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Original Research

Analysis of the Dynamic Change of the Environmental Carrying Capacity and Influencing Factors of Mature Coal Cities

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Abstract

The evaluation of environmental status and the analysis of the influencing factors are significant to the transformation and high-quality development of mature coal cities. Choosing five typical mature coal cities in China as the case study, this study constructed the comprehensive evaluation system of ECC (environmental carrying capacity). It assessed the temporal variation of ECC from 2010 to 2019 with normal cloud mode. Then the main influencing factors were identified by analyzing the interaction mechanism between factors via BP-DEMATEL mode. The results indicated that: (1) The ECC level of most cities improved significantly. (2) The ECC levels of resource-environment subsystem were higher than that of society-economy subsystem. (3) Proportion of environmental protection spending, comprehensive utilization rate of industrial solid and atmospheric pollutants emission intensity were the main driving influencing factors, while the proportion of subsidence area and urbanization rate were the main characteristic influencing factors of most cities. Meanwhile, each city has some main influencing factors which are different from each other. This study compares the changing trend of ECC in different mature coal cities and analyzes the reasons, which provides scientific basis and decision-making reference for the formulation of relevant policies.

Keywords: mature coal cities, environmental carrying capacity, influencing factors, normal cloud mode, BP-DEMATEL model

Introduction

Coal is the main energy source in China. In 2010-2020, raw coal accounts for more than 70% and 56% of its production and consumption of primary energy resources respectively, and the status that taking coal as the main energy source will not change for a long time. According to the guarantee term of coal resources and the accumulation degree of resistance in development, coal cities in China can be divided into four types: growing coal city, mature coal city, declining coal city and regenerating coal city [1]. Growing coal cities take 22% of all prefecture-level coal cities. Their coal resources reserves are large but the mining modes may not be standardized. The economic development

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is unbalanced although the growth is rapid. The proportion of mature coal cities is about 48%. The coal output of these cities is stable and the mining and processing system is complete. The development level is relatively high, but these cities suffer serious ecological environment damage. Declining coal cities account for 24% and there are many obstacles in the process of development: coal resources depletion, environmental damage, high unemployment, low social security and so on. Regenerating coal cities only take 6% and most coal mines of these cities have been shut down. Their industrial structure has been transformed, and the economic, social, ecological and environmental problems caused by coal mining have been basically solved, but the innovation development ability may be insufficient.

Among the above four types of cities, the sustainable development ability of mature coal cities is particularly concerned as they are at the important stage of transformation, and how to maintain the resource superiority and improve environmental quality is the key issue. These cities are undergoing large-scale coal mining and the ecological environmental problems are prominent: the air quality is generally poor, the increasement of solid waste is rapid, the destruction and pollution of water system is serious, and the areas with ground fissures and surface collapse are large. Therefore, in order to formulate targeted policies for these cities, it is necessary to estimate the status of environment and identify the influencing factors scientifically.

ECC (environmental carrying capacity) is an index often used in environmental status assessment. It can select relevant indicators, according to the research object, to conduct the quantitative measurement of environmental status, so as to reflect the level of environment directly. This study selected five typical mature coal cities in China as the case study. The change trend of ECC level was analyzed by normal cloud model, then BP-DEMATEL model was used to find the main influencing factors. Based on the results, we could compare the status of ECC of these cities and identify the same and different driving elements.

