which affected the overall green development score.

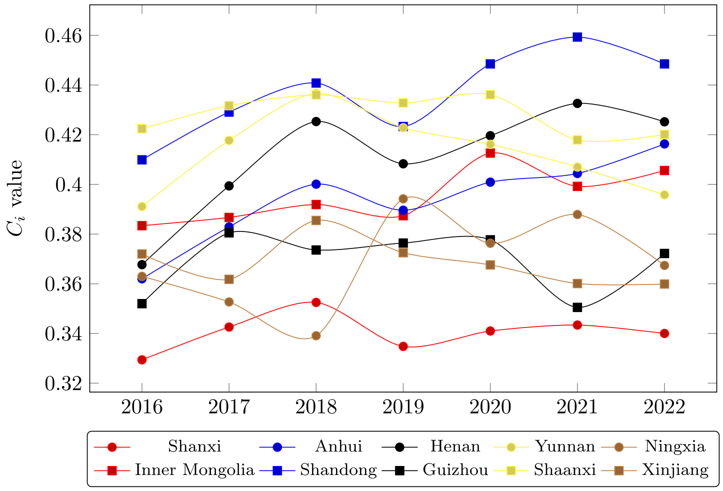

Fig. 3. Annual Evaluation Value of the Coal-resource-based Provinces.

Ningxia, Guizhou, Xinjiang and Shanxi were provinces with worse green development levels. The common features of these provinces were that they had rich coal resources and were in a stage of rapid development of industrialization and urbanization. Therefore, their economic and social development was closely related to coal production and consumption, forming an economic development model with high energy consumption and environmental pollution. In the context of carbon neutrality, the economic development model that mainly relies on resources is no longer suitable. It is necessary to accelerate the upgrading of industrial structure, strictly control the development of industries with high energy consumption and high carbon dioxide emissions, and increase the proportion of tertiary industry. At the same time, they should improve the clean and efficient use of coal and develop regional wind and solar energy resources.

From the perspective of the annual evaluation results, as shown in the Fig. 3, the green development level of the ten provinces showed a fluctuating trend, which indicates that considering the time weight in the evaluation process was necessary. The C_i values of Shandong, Inner Mongolia, Anhui and Henan, which are better green development provinces, generally increased, indicating that their green development levels gradually increased. However, the C_i values of Ningxia and Yunnan showed a fluctuating downward trend in recent years. They should identify obstacles that limit green development and develop policy proposals that address these problems. The other four provinces showed a relatively smooth fluctuating trend, which could transform the mode of economic growth and promote the level of green development with a green economy. We analyzed the factors restricting their green development level using the obstacle analysis method which is discussed in the next section.

5.3. Results and discussion of obstacle analysis

We applied an obstacle model to calculate the obstacle degree of coal-resource-based provinces and identified the major obstacle factors. The Fig. 4 shows temporal changes in economic, energy and environmental factors restricting the green development of coal-resource-based provinces. The obstacle degree fluctuated over time, demonstrating that the obstacles to green development in coal-resource-based provinces were dynamic. At the same time, the ranking of provinces in the same obstacle factor rarely changed over time, indicating that the importance of an obstacle factor for a province was relatively fixed. In addition, the economy was the greatest obstacle factor to the green development of coal-resource-based provinces, with the main range of obstacle degrees above 0.3 except for Shandong. The obstacles caused by energy were relatively concentrated, and those caused by the environment were scattered, which indicated that coal-resource-based provinces had similar difficulties in energy transition but different difficulties in environmental protection.

The province most restricted by economic development was Inner Mongolia. The industrial structure of Inner Mongolia was dominated by agriculture, animal husbandry and industry, and the proportion of tertiary industry was relatively low. In addition, its scientific and technological innovation ability was weak. As a result, increasing the proportion of the tertiary industry and scientific research investment are the main directions of green development in Inner Mongolia. Shandong was the most affected by the energy factor. Shandong is the leading province in regard to electricity production in China. However, it still cannot meet the needs of a large number of people and economic development and needs to transfer electricity from other provinces. In addition, Shandong mainly relies on thermal power generation, accounting for more than 85%. Therefore, to overcome the energy obstacle, Shandong should take advantage of its developed economy, increasing investment in clean energy and improving the energy supply structure. The environment had an important impact on both Shaanxi and Shandong. Due to natural conditions, Shaanxi had low vegetation coverage, which reduced the carrying capacity of the environment. In addition, Shaanxi and Shandong were both major provinces for the development and utilization of coal resources and thermal power, which led to high carbon dioxide emissions and increased environmental pollution. They should add more green spaces, and shift fossil energy to low-carbon energy through carbon capture, utilization and storage (CCUS) technology.

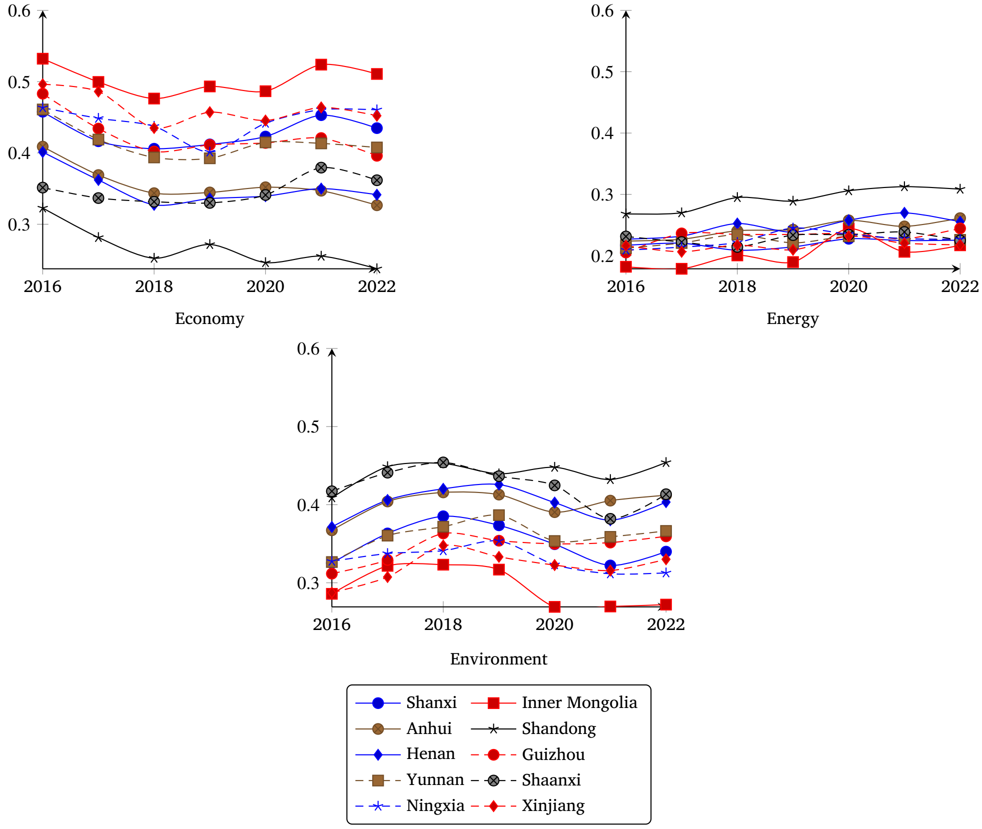

Fig. 4. The Change of Obstacle Degree in Economy, Energy and Environment During 2016-2022.

To further explore the obstacles restricting the green development of coal-resource-based provinces, we analyzed the obstacle results of the ten provinces in 2022. According to 18 indicators, the obstacle degree of the ten coal-resource-based provinces in 2022 was ranked, and the first six factors were selected for analysis. As shown in Table 3, the total obstacle degree of the top six obstacle factors in each province was over 54%, indicating that they were representative of the 18 obstacle factors.

There were some common features that obstructed the green development of coal-resource-based provinces. First, the main indicators that limited the green development of coal-resource-based provinces were average wind power density at 70 m (X8), technology market transactions (X4), full-time equivalent of R&D personnel of industrial enterprises above designated Size (X5), per capita carbon dioxide emissions (X16), carbon emissions intensity (X17) and degree of self-sufficiency in raw coal (X12), all of which appeared more than 6 times. They all belonged to energy, economy and the environment respectively, which indicated that coal-resource-based provinces should jointly promote economic development, low-carbon energy and environmental protection. While using coal resources to ensure energy security, they should increase investment in clean energy systems and low-carbon technologies to reduce carbon dioxide emissions from economic activities. Second, technological capacity, represented by technology market transactions and the full-time equivalent of R&D personnel of industrial enterprises above a designated size, was the core obstacle for better green development, with an average obstacle degree of 27.48%. Coal-resource-based provinces should take scientific and technological innovation as the main driving force for green development, developing low-carbon and zero-carbon technologies, such as low-carbon utilization of fossil energy, new power systems dominated by renewable energy, and the electrification level of terminal energy consumption, in energy-intensive industries.

6. Conclusions and suggestions

In this paper, to evaluate the balanced green development of coal-resource-based regions, we presented a green development indicator system of coal-resource-based regions (GDISCR) based on the 3E system. Furthermore, we proposed a novel comprehensive evaluation model, namely, the dynamic spatial TOPSIS method, for assessing the green development level with the GDISCR. Third, we introduced the obstacle analysis model to identify the obstacle factors restricting the green development of coal-resource-based regions from multiple dimensions. Finally, through the evaluation of ten coal-resource-based provinces, we analyzed the strengths and weaknesses of green development between different coal-resource-based provinces.

Table 3
The Obstacle Degree of the Ten Provinces in 2022.

Provinces	Items	Order					
		1st	2rd	3th	4th	5th	6th
Shanxi	Obstacle factors	X4	X5	X16	X8	X17	X14
	Obstacle degree	0.1536	0.1295	0.0829	0.0816	0.0661	0.0551
Inner Mongolia	Obstacle factors	X4	X5	X17	X8	X1	X16
	Obstacle degree	0.1839	0.1617	0.0688	0.0649	0.0565	0.0517
Anhui	Obstacle factors	X16	X17	X4	X8	X5	X12
	Obstacle degree	0.1046	0.1045	0.0986	0.0894	0.0805	0.0651
Shandong	Obstacle factors	X17	X16	X8	X12	X14	X11
	Obstacle degree	0.1143	0.1114	0.0926	0.0810	0.0753	0.0684
Henan	Obstacle factors	X4	X16	X17	X8	X5	X12
	Obstacle degree	0.1278	0.1045	0.1034	0.0834	0.0800	0.0645
Guizhou	Obstacle factors	X4	X5	X16	X17	X8	X13
	Obstacle degree	0.1347	0.1223	0.0976	0.0926	0.0822	0.0577
Yunnan	Obstacle factors	X4	X5	X16	X17	X8	X12
	Obstacle degree	0.1519	0.1273	0.1070	0.1057	0.0884	0.0580
Shaanxi	Obstacle factors	X5	X17	X16	X8	X4	X18
	Obstacle degree	0.1343	0.1131	0.1114	0.0981	0.0669	0.0639
Ningxia	Obstacle factors	X4	X5	X8	X14	X12	X18
	Obstacle degree	0.1619	0.1416	0.0794	0.0715	0.0672	0.0644
Xinjiang	Obstacle factors	X4	X5	X16	X17	X8	X12
	Obstacle degree	0.1587	0.1402	0.0807	0.0764	0.0724	0.0537

6.1. Main conclusions

(1) The green development indicator system of coal-resource-based regions (GDISCR) and dynamic spatial TOPSIS method established in this study could effectively evaluate the green development level of coal-resource-based regions. When they were combined with the obstacle analysis model, we identified the green development level and obstacle factors of coal-resource-based regions, which were helpful to the government formulating a green development strategy.

(2) Sorted by green development level, the coal-resource-based provinces could be divided into better and worse types. Shandong, Shaanxi, Henan, Anhui, Yunnan and Inner Mongolia belonged to better green development provinces, most of which showed a steady or upward green development trend. They should maintain their green development advantages and enhance the level of green development through the development of a green economy. Ningxia, Guizhou, Xinjiang and Shanxi were provinces with worse green development levels. They should improve the energy supply structure by developing clean coal technology and regional wind and solar energy resources to reduce environmental pollution.

(3) The obstacles restricting the green development of coal-resource-based provinces were dynamic, but the importance of an obstacle factor for provinces was relatively fixed. In addition, the greatest obstacle to the green development of coal-resource-based provinces was the economy, in which technological capacity was the core, and they had similar difficulties in energy transition but different difficulties in environmental protection. To obtain a better green development level, coal-resource-based provinces should increase investment in clean energy and reduce carbon dioxide emissions from economic activities through low-carbon technologies.

6.2. Suggestions and limitation

Based on the evaluation and analysis results, we propose corresponding suggestions for improving the green development level of coal-resource-based regions.

(1) Promote economic growth and low-carbon technologies. Coal-resource-based regions should transform the mode of economic growth and promote the level of green development with a green economy, strictly controlling the development of high-energy consumption and high-emission industries. In addition, they should increase investment in clean energy through cross-regional cooperation and reduce carbon dioxide emissions from economic activities through low-carbon technologies.

(2) Coordinating energy security and clean utilization. Coal will still play a role as the main consumption fuel before clean energy is reliable. Coal-resource-based regions should improve the clean and efficient use of coal to ensure the country's energy security. In addition, they should make full use of wind, solar, hydro and other renewable resources and accelerate the coordinated development of renewable and coal-based energy, establishing a multienergy complementary integrated energy system.

(3) Strengthen environmental construction and pollution control. Coal-resource-based regions could increase regional carbon sinks through afforestation and urban greening and promote environmental infrastructure construction, improving environmental carrying capacity. Furthermore, they should strengthen the control of high-polluting enterprises, eliminate backward production capacity, and reduce the emission intensity of major pollutants per unit of product.

Although we provide a useful discussion on the green development level assessment and obstacle analysis of coal-resource-based regions, this study still has limitations. First, the number of sample provinces selected in the case study may be somewhat small. Second, the time span chosen for this study may be somewhat short. In the future, we will verify the validity of the study by including a broader temporal dimension and more cases.

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CRediT authorship contribution statement

Yutong Chun: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jun Zhang:** Project administration, Funding acquisition, Conceptualization. **Yijie Han:** Data curation.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Data availability

Data associated with this study was from the National Bureau of Statistics of China, the China Energy Statistical Year book, China Electric Power Statistical Year book and the China Emission Accounts and Datasets (CEADs).

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