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Model-based temporal evolution and spatial equilibrium analysis of green development in China's Yangtze River Economic Belt from 2009 to 2018

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ABSTRACT

Green development is one of the important guidance and core contents of high-quality development of regional economy and society, and its spatial–temporal pattern evolution analysis is helpful to the scientific formulation of relevant policies. However, the green development evaluation is faced with multi attribute decision making difficulties. In view of this, firstly, based on discussing the connotation of green development from ontology, epistemology, axiology and methodology, a new evaluation indicator system from the four dimensions of energy conservation, emission reduction, efficiency increase and harmony was explored. Then, coupling symmetric cross entropy multi attribute decision making and Gini coefficient method, a comprehensive evaluation framework of temporal evolution and spatial equilibrium of green development was constructed and applied in 11 provinces (cities) of China's Yangtze River Economic Belt (YEB) from 2009 to 2018. The results show that during the study period, the green development level of YEB has improved year by year, but there was still a large gap. Among the 120 research samples, only 41.7% had a ranking score of more than 6, and only Chongqing in 2017 had a ranking score of more than 8. The Gini coefficient of green development in 11 provinces (cities) is about 0.2, which is balanced on the whole, but there is a significant difference in the indicators, such as proportion of new energy power generation, sulfur dioxide emission per 10^4 RMB yuan GDP and proportion of investment in environmental protection; The effect of energy conservation and emission reduction is obvious, while efficiency increase and harmony need to be improved. The complementary role of 11 provinces (cities) in YEB's green development has become increasingly prominent, which made that YEB (as a whole) ranked second in comparison with 11 provinces (cities) in 2018.

1. Introduction

Green development is a mode of economic growth and social development aiming at efficiency, harmony and sustainability (Li et al., 2020). Facing the dual pressure of global climate change and frequent human activities, as well as the current and future social and economic needs, the role of promoting green development is becoming increasingly prominent (Feng et al., 2017). While it is common awareness of the importance of evaluating the green development, revealing its annual ranking and regional equilibrium can help the scientific formulation of relative measures.

In this process, many aspects need to be considered, such as natural, social, environmental, economic, technical indicators, and so on (Zhu and Zhang, 2019). Therefore, green development assessment faces the problem of multi-attribute decision-making, of which the green development indicator system has been studied and explored continuously. Green development evaluation indicator system has been constructed by WECD (World Commission on Environment and Development) in 1987 (WECD). OECD (organization for economic cooperation and development) has established four types of green economy: natural asset base, environmental and resource productivity in economic activities, environmental factors of quality of life, policy response and economic opportunities (OECD, 2011). UNEP (United Nations Environment Programme) has subsequently explored a new green economy measurement framework covering resource efficiency, economic transformation, social progress and human well-being (UNEP, 2012). CCIEE

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(China Center for International Economic Exchanges) and WWF (World Wide Fund for Nature or World Wildlife Fund) have constructed a provincial green economy indicator system of China, which includes three first level indicators, six second level indicators, 14 third level indicators and 30 fourth level indicators, including social and economic development, resource and environmental sustainability and green transformation drive (Zhang, 2013). Wang et al. (2018) develop the green development evaluation indicator system from enhancement of living environment, treatment and utilization of pollutant, improvement of ecological efficiency, optimization of economic growth and development of innovative potential. Xiang (2019) used factor analysis and cluster analysis to calculate the correlation of indicators, combined with PSR (Pressure-State-Response) model to determine three criteria and 22 secondary indicators; Guo (2020) has constructed a comprehensive evaluation indicator system of green development with four criteria layers and 23 indicators. Li et al. (2020) established an indicator system in terms of five dimensions: living environment, pollutant treatment and utilization, ecological efficiency, economic growth and innovative potential. Obviously, the evaluation indicator system of green development has not yet reached a consensus, and scholars have constructed the applicable indicator system from different angles based on the actual research problems. Therefore, closely following the development of the times and starting from the expansion of philosophical connotation and the current situation of economy and society, it is still an important topic to explore the performance evaluation indicator system of green development.

At present, a considerable number of articles have conducted in-depth research on the boundary characteristics and evaluation analysis of green development (Dong et al., 2021; Fang et al., 2020; Guo et al., 2021; Hou et al., 2019; Li et al., 2020; Sun et al., 2018; Wang et al., 2018; Wang et al., 2019). In the process of decision analysis, TOPSIS (technology for order preference by similarity to ideal solution) method is favored by scholars because of its simple calculation and strong applicability (Wang et al., 2021; Diao et al., 2020; Yu et al., 2021). However, Liu and Qiu (1996) had discovered that there was a problem that TOPSIS could not be sorted, and then proposed the included angle measurement method, which was compared with TOPSIS to obtain better results. Further, some scholars found that the included angle measurement method also has shortcomings (Kong and Liu, 2009), only considering the included angle closeness of the two schemes and ignoring the length difference; If the included angles of the two schemes are exactly the same and the lengths are different, the included angle method cannot get the correct conclusion, and then the relative entropy ranking method is proposed (Zhao et al., 2010). Furthermore, Lu and Li (2016) found that the relative entropy does not satisfy the symmetry and trigonometric inequality, which is not the real distance between the scheme and the ideal scheme and the negative ideal scheme, but it is of practical significance to take it as the difference measure between the scheme and the ideal scheme and the negative ideal scheme. Based on this, the relative entropy ranking method was improved and a new ranking method, symmetric cross entropy multi attribute decision making method (SCEMADM) was obtained, which satisfies the symmetry and boundedness of relative entropy. SCEMADM has been proved to be a reasonable and efficient multi-attribute decision analysis tool with effectiveness and rationality, but we found that this method has rarely been applied (Feng et al., 2018), so it is necessary to carry out more application practice and comparative research with TOPSIS.

As one of the major national strategic development areas and a leading demonstration belt for the construction of ecological civilization, YEB has unique advantages and great development potential. However, its development faces many difficulties and problems to be solved urgently, including the low level of sustainable development, the grim situation of ecological environment, and the arduous task of transformation and upgrading of energy intensive industries (Li et al., 2020; Zhao et al., 2021). However, it spans East, middle and West China, resulting in various differences in economy, society and nature among 11 provinces (cities) (Yang et al., 2022). Under this background, to promote the high-quality development of YEB, it is necessary to innovate the regional coordinated development mechanism and ensure the orderly promotion and spatial equilibrium of green development. Therefore, it is of great significance to explore the temporal and spatial pattern evolution trend of green development of YEB.

In view of this, this study aimed to explore the temporal evolution and spatial equilibrium characteristics of green development in China's YEB from 2009 to 2018 by coupling SCEMADM and Gini coefficient methods, and compared with TOPSIS method. According to all the sixteen indicators' data in 2009–2018 in YEB, we analyze the main contradictions in the green development process of 11 provinces (cities) in the YEB based on the Cannikin's law. The specific objectives of the present study were to: (1) Explore the temporal evolution of green development in the YEB from 2009 to 2018; (2) Reveal the spatial equilibrium of green development in the 11 provinces(cities); (3) Discover the short board and analyze the corresponding countermeasures.

2. Methods

In this section, we first discuss the Era Connotation of green development, and then construct a new evaluation index system of green development; Then it describes the two main methods used, SCEMADM and Gini coefficient method. The main symbols, variables and their meanings in the method framework are shown in Table 1.

2.1. Analysis and construction of indicator system

As a new economic growth and social development mode, green development is derived from green economy (Fang, 2010). As early as the 1990s, there have been researches on green development, among which the British environmentalists described the blueprint of "green economy" in the blue book of green economy. Although the "green economy" at this time was not completely equivalent to the concept in today's sense, the new ideas contained in it have been widely spread all over the world. It is on the basis of this concept that China has put the concept of green development on the agenda.

The concept of green development runs through the construction of ecological civilization, which is an indispensable content in the construction of social economy, politics, culture and so on. It is a new concept of integration and development, which unifies the ontology, epistemology, axiology and methodology of development. As the theme of the times, development is the most important existing factor of the society. All practical purposes, concepts and policies in the field of social

Table 1
Nomenclature.

Abbreviations and symbols	Meanings
YEB	Yangtze River Economic Belt
E-E-E-H	Energy conservation, emission reduction, efficiency increase and harmony
SCEMADM	Symmetric cross entropy multi attribute decision making
AHP	Analytic hierarchy process
CRITIC	Criteria Importance Though Intercrieria Correlation
TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution
O_i	The i-th evaluation object
C_j	The j-th evaluation indicator
y_{ij}	The value of C_j for O_i
z_{ij}	The standardized value of y_{ij}
w_j	The weight of indicator C_j
x_{ij}	The weighted value of z_{ij}
X^+	Positive ideal solution vector
X^-	Negative ideal solution vector
D_i	Relative closeness between O_i and positive ideal object
G	Gini coefficient

life should be unified on development, thus forming the ontological concept of development (Li, 2018). As far as ontology is concerned, the organic unity of nature, human and society is the basis of the concept of green development; for epistemology, green development goes beyond the one-sided vision of seeking development and full submission to nature, liberates the development of human and nature from the opposite, and realizes the real inseparable relationship between human and nature (Chen and Ha, 2018); In terms of axiology, green development has changed from focusing only on human value to focusing on the combination of human value and natural value; in terms of methodology, green development is not only a theory, but also a dialectical result of combining theory with practice, which is a scientific answer to the question of how to realize sustainable development.

Under the premise of low consumption and low emission, more consideration of ecological environment can be regarded as the important characteristics of green development and improving quality and efficiency and reasonable innovation are the ways to realize green development. The purpose of green development is to realize the rapid, reasonable and common development of human and natural environment with unremitting efforts. In a nutshell, green development is to consider energy conservation, emission reduction, efficiency increase and harmony, i.e. E-E-E-H (Fig. 1), and promote energy conservation, emission reduction and efficiency increase by innovation and technology, so that human and nature can develop together.

In this study, based on the above analysis and the previous studies (Cheng and Ge, 2020; Feng et al., 2017; Gao, 2019; Guo, 2020; Li et al., 2020; Zhou et al., 2020; He et al., 2021; Long et al., 2021; Sun et al., 2018; Wang et al., 2018; Wang et al., 2021; Xiang, 2019; Zhang, 2013; Zhu and Zhang, 2019), a new evaluation indicator system was constructed from four aspects of energy conservation, emission reduction, efficiency increase and harmony, i.e. E-E-E-H, as shown in Table 2.

2.2. SCEMADM method

In the TOPSIS method, Euclidean distance is generally used to measure the difference of objects. However, the evaluated object with closer distance to the ideal solution may also be closer to the distance of the negative ideal solution, and the point corresponding to the object may just fall on the vertical line corresponding to the positive ideal solution and the negative ideal solution, which will lead to the ranking result that cannot reflect the advantages and disadvantages of each evaluated object. SCEMADM method replaces Euclidean distance with symmetric cross entropy, which can effectively overcome the above problems to some extent (Lu and Li, 2016). The main steps are as follows:

Suppose $O = (O_1, O_2, \ldots O_m)$ and $C = (C_1, C_2, \ldots C_n)$ are the object set and indicator set in the multi attribute decision making problem respectively. y_{ij} $(i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)$ is the value of indicator C_j for object O_i. The objective decision matrix is:

Table 2
Evaluation indicator system of green development.

Code	Criteria	Indicators	Direction
C_1	Energy conservation	Energy consumption per 10^4 RMB yuan GDP (10^4 tons of standard coal)	−
C_2		Water consumption of per 10^4 RMB yuan GDP (m^3)	−
C_3		Public transport per 10^4 people (standard station)	+
C_4		Proportion of new energy power generation (%)	+
C_5	Emission reduction	Chemical oxygen demand emission per 10^4 RMB yuan GDP (tons)	−
C_6		Sulfur dioxide emission per 10^4 RMB yuan GDP (tons)	−
C_7		Comprehensive utilization rate of industrial solid waste (%)	+
C_8		Urban sewage treatment rate (%)	+
C_9	Efficiency increase	Proportion of science and education investment in GDP (%)	+
C_{10}		Industrial added value rate (%)	+
C_{11}		GDP per capita (10^4 yuan)	+
C_{12}		Proportion of output value of the tertiary industry (%)	+
C_{13}	Harmony	Proportion of environmental protection investment in GDP (%)	+
C_{14}		Forest coverage (%)	+
C_{15}		Green coverage rate of built-up area (%)	+
C_{16}		Proportion of days with excellent air quality (%)	+

$$Y = \begin{pmatrix} y_{11} & y_{12} & \cdots & y_{1n} \\ y_{21} & y_{22} & \cdots & y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ y_{m1} & y_{m2} & \cdots & y_{mn} \end{pmatrix} \tag{1}$$

Based on $Y = [y_{ij}]_{m\times n}$, the standardized decision matrix is established according to Eq. (2).

$$z_{ij} = y_{ij} / \sum_{i=1}^{m} y_{ij}^2 \tag{2}$$

Determine weight. This study considers the expert experience, the statistical law of objective data and the correlation between indicators, and adopts the combined weighting method of AHP and CRITIC. The weight of C_j is:

$$w_j = \sqrt{a_j b_j} / \sum_{j=1}^{n} \sqrt{a_j b_j} \tag{3}$$

where a_j and b_j are the weight of AHP and CRITIC method respectively.

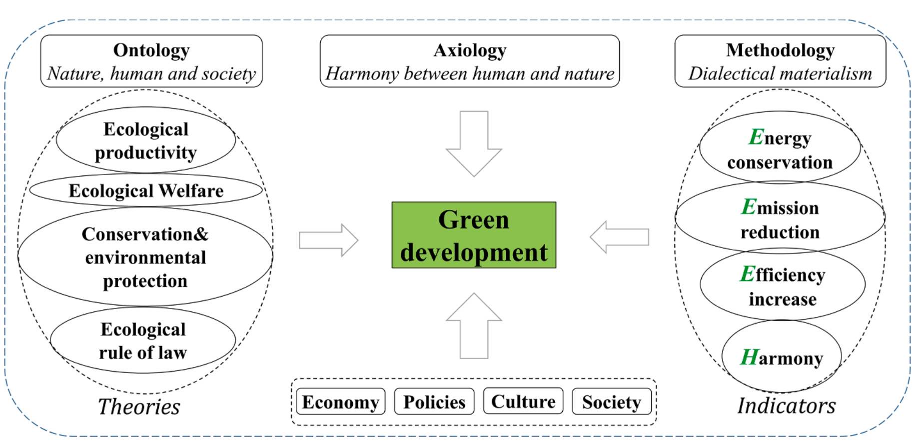

Fig. 1. The ideology of green development.

Determine the weighted normalization matrix and the ideal solution. The dimensionless decision matrix is multiplied by the weight of each index to obtain the weighted decision matrix $X = [x_{ij}]_{m\times n}$. Where $x_{ij=} w_j{\cdot}z_{ij}$.

For the positive indicator (+) and negative indicator (-), calculate positive ideal solution vector X^+ and negative ideal solution vector X^-:

$$x_j^+ = \max_i\{x_{ij}\}, x_j^- = \min_i\{x_{ij}\}\ (+) \tag{4}$$

$$x_j^+ = \min_i\{x_{ij}\}, x_j^- = \max_i\{x_{ij}\}\ (-) \tag{5}$$

$$X^+ = \{x_1^+, x_1^+, \cdots, x_n^+\},\ X^- = \{x_1^-, x_1^-, \cdots, x_n^-\} \tag{6}$$

Calculate symmetric cross entropy. Suppose D_i^+ is the symmetric cross entropy between O_i and X^+. D_i^- is the symmetric cross entropy between O_i and X^-.

$$D_i^+ = \sum_{j=1}^{n}\left[x_j^+\ln\frac{2x_j^+}{x_j^+ + x_{ij}} + (1-x_j^+)\ln\frac{2(1-x_j^+)}{2-x_j^+-x_{ij}} + x_{ij}\ln\frac{2x_j^+}{x_j^+ + x_{ij}} + (1-x_{ij})\ln\frac{2(1-x_j^+)}{2-x_j^+-x_{ij}}\right] \tag{7}$$

$$D_i^- = \sum_{j=1}^{n}\left[x_j^-\ln\frac{2x_j^-}{x_j^- + x_{ij}} + (1-x_j^-)\ln\frac{2(1-x_j^-)}{2-x_j^--x_{ij}} + x_{ij}\ln\frac{2x_j^-}{x_j^- + x_{ij}} + (1-x_{ij})\ln\frac{2(1-x_j^-)}{2-x_j^--x_{ij}}\right] \tag{8}$$

Calculate the relative closeness degree. Relative closeness degree D_i of each object to the positive ideal object is calculated by Eq. (9). The closer the value of D_i is to 1, the closer the evaluation object O_i is to the optimal object; The smaller the value of D_i, the worse the evaluation object O_i.

$$D_i = D_i^- / (D_i^+ + D_i^-) \tag{9}$$

2.3. Gini coefficient

Gini coefficient, a commonly used economic measurement for income inequality or wealth distribution (Atkinson, 1970; Bosi and Seegmuller, 2006), can theoretically range from 0 to 1, with higher values indicating greater inequality. The Gini coefficient is calculated based on the Lorenz curve, a graph of cumulative percentage of household income on percentage of cumulative population with population is ordered from lowest to highest income (Barr, 1988). Generally, 0.4 is taken as the warning value of Gini coefficient. More than 0.4 indicates a large income gap.

Similarly, the 16 indicators proposed in section 2.1 reflects the green development level from various aspects, and there is imbalance in many indicators according to the economic and social development data of 11 provinces (cities) in YEB, which is relatively consistent with the problem of equal income distribution of residents. Therefore, in this study, Gini coefficient method was considered to describe the spatial equilibrium degree of region green development level and a simple Gini coefficient formula derived by Zhang (2007) was used to calculate the Gini coefficient of the 16 indicators. The formula is as follows:

$$G = 1 - (2\sum_{i=1}^{n-1}p_i + 1)/n \tag{10}$$

where G is Gini coefficient; p_i is the percentage of the sum of each indicator from the first object to the i-th one in the total amount; n is the number of groups.

According to the international standards and equilibrium analysis reality of green development, the division and connotation of Gini coefficient is described in Table 3.

3. Results

3.1. Study area

YEB in China refers to the economic belt around the Yangtze River, starting from Yunnan in the West and reaching Shanghai in the East (Fig. 2). It covers 11 provinces (cities) including Yunnan, Sichuan, Guizhou, Chongqing, Hunan, Hubei, Jiangxi, Anhui, Zhejiang, Jiangsu and Shanghai, covering an area of about 2.0523 million km^2, accounting for 21.4%, while the population and GDP exceed 40% of China's total.

In this study, 11 provinces (cities) with 10-year socio-economic data records (from 2010 to 2019) were downloaded from the National Bureau of Statistics (https://www.stats.gov.cn/) and government websites of the Bureau of Ecology and Environment in each region. The datasets are available and have been processed with quality control with a missing data rate of less than 0.1%.

In addition, the data of 16 indicators of YEB as a whole are calculated, of which 7 indicators, C_1, C_3, C_5, C_6, C_9, C_{11} and C_{13} are obtained based on the basic data of YEB (as a whole), and the rest indicators take the average value of each indicator in 11 provinces (cities).

3.2. Temporal evolution analysis

Fig. 3 depicts the time series evolution from 2009 to 2018. Here, the relative closeness degrees obtained according to Eq. (9) were multiplied by 10 as the ranking score.

From the perspective of province (city), the state of green development is not optimistic. The average value of green development ranking score of 11 provinces (cities) during the study period is 5.6903, and only 42.6% of them have a score of 6 or above. Among the 120 samples studied, the highest score was 8.2233 (Chongqing, 2017), and the worst occurred in Guizhou in 2009. Nevertheless, we can also find that although there is still a large gap with the ideal state, the green development level of YEB basically presents a good trend of steady improvement during this period. Specifically, Shanghai and Chongqing have obvious advantages and continue to be stable, which matches their economic and social development level. As two municipalities directly under the central government in YEB, Shanghai and Chongqing have remarkable comprehensive strength in green development.

In addition, although Hubei declined to a certain extent in 2011, the level of green development in the past decade is basically at a relatively high level. Sichuan and Yunnan are located at the western end of YEB, with superior natural conditions, especially in the development and use of new energy, which makes the regional air condition and harmony index higher. Anhui, Jiangxi and Jiangsu are relatively backward and have not reached 6 points in the past decade. The development and utilization level of new energy in Anhui is weak all the year round, and the tertiary industry accounts for a relatively low proportion. On the whole, Anhui mainly depends on agricultural industry, while the tertiary industry develops slowly and relies too much on fossil energy such as coal, with high pollutant emission and low efficiency; Jiangsu is also subject to the low development and use of new energy, and due to the rapid development of urbanization, the green vegetation cannot even be supplied manually, and the degree of harmony is low under the

Table 3
Division and connotation of Gini coefficient.

Grade	Gini coefficient	Description
I	[0,0.2)	Absolute equilibrium
II	[0.2 ~ 0.3)	General equilibrium
III	[0.3 ~ 0.4)	Low disequilibrium
IV	[0.4 ~ 0.5)	General disequilibrium
V	[0.5 ~ 1]	Serious disequilibrium

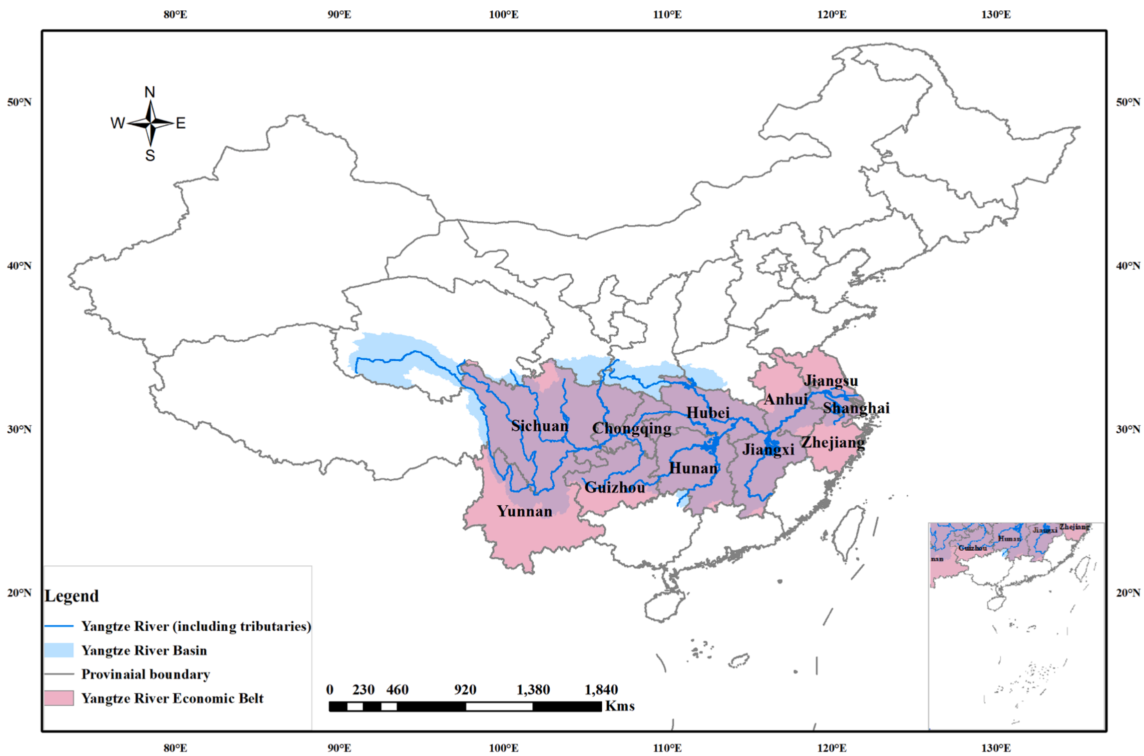

Fig. 2. Location of the administrative division of YEB.

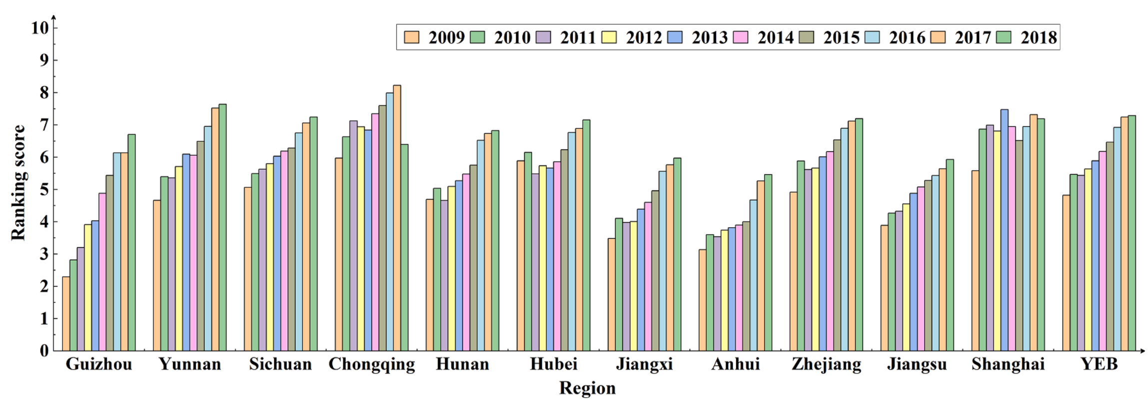

Fig. 3. The green development temporal evolution in 11 provinces(cities) of YEB.

condition of low natural background value; Similar to Anhui, Jiangxi's tertiary industry develops slowly and the process level is relatively low, resulting in high water consumption per unit of GDP.

On the whole, the green development level of YEB during the study period reached a score of 6.1356, while the average value of 11 provinces (cities) is only 5.6903, which reflects that the provinces (cities) in YEB have realized complementary advantages to a certain extent. Fig. 4 shows that the ranking of green development in 11 provinces (cities) has great uncertainty. However, the ranking of YEB (as a whole) shows a steady upward trend. Specifically, in comparison with 11 provinces (cities), YEB (as a whole) ranked sixth or seventh in its green development score from 2009 to 2013, fourth or fifth in 2014–2017, and jumped to second place in 2018, second only to Yunnan, which reflects that this complementary role is becoming more and more prominent.

3.3. Spatial equilibrium analysis

Fig. 5 depicts the spatial equilibrium situation of green development in 11 provinces(cities) of YEB from 2009 to 2018 based on Gini coefficient. Obviously, the spatial equilibrium state of 11 provinces (cities) varies greatly in 16 indicators, but the interannual change is weak and fluctuates in a small range. This verifies the significance of the economic and social differences in YEB. Concurrently, driven by the national strategic layout and policies, the region maintains a good coordinated development trend.

By comprehensively considering 16 indicators through weighting method, the spatial equilibrium index of green development level of 11 provinces (cities) in YEB from 2009 to 2018 was stable around 0.2, and fluctuated slightly up and down at the critical point of absolute equilibrium and general equilibrium. However, from the perspective of single indicators, there are significant differences in some indicators and there are no signs of improvement, such as proportion of new energy power generation (average 0.42), sulfur dioxide emission per 10^4 RMB yuan GDP (average 0.41) and proportion of investment in environmental protection (average 0.40). In addition, although the average Gini coefficient of per capita GDP is 0.28, which is close to the imbalance, the gap has narrowed year by year, from 0.33 in 2009 to 0.25 in 2018. Focusing on C_3, C_8, C_9, C_{12}, C_{15}, C_{16} and other indicators, they all

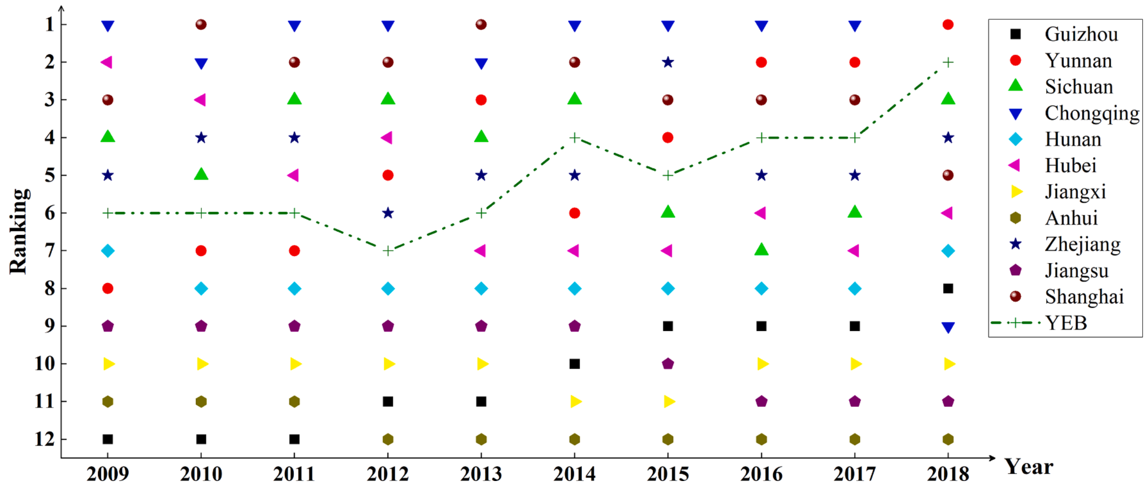

Fig. 4. The green development ranking of YEB and its 11 provinces(cities).

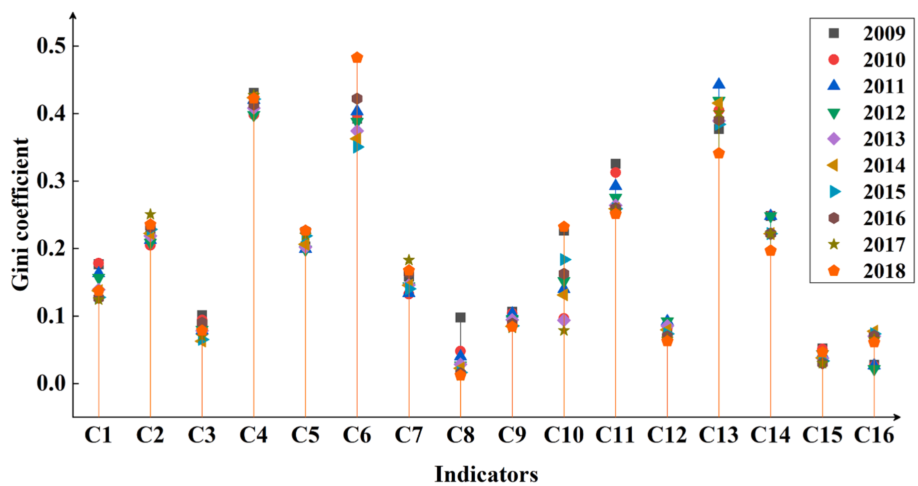

Fig. 5. The Gini coefficient of green development in 11 provinces(cities) of YEB.

showed good results, and the Gini coefficient was basically below 0.1. These indicators cover science and technology, public transport, sewage treatment and green area, reflecting the common determination of YEB in environmental governance and protection, and considerable human and material resources have been invested. In order to further build YEB into a coordinated development belt of interaction and cooperation between the East, China and the West with global influence, we still need to strengthen efforts, strive to advance together and develop with high quality.

4. Discussion

4.1. E-E-E-H cask effect analysis

In order to analyze the current situation of green development in 11 provinces (cities) of YEB, explore their shortcomings and implement accurate policies, this section discusses their coordinated development in four aspects, E-E-E-H. According to the Cannikin's law, how much water a bucket can hold does not depend on the highest piece of wood on the bucket wall, but on the shortest piece on the bucket wall. Only by heightening it can the bucket be filled with water. The same is true for regional green development. If there are shortcomings, we should consider identifying them as soon as possible and making up for them; At the same time, we should "consolidate the strong and make up for the weak", that is, first consolidate the advantages and then make up for the weak.

Fig. 6 depicts the green development ranking values in 11 provinces (cities) of YEB in 2018 in view of the four aspects, i.e. E-E-E-H. It is obvious that the 11 provinces (cities) have made good achievements in emission reduction, followed by energy conservation. However, there is an urgent need to optimize and improve efficiency increase and harmony.

Obviously, YEB has outstanding performance in energy conservation and emission reduction, but it lags behind in efficiency increase and harmony. In terms of provinces, Anhui's green development is relatively backward (5.4625), but it shows a high level in emission reduction (9.3595), while the other three aspects do not reach 5, especially in harmony (only 2.4182). It is found that Anhui has many shortcomings in green development and should continue to do well in emission reduction and strive to develop process technology to save energy and increase efficiency. Especially, the most important thing is to strengthen environmental protection, improve forest coverage and optimize air quality. Correspondingly, Yunnan had the highest level of green development in 2018, with a ranking score of 7.6450. This province has shown good results in four aspects of E-E-E-H, and the relatively backward aspect is the increase of efficiency. Increasing investment in science and technology, optimizing industrial structure and increasing GDP are the main affairs facing Yunnan.

In addition, the harmony of Jiangsu is more significant, and the ranking score is only 0.8347, which is close to the negative ideal

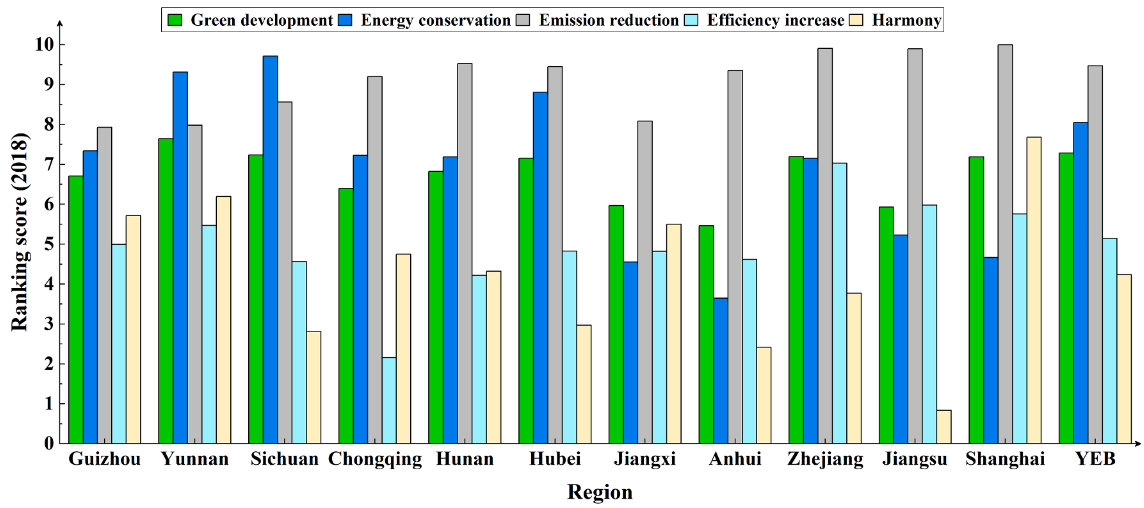

Fig. 6. E-E-E-H analysis of green development in YEB (2018).

solution. As a result, Jiangsu ranks 10th (penultimate) in the overall green development level when the other three aspects are good. For Jiangsu, increasing investment in environmental protection and optimizing air quality are the top priorities of the current green development strategy. Other provinces can also find weaknesses according to Fig. 6, so as to trace the original indicators and explore the direction of regulation. Not listed one by one.

4.2. Comparison with TOPSIS

TOPSIS is a multi-attribute decision analysis method based on ideal solution approximation, which has been successfully and widely used in many fields (Foroozesh et al., 2022; Jato-Espino et al., 2018; Vavrek and Chovancová, 2019; Wang et al., 2021). The basic principle of TOPSIS method is to sort by detecting the distance between the evaluation object and the optimal solution and the worst solution. If the evaluation object is closest to the optimal solution and furthest away from the worst solution, it is the best; Otherwise, it is not optimal. The SCEMADM method used in this study improves the distance function in TOPSIS. Therefore, in order to verify the effectiveness of SCEMADM method in the ranking of green development in YEB from 2009 to 2018, this section compares the ranking results with the traditional TOPSIS method. On the one hand, rank 120 samples according to the results of this study (1–120), and observe the distribution of the ranking values of two methods, as shown in Fig. 7 (Left); On the other hand, the ranking of the two methods is presented at the same time (1–120), and the fitting of the two methods is observed, as shown in Fig. 7 (Right).

Fig. 7 show that although the ranking values of SCEMADM and TOPSIS fluctuate many times, they have basically the same ranking results within the controllable range. From the comparison of ranking, it shows that the head and tail are consistent, the middle fluctuates greatly, and the two ends tend to be stable. Importantly, the former expands the interval length of sorting values to both ends, from [2.9428,6.3780] to [2.2930, 8.2233], which is more conducive to distinguishing samples and furtherly realizing the comparable ranking.

5. Conclusion

In this study, we proposed a model-based analysis framework that can determine the spatiotemporal variation in region green development, and we demonstrated its application in YEB from 2009 to 2018. From this study, the following conclusions were obtained:

(1) Green development is a dynamic concept, which needs to be studied in combination with the characteristics of the times. Energy conservation, emission reduction, efficiency increase and harmony are the four important characteristics of green development. Based on this, this study constructed an E-E-E-H evaluation indicator system of regional green development.

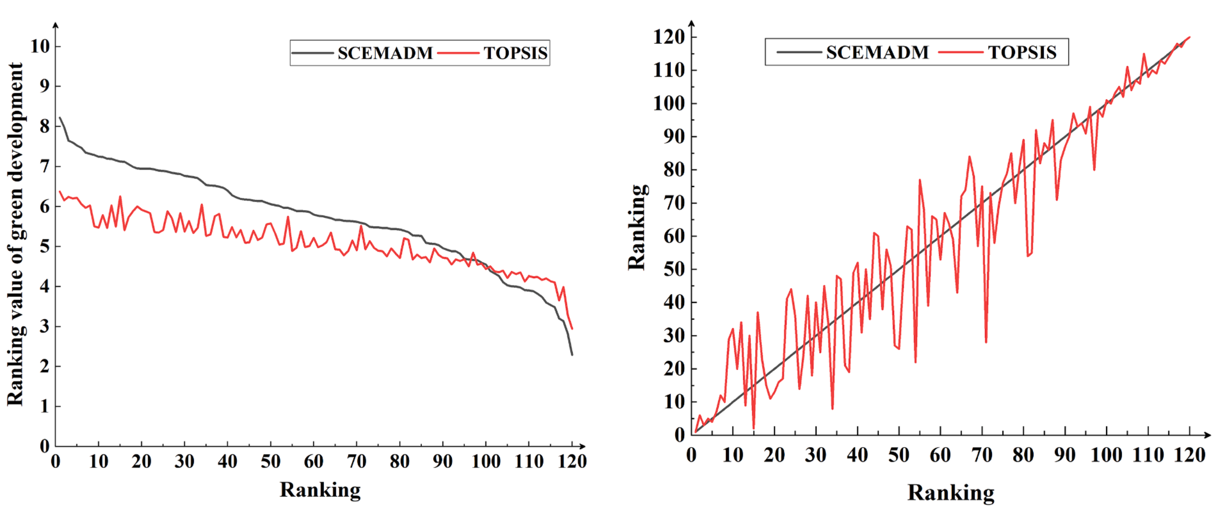

Fig. 7. Comparison between SCEMADM and TOPSIS.

(2) This paper studied the evolution trend of green development in YEB from the time dimension. The overall ranking score of green development of YEB increased from 4.8229 in 2009 to 7.2874 in 2018, an increase of 51.1%. The complementary advantages of 11 provinces (cities) have significantly promoted the overall green development of YEB, however, the situation is not optimistic, only 42.6% of the samples reached more than 6 points from the perspective of provinces (cities).

(3) From 2009 to 2018, 11 provinces (cities) of YEB were basically in the equilibrium state, and the Gini coefficient hovered around 0.2, but there was a large gap between 16 indicators, including the proportion of new energy power generation, Sulfur dioxide emission per 10^4 RMB yuan GDP and proportion of investment in environmental protection are in the state of general disequilibrium.

According to the above conclusions, YEB in the era of high-quality development needs to continue to optimize its outstanding advantages in energy conservation and emission reduction, adjust the industrial structure, improve resource utilization efficiency, increase scientific and technological investment, strive to make great progress in efficiency and harmony, and promote the green development of the region. In addition, overall planning, coordinated governance of upstream, middle and downstream, and further amplifying the complementary advantages of 11 provinces (cities) are one of YEB's important strategies for green development in the future.

The proposed coupling model based on SCEMADM and Gini coefficient as a method of decision ranking and equilibrium analysis is practical and effective, and the spatiotemporal variation in region green development provides some guideline for formulating policies for sustainable and high-quality development. The results of this study can not only help guide green development strategy in China's YEB but also contribute to regional coordination and environmental protection.

CRediT authorship contribution statement

Yafeng Yang: Conceptualization, Methodology, Software, Writing - review & editing. **Hongrui Wang:** Supervision, Funding acquisition. **Cheng Wang:** Methodology, Visualization. **Bo Yang:** Data curation..

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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