The concept of ECC comes from the meaning of environmental capacity. Environmental capacity refers to the growth limit of plants or animals in a specific environment, or the largest number of pollutants taken in by a regional environmental system [2, 3]. Gradually, ECC develops into a comprehensive theory which involves environment, resource, economy, society and so on. It emphasizes the interaction effect between socio-economic system and environmental system. Now ECC is regarded as, within the elastic limit of the ecosystem, the number of pollutants that can be taken in, the economic scale and the population that can be carried by the environmental system [4, 5]. As the development of the research, abundant research achievements have been made and a variety of evaluation methods have been formed. Common evaluation methods of ECC include four kinds: environmental capacity calculation, evaluation by index system, simulation and prediction, and estimation of the balance between supply and demand. Environmental capacity calculation is to calculate the total amount of pollutants could be carried by regional environment. The results can directly present the carrying capacity to pollutants of the environmental system. Reghunathan V M et al. analyzed the environmental capacity of Vellayani Lake (India), and found the main influencing factors leading to the low ECC of the lake [6]. Pickett et al. studied the pollutant capacity and load allocations of Upper Chehalis River in Washington State [7]. Zhu Tao et.al calculated the environmental carrying rate of air pollutants in Tongling City, then identified source layout influence area, pollutant accumulation influence area and receptor influence area [8]. Evaluation by index system is to choose key factors to construct the index system, so as to evaluate ECC quantitatively. Relevant researches evaluate ECC based on a single element or multiple elements. Widodo B. et al. studied the impact of civilization on ECC in Yogyakarta area from the perspective of land and water [9]. Lu Lin et al. assessed the ECC of cities in Bohai Bay Region of China by the comprehensive index constituted by water, atmosphere, surface water and offshore area [10]. Cheng Fei et al. designed a comprehensive system including natural environment subsystem and social environment subsystem, then researched the status of ECC of some coral reef islands and the balance between the two subsystems [11]. Simulation and prediction are to simulate the operation of the composite system by analyzing the interaction mechanism between elements in the environmental system and establishing a simulation model, or predict the carrying capacity by setting different values of key indicators and designing various scenarios. Hu Dian et al. built a SD model according to the relationship in the environmental system. Based on this model they predicted the future trend of ECC of Fuzhou City and found the optimal development mode by simulation [12]. Ning Jia et al. set four scenarios of pollutant discharge amount and predicted the speed of economic growth of western China under different levels of ECC [13]. Estimation of the balance between supply and demand is to estimate the ECC level by comparing the supply and demand between load carrying objects and load carrying subjects such as resources, environment and ecology. From the perspective of emergy analysis, Jung Chanhoon et al. evaluated the ECC of Jeju Island in different periods by indicators of percent renewable, emergy yield ratio and environmental loading ratio [14]. Suwarno and Widjaya calculated the ECC of Goa Kiskendo Forest Tourism based on the regional biophysical conditions and management capabilities, and explored the relation between tourism and environmental sustainability [15].

Among the above evaluation methods, evaluation by index system is the most common one. The statistical methods such as entropy, fuzzy evaluation, analytical hierarchy process and principal component analysis are often used in evaluation process. However, these traditional methods can't solve the problems of fuzziness and randomness. Considering that ECC is a complex system with numerous influencing factors, it is important to choose a method which can deal with fuzziness and randomness to evaluate ECC level scientifically and accurately. Cloud model can conduct the uncertainty transformation between qualitative concept and quantitative characterization, and reflect the inherent interaction between randomness and fuzziness. Now, cloud model has been successfully used in many fields and it provides a new method for evaluation. Shi et al. put forward a system energy effectiveness evaluation method based on cloud model and applied it in airborne EW system [16]. Combined with cloud model's advantages of integrating the qualitative and quantitative concepts well, Huang and Qiu evaluated the security capability of urban rail signal system, and found out the defects in the operation of urban rail signal system [17]. Guo et al. proposed a multi attribute evaluation method based on cloud model then assessed the data link system fighting effectiveness. This provided a new idea for evaluation and decision of multi attribute object system [18]. Xu et al. calculated the air quality index of Shenyang City via cloud model [19]. He and Ruan used normal cloud model to study the change of ecological security level of Anhui Province in 2010-2019 [20].

Among the research on the influencing factors of carrying capacity, the methods often being applied are regression model, obstacle degree model, spatial econometric model and geographical detector model. These methods are useful in analyzing the influence of factors on carrying capacity, or reflect the influence of factors on spatial and temporal differentiation and the spatial effect on carrying capacity. Compared with these methods, the advantage of BP-DEMATEL model is that it not only can estimate the importance of each factor, but also reflect the interdependence and restriction relationship among factors. This model forms a new way to explore the main influencing factors. Zhang and Chen used BP-DEMATEL model to identify the main influencing factors of bidding evaluation of green procurement of government public projects [21]. Zhang and Zhu analyzed the relationship between the influencing factors of entrepreneurial environment in different municipalities in China quantitatively based on this model, then identified the driving influencing indicators and characteristic influencing indicators, and put forward corresponding suggestions according to the characteristics of each municipality [22]. Zhang et al. studied the key factors affecting the $PM_{2.5}$ concentrations and the relation between factors via BP-DEMATEL model [23]. Li et al. found out the main influencing factors of ecological security of The Pearl River Delta urban agglomeration in China with BP-DEMATEL model. The results indicated that ecological factors are the most important guarantee of urban ecological security in this region [24]. Chen et al. used BP-DEMATEL model to identify the key factors affecting the symbiotic security of water-energy-food ecosystem in the Yangtze Basin, and proposed that this area should pay more attention to energy conservation [25].

In previous research on ECC, there were few about coal cities; the studies analyzing influencing factors of ECC were insufficient neither. Therefore, this study chose typical mature coal cities in China as the case study, then built the comprehensive index system according to the characteristics of these cities. Then normal cloud model was used to evaluate the temporal variation of ECC and the balance between systems. Furthermore, we chose BP-DEMATEL model to identify main influencing factors of each city.

Material and Methods

Study Area

The selection of study area is as follows: the top 8 provinces in raw coal production of China in 2019 are Inner Mongolia, Shanxi, Shaanxi, Xinjiang, Guizhou, Shandong, Anhui and Henan. Therefore, we consider to select the study area from the above provinces. Finally, five mature coal cities are chosen and their basic information is shown in Table 1. These five cities are among the 14 coal energy bases of China and they have typical characteristics of mature coal cities and the main types of coal resources in these cities are different.

Table 1. Basic information of study area

City	Province	Area (km^2)	Coal reserves (10^8 Ton)	Coal energy bases	Main types of coal resources
H	Anhui Province	5533	138	Huainan and Huaibei coal base	1/3 Coking coal
C	Shanxi Province	9490	808	Jindong coal base	Smokeless coal
N	Shandong Province	11000	254	Luxi coal base	Gas coal
S	Henan Province	7882	103	Henan coal base	Fat coal, Gas coal, coking coal
J	Shaanxi Province	18117	60	Huanglong coal base	Long-flame coal

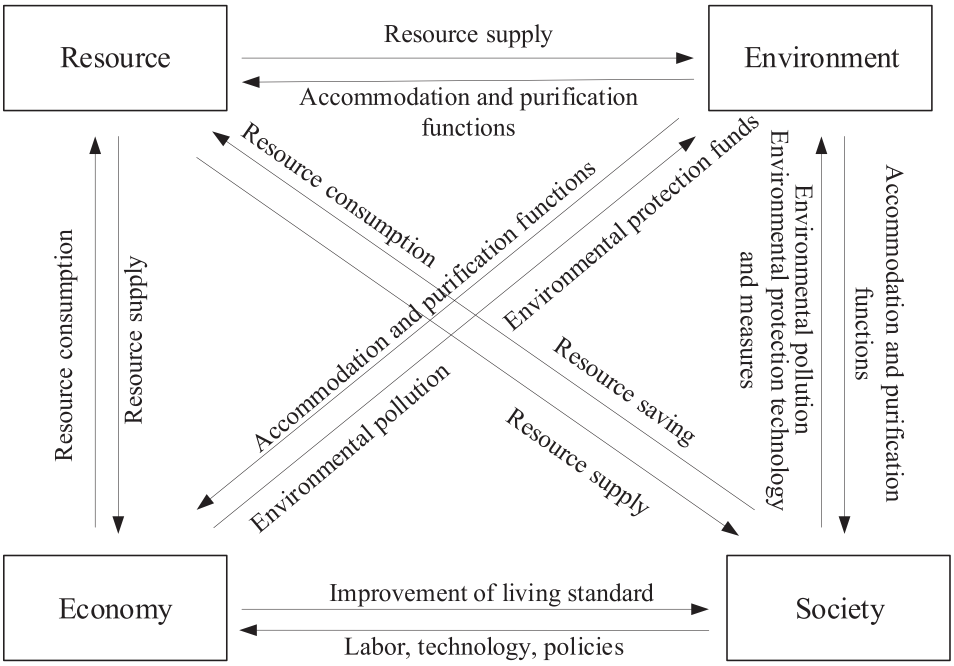

Fig. 1. Urban environmental carrying capacity system.

The data mainly come from the website of the National Bureau of Statistics of China, China Urban Statistical Yearbook, China Mining Yearbook, China Energy Statistical Yearbook. And Environmental Status Bulletin, Water Resources Bulletin, Statistical Yearbook, Economic and Social Development Bulletin of each city.

Assessment Indicator System

The regional environmental system is affected by various factors, so the elements related to ECC should be involved in the construction of indicator system. As shown in Fig. 1, the urban ECC system is influenced by resources, environment, economy, society and so on. Environment and resources provide space, purifying function and necessary materials for human. Sufficient resources and good environment are essential guarantee for sustainable development, while the depletion of resources and the deterioration of ecological environment will restrict social and economic development. Economic and social development will lead to resource consumption and environmental damage inevitably. However, benign economic development and social progress are good for resource saving, and they can also provide funds and technology for improving the environment quality. Realizing the virtuous cycle of economic and social development and resource and environment protection is the way to improve the carrying capacity level of environmental system. In view of this, this study designed the subsystems from two dimensions of resource-environment and economy-society to analyze the relation between subsystems and their effects on ECC.

In order to choose the indicators more scientifically and comprehensively, we combined PSR (Pressure-State-Response) framework model and the results of index frequency analysis of related literatures. