



Analysis on the resource and environmental carrying capacity of coal city based on improved system dynamics model: a case study of Huainan, China

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Received: 29 April 2022 / Accepted: 7 December 2022 / Published online: 23 December 2022
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Abstract

As the major energy bases, numerous coal cities in China are facing severe challenges in terms of resources and environment. In order to overcome the disadvantages of static evaluation, this study selected Huainan city, a typical coal city in China, as the case, and combined with the improved SD (system dynamics) model, analyzed its RECC (resource and environmental carrying capacity) systematically and dynamically. Firstly, a SD model of RECC system including resource-environment and society-economy subsystem was constructed. Then, the control parameters were determined objectively according to the analysis results of BP-DEMATAL model. Thirdly, we designed 18 simulation scenarios based on orthogonal test to dynamically predict the development trend of RECC in different conditions. Results show that: (1) From 2019 to 2030, the RECC of Huainan is generally on the rise. (2) In all simulation scenarios, test 12 is the most effective way of improving RECC. (3) The factors with the greatest influence on the simulation results are GDP, output value of secondary production, total expending on environmental protection, and coal production. This study provides a reference for the analysis method of RECC and the sustainable development of coal cities.

Keywords Resource and environmental carrying capacity · Coal city · System dynamics model · BP-DEMATAL mode · Orthogonal test · Huainan city

Introduction

China is the largest producer and consumer of coal in the world. Coal accounted for 56% of China's total energy consumption in 2021. Although the proportion of coal in energy consumption is decreasing year by year, its status as the main energy resource will not change for a long time. China's coal cities play a vital role in coal supply. They are numerous and widely distributed, but serious resource and environmental problems exist in these cities nowadays. Because of the non-renewability of coal resources, the advantages of energy resources of coal cities will be weakened gradually. At the same time, coal mining and rapid urbanization would result

in resource degradation in terms of cultivated land, water, and other resources inevitably. On the other hand, various environmental problems in coal cities are becoming more serious: The land damaged by coal mining is increasing at the rate of 800 km² per year, and this leads to serious damage to the ecological environment both on the surface and underground of mining areas, while the restoration speed is lagging behind. Air quality of these cities is poor, with PM_{2.5} and PM₁₀ concentrations exceeding the standard. The comprehensive utilization rate of coal solid waste is insufficient, resulting in huge discharge of that. These problems have affected the sustainable development of coal cities and hindered the coordinated development of regions. In view of the serious resource and environmental problems in coal cities, the Chinese government has formulated a series of policies and regulations to promote the transformation and sustainable development of these cities. Moreover, lots of scholars have also carried out many researches on this issue.

RECC has become an important index to estimate the conditions of regional economic and social development and a criterion to measure regional sustainable development

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level. In 2017, the Chinese government issued *Several Opinions on Establishing a Long-term Mechanism for the Monitoring and Early Warning of Resource and Environment carrying Capacity*, which takes RECC as the evaluation standard for rational regional development. At present, the contradiction between social and economic development, environmental protection, and resource conservation is prominent in most coal cities. Therefore, analyzing the existing problems, finding the shortcomings that restrict economic and social development and making scientific prediction with the method of RECC is of great significance for coal cities to correctly understand the development status, rationally choose the transformation path and realize sustainable development.

In order to evaluate and simulate the RECC of coal city dynamically, this study chooses Huainan, a typical coal city in China as the case, and selects the factors with the characteristics of coal city to construct the SD model. Then we use the SD model to simulate the change of RECC in different scenarios. By comparing the results of different scenarios, the optimal path to improve the RECC is selected. The results can not only reflect the status of RECC in recent years, but also predict its change trend under different conditions dynamically. Meanwhile, comparing with traditional SD model, we make the simulation process more scientific and efficient by the methods of BP-DEMATEL mode and orthogonal test. The results of this study enrich the research methods of RECC and provide theoretical reference for sustainable development of coal cities.

Literature review

The study of carrying capacity has lasted for more than 100 years, and carrying capacity has been regarded as an important criterion to measure the harmony of man-land relationship. Among them, RECC integrates the concepts of resource carrying capacity and environmental carrying capacity, reflects the core view of sustainable development, and gradually becomes a new perspective of research on carrying capacity (Feng et al. 2018). On the one hand, scholars focus on different geographical units, and their research results reflect the RECC of regions at different scales: For example, taking cities as the research objects, Zhang et al. (2018) constructed a comprehensive evaluation index system from the aspects of water resources, land, air quality, energy, and solid waste discharge, etc., and took Tianjin as a case to evaluate the regional RECC of this city. Meanwhile, RECC in some special regions has also attracted the attention of scholars; Wang and Liu (2019) chose Tibet, an area with extremely fragile ecological environment, as the research object and found that the overall situation of RECC in this area is in jeopardy. As to the RECC of large areas, relevant

studies mainly discuss the balance of various resources and environmental elements, and the differences in the spatial distribution of RECC. Shi and Sun (2017) analyzed the RECC of the economic zone on the west coast of Taiwan Strait, and the results showed that the land resources and water resources in this region were insufficient, while the atmospheric environment and aquatic environment were generally in good condition. Cheng et al. (2016) researched the RECC and social-economic development of 31 provinces in mainland China, and showed the spatial distribution and difference of resource and environmental pressure. On the other hand, the influence of RECC in the development of economy and society is also the focus of scholars. For example, in order to investigate the relationship between RECC and urban spatial development, Xie et al. (2020) explored the relationship between RECC and land space development zoning layout in Henan Province by three-dimensional magic cube evaluation model. RECC will affect the production layout of the industry inevitably. Xiong et al. (2022) studied the spatio-temporal coupling coordination relationship between animal husbandry and RECC of China, and found out the main driving factors. Moreover, the effect of RECC level on economic development has also triggered the thinking of scholars. Fu et al. (2020) studied the level and characteristics of each kind of carrying capacity in Haihe River Basin quantitatively, and conducted trade-off analysis on economic carrying capacity and RECC. At present, the research objects of RECC are more and more diversified, and abundant achievements of relevant research have been achieved. However, researches on coal cities, the regions with special resource endowment and prominent environmental problems, are still insufficient. Therefore, it is of great significance for the sustainable development of coal cities to study the changes of RECC, find out the main factors restricting sustainable development, and predict RECC level effectively.

In the 1950s, J. W. Forrester (Meadows and Rome 1973) created SD, which was later used in the famous global model *Limits to Growth*. At present, SD model has been successfully applied in many fields due to its applicability to complex and nonlinear problems. In the field of economic development and public service research, SD model plays a good role in scientific prediction: Liu (2013) described the relationship between human capital and economic development based on SD, and simulated the development trend of the indicators of human capital and economic systems. Considering the dynamic and multidimensional characteristics of product service system, Lee et al. (2012) employed SD to construct a multi-dimensional system including dynamics and triple bottom line, then simulated the sustainability of product service of public bicycle system. SD model provides an ideal method for different industries to carry out output scale assessment, industrial structure analysis,

and production system risk warning: Nicholson et al. (2018) applied SD to the research of animal husbandry and they built the SD model of Brazilian dairy supply chain. The simulation results illustrated the impact of increasing milk production on the country-level, and the difference of the impact caused by production improvement on small farms and large farms. Ebert et al. (2017) introduced the application of SD model in the field of electricity, such as the importance of resource diversification in the security of energy supply in Finland, China's approach to reducing CO₂ emissions and other cases. Combined with these application cases, they emphasized the value of SD model. El-Sefy et al. (2019) adopted SD to overcome the limitations of current risk assessment techniques. The SD model was used to simulate the thermal dynamic processes in the reactor core, the secondary coolant system, and the pressurized water reactor. Therefore, the systematic risk of nuclear power plant could be assessed dynamically. In addition, SD model can also conduct effective prediction and simulation in the research of environmental protection and public health: Chen et al. (2021) analyzed the evolution of power generation structure and power carbon emission in four development modes, and provided decision-making basis for realizing dual carbon goal of power system supply side. Lu et al. (2021) constructed the Susceptible-Exposed-4-infected-Removed-2 model based on SD, then they successfully predicted the development trend of COVID-19 epidemic and provided corresponding suggestions for epidemic prevention and control. However, there are few studies on the application of SD model in the research of RECC. Tan et al. (2017) constructed the SD model of "land urbanization-resource

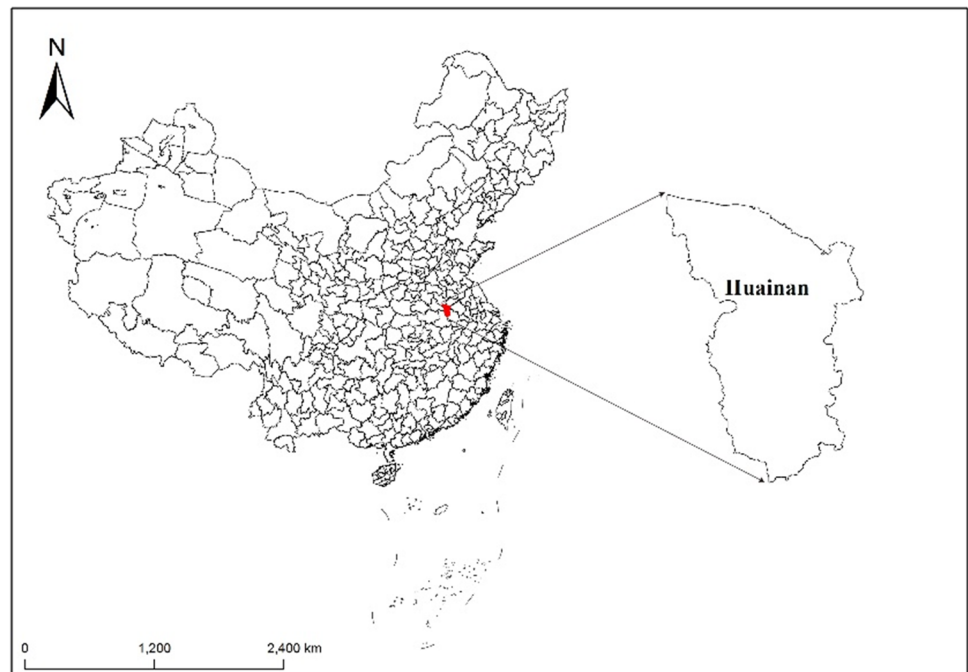
and environment carrying capacity" to simulate the change trend of urban RECC under different scenarios. Kuang et al. (2021) used SD model to explore the changes of urban RECC in different ecosystem management modes, providing a reference for the choice of economic and social development modes. These researches show that SD model has good applicability for solving various problems. However, on the one hand, SD model is rarely used in the study of RECC. On the other hand, there is some deficiency in simulation process of SD model such as subjectivity in control parameter selection and incompleteness in scheme design.

In view of the shortcomings of relevant researches, this study selects factors to construct SD model, then evaluates and simulates the change trend of RECC of a coal city. Furthermore, we improve SD model by BP-DEMATEL model and orthogonal experiment to make the design of simulation scheme more scientific, the efficiency of simulation experiment higher, and the simulation results more reference.

Study area

Huainan is located in the central and northern part of Anhui Province, on the bank of Huaihe River and in the hinterland of the Yangtze River Delta. The location of Huainan in China is shown in Fig. 1. The city is divided into two landforms by Huaihe River: the north of the river is flat, which is part of Huaibei Plain; South of this river is hilly landform. The city is a transitional region between subtropical monsoon climate and temperate monsoon climate, with four distinct seasons and suitable temperatures.

Fig. 1 The location of Huainan city in China



The resource superiority of coal in Huainan is prominent: this city has an entire coal field with the largest reserves and the best quality in the east and south of China; meanwhile, Huainan is one of the regions with the richest coal resources in Anhui Province and even east China. According to the data of 2015 in General Plan of Mineral Resources of Huainan City (2016–2020), the city had 13.807 billion tons of coal reserves. The coal resources of Huainan are concentrated in distribution, complete in varieties, and good in quality. It enjoys the reputation of “green energy” because of the characteristics of low sulfur, low phosphorus, high calorific value, and high ash melting point. Coal mining in Huainan has lasted for a long time. Huainan mining area was formed in the 1930s. After long-term development, it has become a key national energy base and made great contributions to China’s economic development. However, the ecological environment of Huainan has been polluted and destructed seriously: Coal gangue discharge is huge, occupying a lot of farmlands. At present, the area of surface subsidence caused by coal mining has exceeded 300 km² (Dong et al. 2015), which has become a major systemic ecological problem. Meanwhile, the air pollution in Huainan is serious, too. In recent years, the days with good air quality is mostly below 70%.

Data

The data are mainly from “China Urban Statistical Yearbook 2010–2020” (From the website of National Bureau of Statistics), “Environmental Status Bulletin of Anhui Province” (From the website of Department of Ecology and Environment of Anhui Province), “Statistical Yearbook 2010–2020 of Anhui” (From the website of Bureau of Statistics of Anhui Province), “Statistical Yearbook 2010–2020 of Huainan” (From the website of Bureau of Statistics of Huainan City), and *National Economic and social development Bulletin of Huainan* (From the website of Bureau of Statistics of Huainan City).

Methods

The technology roadmap is shown as Fig. 2. It illustrates the process that how we use SD model to predict and simulate the RECC of Huainan and the improvement we made to let the simulation more objective, efficient, and accurate.

BP-DEMATEL mode

In order to avoid the subjectivity of control parameters selection in the simulation process, we consider to select the control parameters according to the effect of factors on the system. DEMATEL (Decision Making Trial and Evaluation Laboratory) model establishes a direct influence matrix according to

the relationship between factors in the system, and obtains the center degree and the cause degree of each factor. In this way, the importance of each factor as well as the interdependent and restrictive relationship between factors can be estimated, and the key influencing factors in the complex system can be identified (Khoshnava et al. 2018). However, the above analysis will be more difficult when there are too many factors in the system, and the interaction between them is more complex. Therefore, we combined the adaptability of BP neural network to analyze the internal law of the system and the relationship between factors (Zhao et al. 2020). BP-DEMATEL model can conduct reverse transmission of error information from output layer to input layer, so as to strengthen the correlation between influencing factors and result factors. Considering the advantage of BP-DEMATEL model, we chose it to determine the driving force of each factor and find the factors with the greatest influence on the RECC system, thus providing a basis for the selection of control parameters in the simulation schemes. The specific steps are as follows:

- (1) Total weight vector

$$\omega = \text{mean}(|W| \times |w|) = (\omega_1, \omega_2, \dots, \omega_n)$$

where $|W|$ and $|w|$ mean the absolute value of each factor in the matrix; The function *mean* means that when the number of rows of $|W| \times |w|$ is more than 1, then take the mean of the product.

- (2) Direct correlation matrix (B), direct influence matrix (X), and full influence matrix (T)

$$B = (b_{ij})_{n \times n} = \begin{bmatrix} b_{11} & b_{12} & \dots & b_{1n} \\ b_{21} & b_{22} & \dots & b_{2n} \\ \vdots & \vdots & & \vdots \\ b_{n1} & b_{n2} & \dots & b_{nn} \end{bmatrix}$$

where $b_{ii} = 0$, $b_{ij} = \frac{\omega_i}{\omega_j}$ (if $\omega_j = 0$, then $b_{ij} = 0$) which is the importance of i to j .

$$X = (x_{ij})_{n \times n} = \frac{B}{\max_{1 \leq i \leq n} \sum_{j=1}^n b_{ij}}$$

$$T = X(I - X)^{-1}$$

where I is the unit matrix and $(I - X)^{-1}$ is the inverse matrix of $(I - X)$.

- (3) The influence degree (a_i), the influenced degree (b_i), the center degree (m_i), and the cause degree (r_i)

$$a_i = \sum_{j=1}^n t_{ij} (j = 1, 2, \dots, n); \quad b_i = \sum_{i=1}^n t_{ij} (i = 1, 2, \dots, n);$$

$$m_i = a_i + b_i (i = 1, 2, \dots, n);$$

$$r_i = a_i - b_i (i = 1, 2, \dots, n)$$

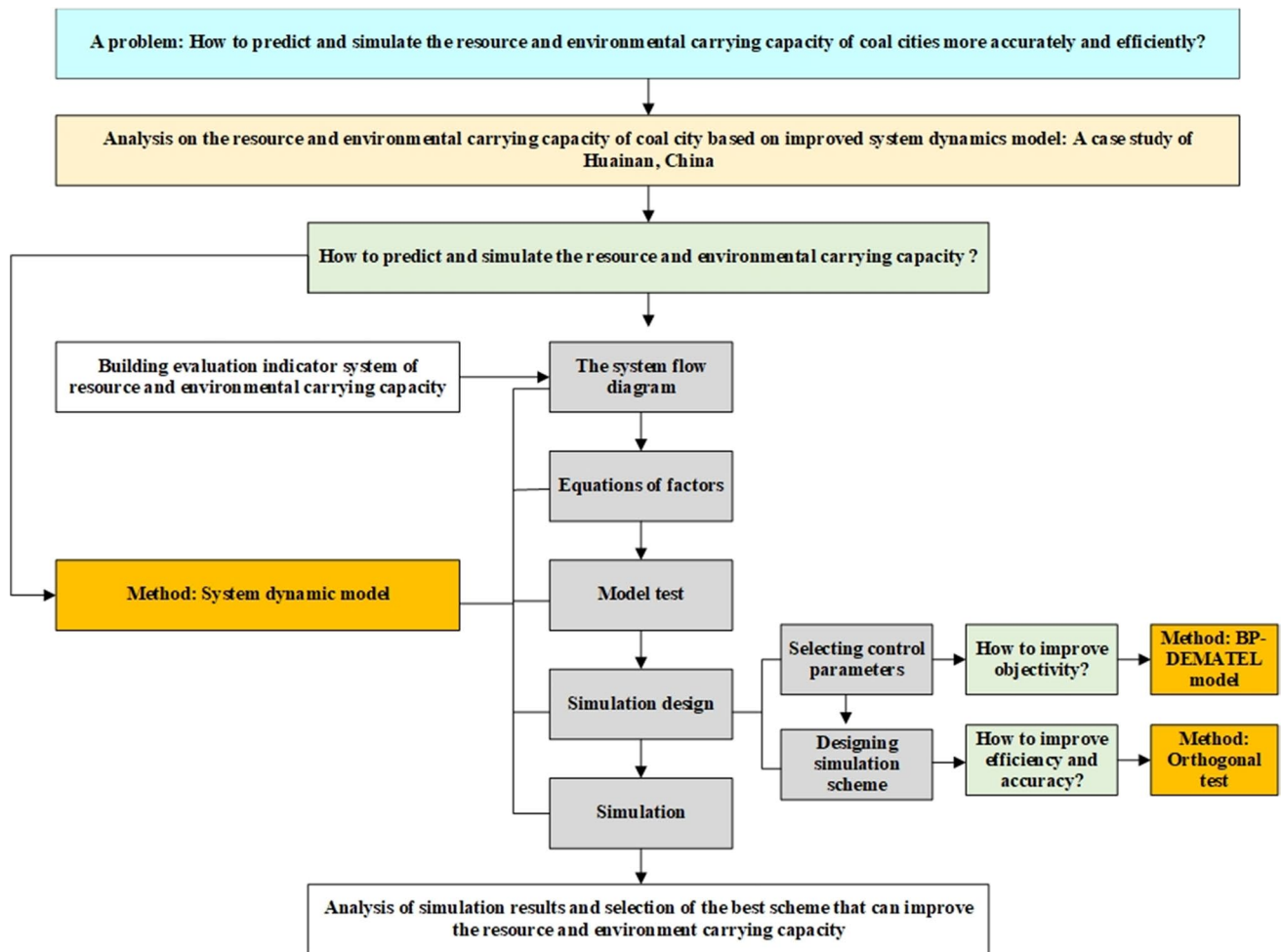


Fig. 2 The technology roadmap

where m_i means the effect of factor i in the whole system. The higher its value is, the more important the factor is. r_i means the causal relationship between factor i and other factors. When $r_i > 0$, it is named as the cause factor, indicating that the factor has a great influence on other factors. When $r_i < 0$, it is named as the result factor, indicating that the factor is easily affected by other factors.

Orthogonal test

In the condition that control parameters and their change ranges were determined, this study applied orthogonal test to plan the simulation scheme. This method can be used to obtain representative and reliable results quickly by conducting multi-factor and multi-level tests with as few times as possible, and get the optimal combination of each factor with different level. Moreover, we can further find the factors with the greatest effect on test results by analysis of variance. Therefore, based on the orthogonal test, we can

comprehensively analyze the influence of different control parameters on RECC.

SD model

(1) The system flow diagram

The regional RECC is an integrated system with complex internal relations due to the influence of many aspects. Considering the availability of data, the spatial boundary of SD model is set as Huainan City, and the main factors affecting the RECC are included in the boundary. In the SD model, the RECC system is divided into two subsystems of resource-environment and society-economy. These two subsystems include six secondary subsystems such as resource utilization and environmental pollution, environmental governance, and social security. We select 42 indicators to build the evaluation system of the RECC (Table 1). In the secondary

Table 1 Evaluation indicator system of RECC

Subsystem	Secondary subsystem	Indicator	Indicator code		
Resource-environment	Resource utilization and environmental pollution	Energy consumption per unit of GDP	I ₁		
		Electricity consumption per unit of GDP	I ₂		
		Water consumption per unit of GDP	I ₃		
		Regional traffic noise value	I ₄		
		Industrial waste water discharge intensity	I ₅		
		Industrial waste gas emission intensity	I ₆		
		Industrial dust emission intensity	I ₇		
		Industrial solid waste discharge intensity	I ₈		
		Industrial COD emission intensity	I ₉		
		Industrial SO ₂ emission intensity	I ₁₀		
	Resource and environmental status	Water resources per capita	I ₁₁		
		Sown area of crops per capita	I ₁₂		
		Coal reserves per capita	I ₁₃		
		Reserve-production ratio of coal resources	I ₁₄		
		Gas penetration rate	I ₁₅		
		Proportion of built-up area	I ₁₆		
		Proportion of subsidence area	I ₁₇		
		Park and green land area per capita	I ₁₈		
	Environmental governance	Control rate of industrial waste water discharge	I ₁₉		
		Comprehensive utilization rate of industrial solid	I ₂₀		
		Treatment rate of industrial dust	I ₂₁		
		Harmless treatment rate of household garbage	I ₂₂		
		Coverage rate of green belt in built-up area	I ₂₃		
		Proportion of days with good air quality	I ₂₄		
		Proportion of environmental protection spending	I ₂₅		
		Economy-society	Population growth and industrial development	Population density	I ₂₆
				Natural population growth rate	I ₂₇
				Urbanization rate	I ₂₈
				Proportion of output value of secondary industry	I ₂₉
				Proportion of coal industrial output value	I ₃₀
				Raw coal production per capita	I ₃₁
			Economic and social development	GDP per capita	I ₃₂
	Growth rate of GDP			I ₃₃	
	Fixed asset investment per capita			I ₃₄	
	Engel coefficient of urban residents			I ₃₅	
	Per capita disposable income of urban residents			I ₃₆	
	Proportion of output value of tertiary industry			I ₃₇	
	Social security		Employment rate	I ₃₈	
			Proportion of education spending	I ₃₉	
			Proportion of R&D spending	I ₄₀	
			Urban road area per capita	I ₄₁	
			Number of beds in medical institutions per 10,000 people	I ₄₂	

subsystem of “Resource utilization and environmental pollution,” ten indicators are included, and they characterize the consumption intensity of different resources and the degree of environmental pollution. The eight indicators in the secondary subsystem of “Resource and

environmental status” represent the resources endowment such as water, farmland, coal, and the environmental state such as subsidence area and green land. We choose the indicators which can reflect the pollutant control level and environmental protection spending to

construct the secondary subsystem of “Environmental governance.” The secondary subsystems above form the “Resource-environment” subsystem. As for the subsystem of “Economy-society,” there are three secondary subsystems. In the secondary subsystem of “Population growth and industrial development,” the six indicators characterize the increasement of population, especially the proportion of urban population, and the industrial scale. Then we select six indicators in the secondary subsystem of “Economic and social development” to analyze the economic level and living standard of residents. Finally, five indicators such as employment rate, spending of education and scientific research, and medical conditions are used to build the secondary subsystem of “Social security.” These indicators are the main variables of the SD model. Then, by adding some necessary intermediate variables, the system flow diagram of SD model is drawn, as shown in Fig. 3. The time boundary of this model is 2010–2030, and the time step is set as 1 year. Among them, 2010–2019 is the modeling and verification stage, 2020–2030 is the prediction and simulation stage, and the base year is 2019.

(2) Equations of factors

According to the time series data and the logical relationship between factors, the equations are determined. Due to the

limited space, the equations of some factors are listed below. Where, K represents the current time, J is the past time, DT is the time from J to K , which is called time step.

Level variable equation (L):

$$\begin{aligned} \text{Total energy consumption} : K &= \text{Total energy consumption} \\ &+ DT \times \text{Change of energy consumption} \end{aligned}$$

$$\text{Population} : K = \text{Population } J + DT \times \text{Change of population}$$

Auxiliary variable equation (A):

$$\begin{aligned} \text{Resource and environmental carrying capacity} &= \\ &\text{Resource and environment} \times 0.5333 + \text{Society} \\ &\text{and economy} \times 0.4665 \end{aligned}$$

$$\begin{aligned} \text{Resource and environment} &= \text{Resource utilization and} \\ &\text{environmental pollution} \times 0.1505 + \text{Resource and} \\ &\text{environment status} \times 0.2032 \\ &+ \text{Environmental governance} \times 0.1796 \end{aligned}$$

$$\begin{aligned} \text{Resource utilization and environmental pollution} &= \frac{0.64}{\text{Energy}} \text{consumption per unit of GDP} \times \\ &0.0098 + \frac{737}{\text{Electricity}} \text{consumption per unit of GDP} \times 0.0116 + \frac{160}{\text{Water}} \text{consumption per unit} \\ &\text{of GDP} \times 0.0093 + \frac{67.5}{\text{Regional}} \text{traffic noise value} \times 0.0075 + \frac{0.7}{\text{Industrial}} \text{waste water discharge} \\ &\text{intensity} \times 0.0239 + \frac{0.43}{\text{Industrial}} \text{waste gas emission intensity} \times 0.018 + \frac{1.77}{\text{Industrial}} \text{dust} \\ &\text{emission intensity} \times 0.0118 + \frac{0.42}{\text{Industrial}} \text{solid waste discharge intensity} \times 0.0124 + \frac{0.21}{\text{Industrial}} \\ &\text{COD emission intensity} \times 0.0227 + 4.32/\text{Industrial SO}_2 \text{ emission intensity} \times 0.0236 \end{aligned}$$

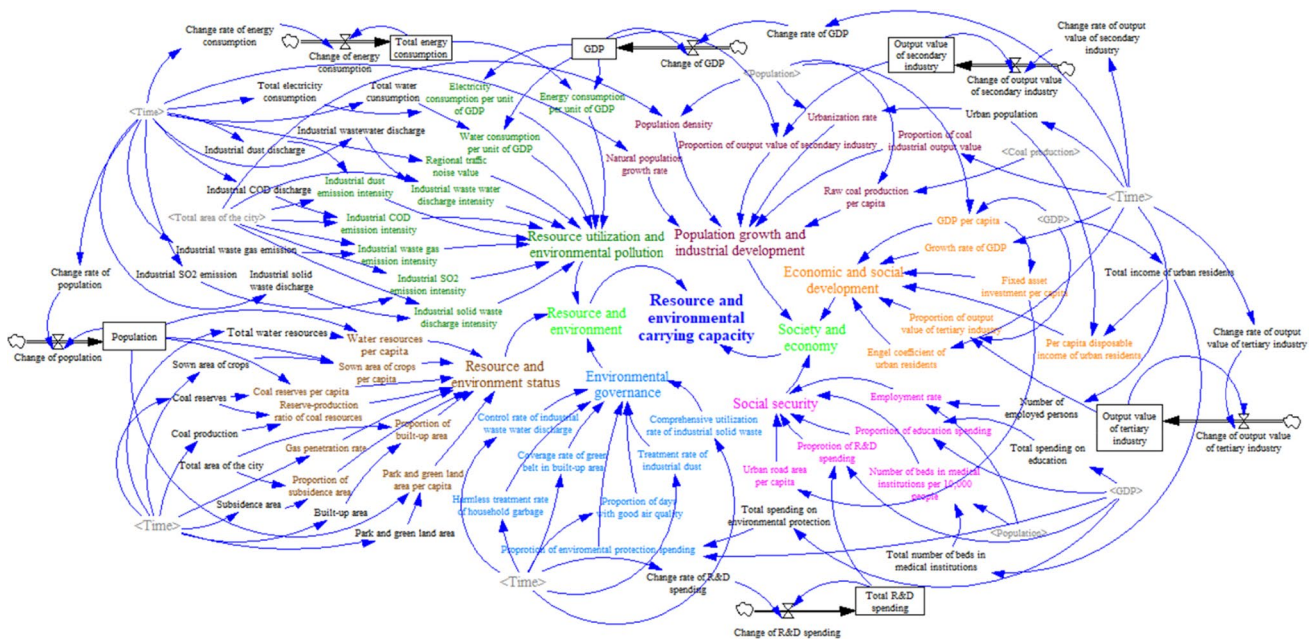


Fig. 3 The system flow diagram of SD model

Energy consumption per unit of GDP = Total energy consumption/GDP/10000

Industrial waste water discharge intensity = Industrial waste water discharge /Total area of the city

Water resource per capita = Total water resources × 10000/population

Reserve – production ratio of coalre sources =

Built – uparea/Total area of the city

Proportion of built – up area = Built – up area/Total area of the city

Proportion of out put value of secondary industry =

Output value of secondary industry/GDP × 100

Urbanization rate = Urban population/Population × 100

Urban road area per capita = Fixed asset investment per capita × 4.22 + 3.451

Change rate of population = WITH LOOKUP

[(0, 0) – 3000, 10], (2010, 0.000837), (2011, 0.004239), (2012, 0.006688), (2013, 0.002805), (2014, 0.010336), (2015, 0.007257), (2016, 0.00897), (2017, 0.000717), (2018, 0.000143), (2019, 0.0005), (2020, 0.0004), (2030, 0.00011)

Change rate of GDP = WITH LOOKUP

[(0, -0.03) – (3000, 10)], (2010, 0.1402), (2011, 0.09402), (2012, 0.05346), (2013, -0.0233), (2014, -0.01275), (2015, 0.06965), (2016, 0.09994), (2017, 0.06899), (2018, 0.143703), (2019, 0.07044), (2020, 0.075), (2030, 0.075))

Change rate of output value of tertiary industry = WITH LOOKUP

[(0, 0) – (3000, 10)], (2010, 0.14471), (2011, 0.139961), (2012, 0.110662), (2013, 0.140819), (2014, 0.091689), (2015, 0.097013), (2016, 0.119063), (2017, 0.104635), (2018, 0.321741), (2019, 0.14114), (2020, 0.1411), (2030, 0.16))

Rate variable equation (R):

Change of energy consumption = Total energy consumption

× Change rate of energy consumption

Change of population = Population × Change rate of population

Constant equation (C):

Total area of the city = 5571

(3) Model test

The SD model needs to be tested to ensure the validity of prediction and simulation results. Two kinds of test are adopted in this study. One is to set rate variables to 0 one by one and judge whether the model structure is reasonable by the extreme situation of the rate equation. The second is to evaluate whether the behavior of the SD model is consistent with the actual situation by the error between simulation value and real value of the main variables.

(4) Dynamic simulation

According to the analysis results of BP-DEMATEL model (Appendix Table 7), we select the control parameters: In the order of values of r_i from largest to smallest, the top 7 indicators are: $I_4, I_{28}, I_6, I_{10}, I_{22}, I_{33}, I_{25}$. Therefore, we choose the control parameters based on those indicators. The industrial waste gas emission intensity and industrial SO_2 emission intensity of Huainan are mainly related to the output value of secondary production and raw coal output, so output value of secondary industry and coal production are regarded as the control parameters. The urbanization rate and employment rate are the ratio of the urban population and the employed number to the population respectively, so they can be controlled by the urban population and the number of employed persons. Harmless treatment rate of household garbage and proportion of environmental protection spending depend largely on the spending on environmental protection, so total spending on environmental protection is set as a control parameter. Besides, GDP is set as one of the control parameters as it is correlated with many variables in the system, and it has a large impact on the level of RECC. Finally, we got seven control parameters which are shown in Table 2.

The change range of these parameters is set according to the regulation target and the regional development status. For example, as Huainan is the main coal energy base in East China, its coal supply should maintain a stable status in the medium and long term. Therefore, referring to the average coal production of the city from 2010 to 2019, the change range of coal production is designed as three modes of slow growth, medium growth, and rapid growth. The change range of urban population and GDP is set according to “14th Five-year Plan and the long-term goal of 2035 of Anhui Province”, and the growth rate of these two variables in recent years. The control parameters and their change range are shown in Table 2.

Designing simulation scheme: Since there are seven control parameters in Table 2, and each parameter has three levels of change range, so three-level orthogonal table $L_{18}(3^7)$ is used to design the simulation scheme.

Table 2 The change range of control parameters

Parameter	Parameter code	Range of change (%)		
		1	2	3
Regional traffic noise value	A	-1.6	-3.2	-4.8
Coal production	B	15	10	5
Total spending on environmental protection	C	15	25	35
Output value of secondary industry	D	2.7	5.4	8.1
Urban population	E	0.5	0.8	1
GDP	F	4.5	6.5	8.5
Number of employed persons	G	0.2	0.7	1.2

Table 3 The simulation scheme based on orthogonal table L18(3⁷)

Test	Parameter code						
	A	B	C	D	E	F	G
1	-4.8	5	15	2.7	0.8	6.5	0.7
2	-1.6	15	15	2.7	0.5	4.5	0.2
3	-4.8	10	15	8.1	0.5	4.5	1.2
4	-3.2	15	15	5.4	1	6.5	1.2
5	-4.8	15	25	5.4	1	4.5	0.7
6	-1.6	5	25	5.4	0.5	6.5	0.2
7	-3.2	5	15	8.1	1	8.5	0.2
8	-4.8	10	25	2.7	1	8.5	0.2
9	-1.6	15	25	8.1	0.8	8.5	1.2
10	-1.6	10	35	2.7	1	6.5	1.2
11	-4.8	5	35	5.4	0.5	8.5	1.2
12	-3.2	15	35	2.7	0.5	8.5	0.7
13	-1.6	5	35	8.1	1	4.5	0.7
14	-4.8	15	35	8.1	0.8	6.5	0.2
15	-3.2	10	35	5.4	0.8	4.5	0.2
16	-1.6	10	15	5.4	0.8	8.5	0.7
17	-3.2	10	25	8.1	0.5	6.5	0.7
18	-3.2	5	25	2.7	0.8	4.5	1.2

Table 3 shows the specific simulation scheme based on orthogonal table L18(3⁷).

Results

Mode test

The test results of the extreme situation of the rate equations are shown in Fig. 4. In each scheme, the RECC had not been

negative values, and the fluctuation range was small, so the model structure could be considered as suitable.

In the test of extreme situation, schemes were designed as follows: Scheme 1—Change of output value of secondary industry is 0; Scheme 2—Change of output value of tertiary industry is 0; Scheme 3—Change of R&D spending is 0; Scheme 4—Change of energy consumption is 0; Scheme 5—Change of population is 0; Scheme 6—Change of GDP is 0; Current—The initially set of the SD system.

Fig. 4 Mode test results of the extreme situation

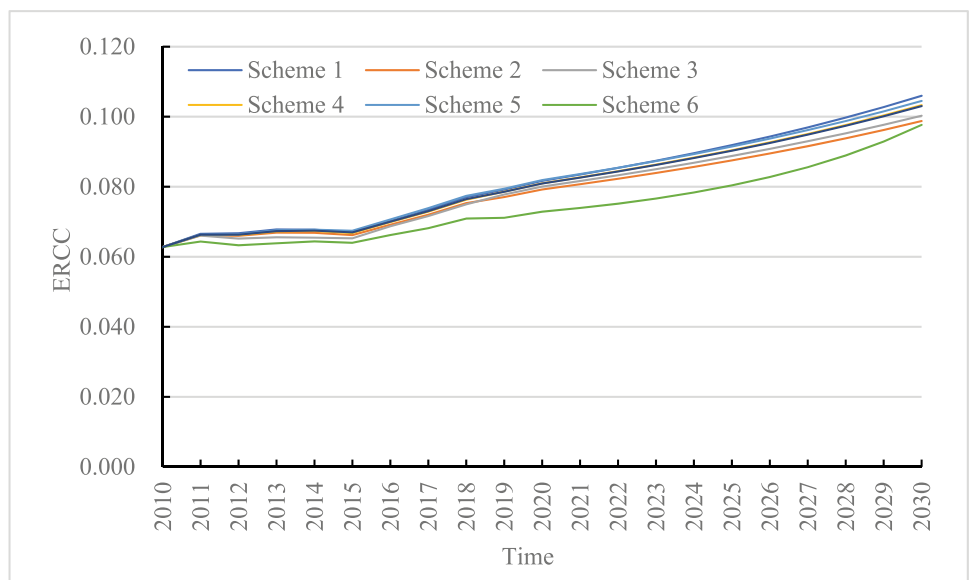
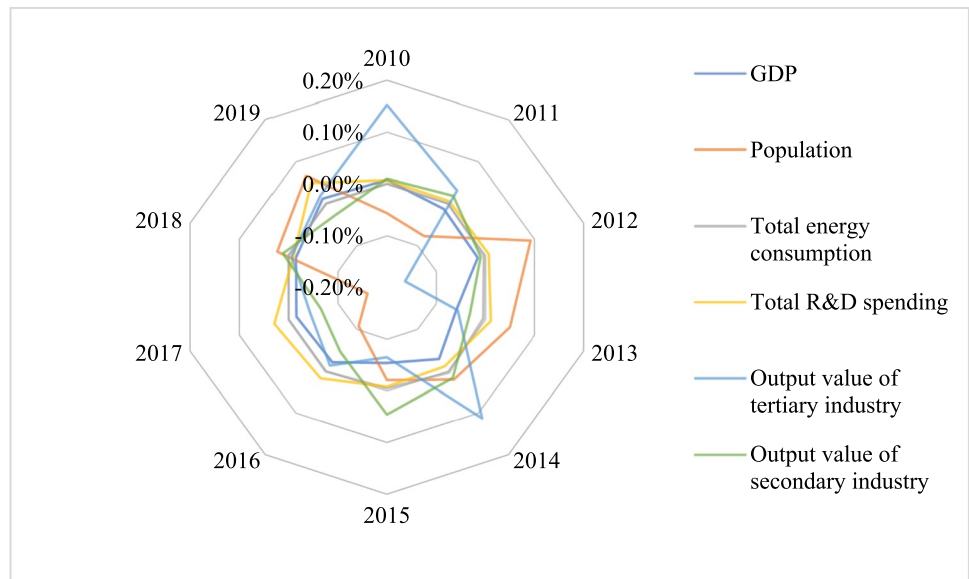


Fig. 5 The error between the simulation value and the real value



Due to the limited space of this paper, only the historical data test results of some core variables are shown here. It could be known from Fig. 5 that the absolute values of error between the simulation value and the real value of the main variables were all within 10%. Therefore, we thought that the simulation results were basically consistent with the actual situation and the model could be used for simulation.

Temporal variation of RECC

Figure 6 shows the evaluation and prediction results of RECC in the current scenario. The RECC showed an overall upward trend from 2010 to 2019. The RECC of the resource-environment subsystem fluctuated slightly from 2010 to 2019, with the values between 0.074 and 0.087. The RECC of the society-economy subsystem showed an upward trend

from 2010 to 2019 with a slight decline in 2015, which was related to the decrease of GDP in that year. The RECC of this subsystem was improved from 0.05 to 0.068 in those years. The prediction results of the model showed that the RECC of the whole system and the two subsystems would continue to improve from 2020 to 2030. Specifically, the whole RECC may increase by 27.24%, while the RECC of the resource-environment subsystem and the society-economy subsystem would improve by 11.1% and 52.2%, respectively.

Simulation of RECC

As shown in Table 4 and Fig. 7, the RECC of each simulation scenario showed a continuous upward trend from 2020 to 2030, but not all scenarios realized an improvement in

Fig. 6 Temporal variation of RECC in the current scenario

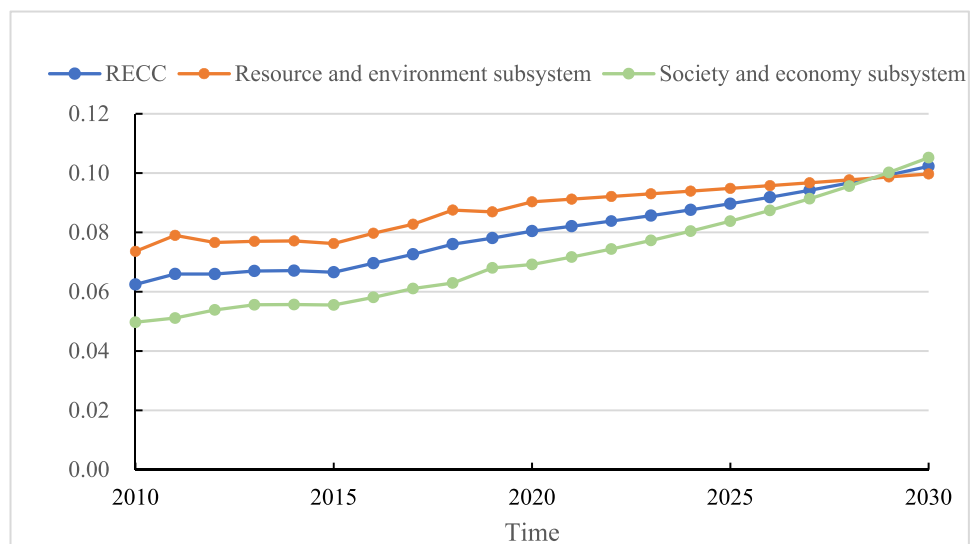


Table 4 The simulation results of RECC in each scenario

Time	Current	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
2020	0.0804	0.0808	0.0804	0.0806	0.0804	0.0808	0.0812	0.0807	0.0809	0.0808
2022	0.0838	0.0838	0.0828	0.0828	0.0833	0.0831	0.0841	0.0842	0.0847	0.0843
2024	0.0876	0.0872	0.0855	0.0853	0.0865	0.0857	0.0874	0.0880	0.0888	0.0881
2026	0.0919	0.0910	0.0886	0.0882	0.0902	0.0887	0.0911	0.0924	0.0935	0.0925
2028	0.0967	0.0953	0.0922	0.0916	0.0944	0.0923	0.0953	0.0974	0.0989	0.0976
2030	0.1023	0.1003	0.0965	0.0957	0.0992	0.0965	0.1001	0.1031	0.1051	0.1034
Time	Current	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17	Test 18
2020	0.0804	0.0813	0.0816	0.0812	0.0815	0.0812	0.0813	0.0805	0.0810	0.0812
2022	0.0838	0.0845	0.0853	0.0850	0.0838	0.0840	0.0837	0.0841	0.0838	0.0836
2024	0.0876	0.0879	0.0893	0.0892	0.0863	0.0872	0.0863	0.0881	0.0870	0.0864
2026	0.0919	0.0918	0.0939	0.0939	0.0893	0.0909	0.0894	0.0926	0.0906	0.0895
2028	0.0967	0.0962	0.0991	0.0993	0.0927	0.0950	0.0929	0.0977	0.0946	0.0932
2030	0.1023	0.1012	0.1050	0.1056	0.0969	0.0997	0.0971	0.1036	0.0994	0.0975

Fig. 7 Comparison of the simulation results of RECC in each scenario

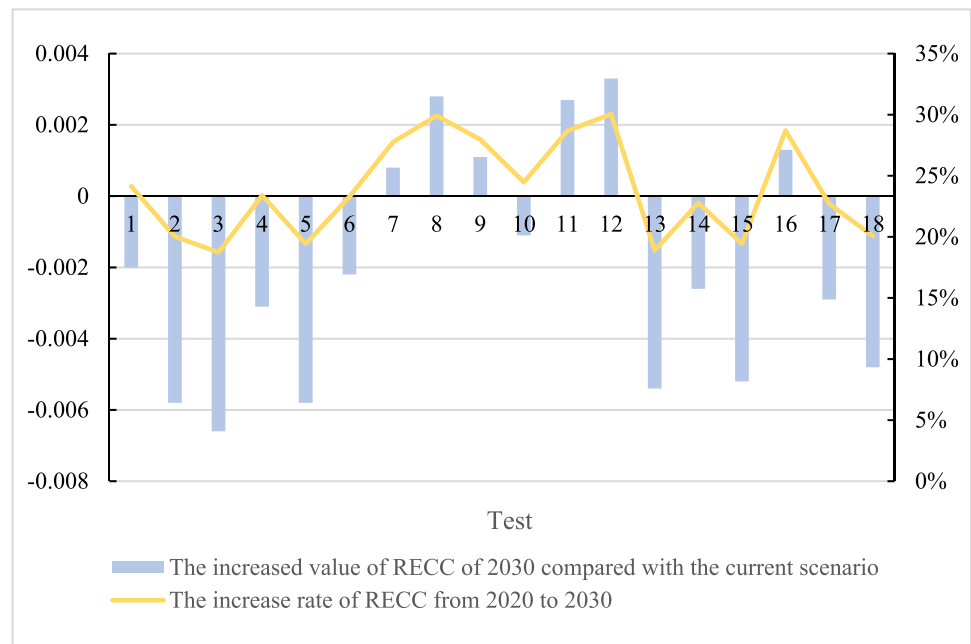


Table 5 The simulation results of RECC of resource-environment subsystem in each scenario

Time	Current	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
2020	0.0903	0.0912	0.0906	0.0909	0.0907	0.0914	0.0919	0.0911	0.0916	0.0914
2022	0.0921	0.0927	0.0918	0.092	0.0922	0.0926	0.0935	0.0932	0.0938	0.0935
2024	0.0939	0.0943	0.0929	0.0932	0.0938	0.0938	0.0952	0.0952	0.0959	0.0956
2026	0.0958	0.0959	0.0941	0.0944	0.0955	0.0951	0.0968	0.0972	0.098	0.0977
2028	0.0977	0.0976	0.0954	0.0956	0.0971	0.0964	0.0986	0.0993	0.1001	0.0999
2030	0.0997	0.0993	0.0967	0.0969	0.0988	0.0977	0.1003	0.1015	0.1024	0.1022
Time	Current	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17	Test 18
2020	0.0903	0.0924	0.0926	0.0921	0.0926	0.0922	0.0924	0.0909	0.0916	0.0919
2022	0.0921	0.0941	0.0948	0.0944	0.0938	0.0939	0.0936	0.0929	0.0933	0.0931
2024	0.0939	0.0958	0.097	0.0965	0.0951	0.0956	0.0949	0.0949	0.0949	0.0943
2026	0.0958	0.0976	0.0992	0.0987	0.0964	0.0974	0.0962	0.0969	0.0966	0.0955
2028	0.0977	0.0993	0.1014	0.101	0.0977	0.0991	0.0975	0.0991	0.0983	0.0968
2030	0.0997	0.1011	0.1038	0.1033	0.0991	0.1009	0.0989	0.1013	0.1001	0.0981

RECC compared with the current scenario. The RECC of 2030 in the current scenario is 0.1023, and the tests whose simulation values are higher than that include tests 7, 8, 9, 11, 12, and 16. The growth rate of the RECC from 2020 to 2030 could be compared by analyzing the results of these six tests. It can be seen that the RECC of 2030 and its growth range are the highest in test 12, which is 0.1056 and 30.05% respectively. Therefore, test 12 could be considered as the optimal scheme.

Table 5 and Fig. 8 indicates that the RECC of resource-environment subsystem would keep increasing in all simulation scenarios. Compared with the RECC of 2030 (0.0997) in the current scenario, the scenarios in which the RECC did not improve included: test 1, 2, 3, 4, 5, 13, 15, and 18. Among the other ten tests, the top 3 ones in terms of the growth rate of RECC were test 12 (12.16%), test 11 (12.1%), and test 9 (11.82%). The simulation results of the secondary

subsystems in these three tests showed that the RECC of environmental governance was the highest, which meant that improving the level of environmental governance would play a leading role in promoting the RECC of the resource-environment subsystem.

According to Table 6 and Fig. 9, in 78% of the simulation scenarios, the RECC of the society-economy subsystem was lower than that in the current scenario. There were only four scenarios in which the RECC was increased, i.e., test 8, 11, 12, and 16. The growth rate of these scenarios was 57.21%, 54.49%, 57.35%, and 54.51%, respectively. Compared with the RECC of 2020, the RECC of 2030 and its increase rate in test 12 were the highest. We could get the conclusion by comparing the simulation results of the secondary subsystems in the above four tests that the RECC of social security is the highest. This showed that, in these scenarios, the

Fig. 8 Comparison of the simulation results of RECC of resource-environment subsystem in each scenario

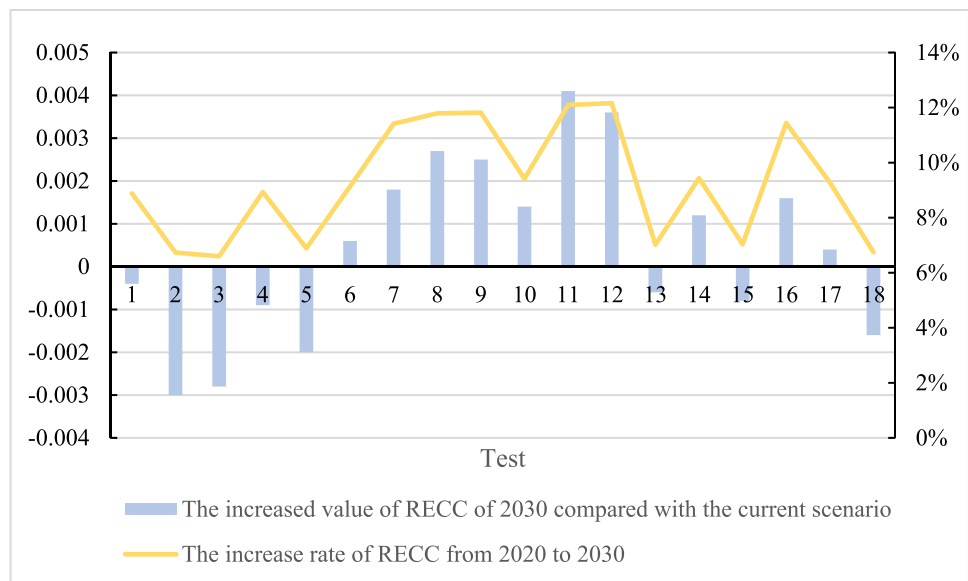
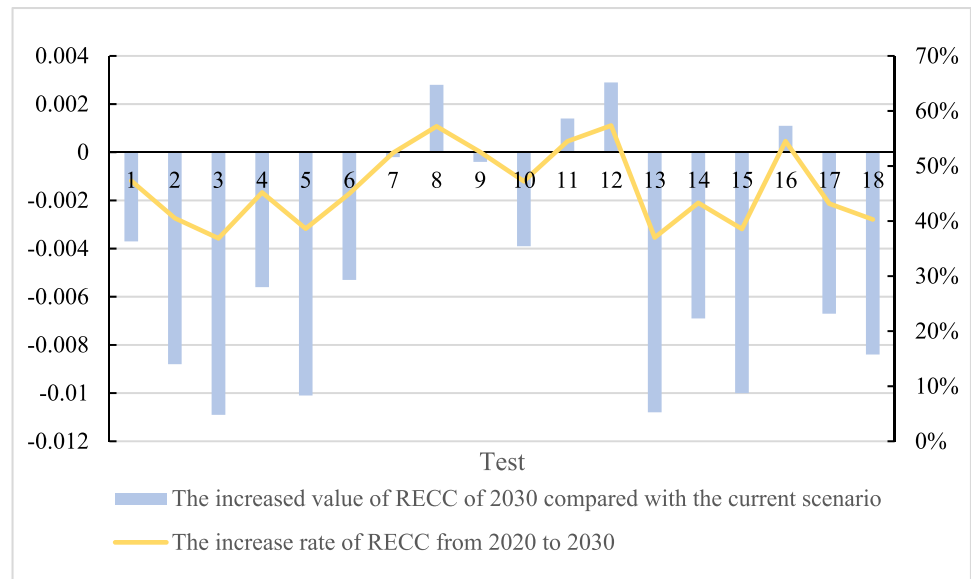


Table 6 The simulation results of RECC of society-economy subsystem in each scenario

Time	Current	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
2020	0.0692	0.0689	0.0686	0.0689	0.0686	0.0686	0.0689	0.0689	0.0687	0.0687
2022	0.0744	0.0736	0.0725	0.0722	0.0731	0.0722	0.0734	0.0739	0.0743	0.0737
2024	0.0804	0.0791	0.077	0.0763	0.0782	0.0765	0.0785	0.0799	0.0808	0.0797
2026	0.0874	0.0854	0.0823	0.0811	0.0842	0.0815	0.0845	0.0869	0.0885	0.0867
2028	0.0956	0.0928	0.0887	0.087	0.0913	0.0876	0.0915	0.0952	0.0975	0.0949
2030	0.1052	0.1015	0.0964	0.0943	0.0996	0.0951	0.0999	0.105	0.108	0.1048
Time	Current	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17	Test 18
2020	0.0692	0.0688	0.0690	0.0687	0.0689	0.0686	0.0687	0.0688	0.0688	0.0690
2022	0.0744	0.0735	0.0743	0.0743	0.0723	0.0728	0.0723	0.0741	0.0730	0.0728
2024	0.0804	0.0789	0.0805	0.0808	0.0763	0.0777	0.0766	0.0803	0.0779	0.0773
2026	0.0874	0.0852	0.0878	0.0884	0.0812	0.0834	0.0817	0.0876	0.0837	0.0827
2028	0.0956	0.0926	0.0964	0.0975	0.0871	0.0902	0.0878	0.0962	0.0904	0.0890
2030	0.1052	0.1013	0.1066	0.1081	0.0944	0.0983	0.0952	0.1063	0.0985	0.0968

Fig. 9 Comparison of the simulation results of RECC of society-economy subsystem in each scenario



RECC of the society-economy system was promoted mainly by improving the level of social security.

On the whole, the increase rate of RECC of the society-economy subsystem was much higher than that of the resource-environment subsystem. The results indicated that Huainan should pay more attention to the development of the society and economy. It should speed up the economic transformation, improve the construction of urban facilities, and promote the level of social security.

The effect of control parameters

Based on the simulation results of those 18 tests, statistical analysis was made to identify the parameters with significant influence on the results. The results of variance analysis showed that the P values of parameters F, D, C, and B were less than 0.05, while parameters A, E, and G were not significant. It showed that the key factors for the simulation of RECC included GDP, output value of secondary production, total spending on environmental protection, and coal production.

Conclusion

This study selected relevant factors and constructed a dynamic analysis model of RECC of the coal city Huainan based on SD. According to the relationship between factors, the system flow diagram was drawn and the equation of each factor was determined. When the mode tests were done, we chose seven control parameters by BP-DEMATTEL model. Then 18 simulation scenarios of RECC were designed by orthogonal test. Results showed that the RECC of Huainan was on the rise from 2019 to 2030 on the whole.

By comparing the results of each simulation scenario, it could be known that the RECC of 2030 and its increase rate compared with 2020 were the highest in test 12. It was worth noting that the growth rate of RECC of society-economy subsystem was much more than that of resource-environment subsystem. Furthermore, we found the factors with significant influence on the simulation results of RECC by analysis of variance. Those factors included GDP, output value of secondary production, total spending on environmental protection, and coal production.

In the optimal scenario, i.e., test 12, the change range of GDP is the largest, the growth of output value of secondary production maintains the lowest speed, the coal production is in a fast growth mode, the growth rate of total spending on environmental protection reaches the highest value, the increasement of urban population is at the lowest level, and the number of employed persons increased at a moderate speed. According to the change range of each control parameter in test 12, it can be known that this scenario achieves the coordinated development of economy and environmental protection by promoting high-quality and rapid economic growth, controlling the development of secondary industry and urbanization, maintaining the advantage of coal resources, increasing investment in environmental protection, and improving environmental governance. It is worth mentioning that this scenario is in accord with the concept of development of Huainan which is “based on coal, extending coal, not only coal, beyond coal.”

Therefore, it can be concluded that the future development mode of Huainan is improving the carrying capacity of the society-economy system significantly, consolidating the dominant position of the coal industry, optimizing the industrial structure, and promoting high-quality and rapid growth of economy. At the same time, Huainan has to increase input

in environmental protection, improve the quality of urbanization development, and achieve coordinated development between economy, society, ecology and environment. Therefore, Huainan should use its advantages and characteristics to develop the coal–electricity–chemical–gas industry chain, realize the deep processing of coal, and increase the economic value of mineral products. In addition, coal mining, transportation machinery manufacturing, and related service industries should also be strengthened. At the same time, this city should take the chance of transformation, establish the substitute and alternative industries actively, increase the proportion of the tertiary industry, and reduce the cost and risk of transformation. In the aspect of mineral resources exploitation and utilization, it should strengthen the exploration of coal resources, develop deep mining, increase the amount of resources, and extend the service period of existing mines. Huainan has to promote the merger, reorganization, and intensive operation of mining enterprises based on the intensity of mining and economies of scale. At the same time, it should exploit various energy sources, such as clean and safe coalbed methane, or build wind power station according to geographical environmental characteristics, and use coal mining subsidence areas to build floating surface photovoltaic power stations. Now the destruction of ecological environment in mining area is the main environmental problem in coal city, it is especially necessary to pay attention to the protection and restoration of ecological environment in mining area. Huainan should increase investment in environmental protection and adopt new technologies to reduce pollution in coal mining and processing. At the same time, the monitoring and early warning system should be established to reflect the status and change trend of ecological environment timely and accurately, so as to provide the basis for the prevention and control of ecological and environmental risks. In terms of social development, Huainan should plan the urban space layout reasonably and promote the construction of new urbanization. It has to provide more jobs and policies to support entrepreneurship, and carry out vocational skills training. At the same time, it should increase investment in scientific research and education, so as to enhance the capacity of collaborative innovation development with the help of universities, science and technology parks, and other institutions, and increase the proportion of high-tech industries.

Discussion

At present, the frequently used forecasting methods include regression model, grey model, ARIMA model, and neural network model. However, these methods are

basically for single value prediction; they cannot reflect the relationship between factors and the influence of factors on the whole system. RECC is a complex system; the relationship between its factors may be nonlinear and high-order, so it should be regarded as an overall feedback system. SD model combines structural model and mathematical model, which can not only reflect the causal relationship and feedback path between factors, but also simulate the development trend of RECC through simulation.

This study applied SD model to analyze the feedback within the system and among the factors, and the development trend of the RECC of Huainan was dynamically simulated in different scenarios, which increased the practical application value of the study. In addition, we also optimized the SD model in two ways: Firstly, BP-DEMATEL model was combined to overcome the subjectivity of the selection of control parameters. Secondly, the simulation scheme was designed based on orthogonal test. By multi-factor and multi-level simulation tests, the representative and high reliability results could be quickly obtained, so as to make the simulation scheme more scientific, the simulation process more efficient, and the simulation results more reliable. However, similar to other prediction models, SD model also forecasts and simulates the future situation based on historical data, and there would be deviation between the results and the real situation inevitably. Moreover, SD model is a dynamic simulation method of single element coupling, which is difficult to realize the adaptive process of the system.

In terms of relevant literature, Sun et al. (2021), Zhang et al. (2019), and Li et al. (2020) used different methods to study the situation of the development of ecological environment and economic society of Huainan in recent years. The results of these studies show that the overall development level of Huainan in recent years is improving. Using SD model, You (2018) concluded that by 2025, the comprehensive development level of economy and ecology of Huainan would be on the rise in all simulation scenarios. These results are consistent with the conclusions of this study.

By improving the simulation process of SD model, this study overcomes the subjectivity of the selection of control parameters and increases the efficiency of simulation and the accuracy of simulation results. The results enrich the research methods of RECC, and also provide a theoretical reference for the selection of sustainable development mode of coal cities. Due to the numerous influence factors in the system of RECC and the limited data sources, the factors involved in this study may not be comprehensive enough. We can obtain relevant data from more sources and try to build a more comprehensive factor set in the future. Besides, because of the complexity and variability of the system, some factors and equations could be further adjusted to reflect the reality more objectively and predict the development trend more accurately.

Appendix

Table 7 The center degree and the cause degree of each indicator

Indicator	a_i	b_i	m_i	r_i	Indicator	a_i	b_i	m_i	r_i
I ₁	0.116	0.161	0.276	-0.045	I ₂₂	0.205	0.090	0.296	0.115
I ₂	0.061	0.301	0.362	-0.239	I ₂₃	0.177	0.105	0.282	0.072
I ₃	0.112	0.165	0.278	-0.053	I ₂₄	0.177	0.105	0.282	0.072
I ₄	1.113	0.015	1.128	1.010	I ₂₅	0.184	0.101	0.285	0.083
I ₅	0.094	0.198	0.292	-0.104	I ₂₆	0.098	0.189	0.287	-0.090
I ₆	0.246	0.075	0.321	0.171	I ₂₇	0.177	0.105	0.282	0.072
I ₇	0.122	0.153	0.274	-0.031	I ₂₈	0.383	0.048	0.430	0.335
I ₈	0.163	0.114	0.277	0.048	I ₂₉	0.107	0.173	0.280	-0.066
I ₉	0.159	0.116	0.276	0.043	I ₃₀	0.121	0.154	0.275	-0.033
I ₁₀	0.216	0.086	0.302	0.130	I ₃₁	0.119	0.156	0.275	-0.036
I ₁₁	0.164	0.113	0.277	0.051	I ₃₂	0.087	0.213	0.300	-0.125
I ₁₂	0.157	0.118	0.275	0.039	I ₃₃	0.142	0.131	0.273	0.011
I ₁₃	0.067	0.276	0.343	-0.210	I ₃₄	0.059	0.313	0.372	-0.255
I ₁₄	0.124	0.149	0.274	-0.025	I ₃₅	0.050	0.366	0.416	-0.316
I ₁₅	0.142	0.131	0.273	0.010	I ₃₆	0.085	0.218	0.303	-0.132
I ₁₆	0.136	0.137	0.273	-0.001	I ₃₇	0.133	0.139	0.273	-0.006
I ₁₇	0.054	0.339	0.393	-0.285	I ₃₈	0.197	0.094	0.291	0.103
I ₁₈	0.175	0.106	0.281	0.068	I ₃₉	0.131	0.142	0.273	-0.010
I ₁₉	0.097	0.192	0.288	-0.095	I ₄₀	0.153	0.121	0.275	0.032
I ₂₀	0.168	0.111	0.279	0.058	I ₄₁	0.051	0.356	0.407	-0.304
I ₂₁	0.088	0.210	0.298	-0.121	I ₄₂	0.123	0.151	0.274	-0.028

Author contribution Keyu Bao and Jun Ruan collected the data. Keyu Bao analyzed the data and wrote the first draft of this paper. Gang He supervised this project and reviewed results. Yanna Zhu and Xiaoyu Hou worked for the manuscript review.

Funding This work was supported by the following programs: (1) Anhui Scientific Research Planning Project in 2022 with the title "Dynamic evaluation and spatial effect analysis of eco-environmental quality of resource-based cities of Anhui Province from the perspective of regional interaction"(NO.2022AH050795).(2) Research foundation for introduction of talents of Anhui University of Science and Technology (No. 2022yjrc16).

Data availability The datasets used and analyzed in this study could be available from the corresponding author on reasonable request.

Declarations

Ethical approval We declare that this manuscript has complied with all the ethical requirements of the journal.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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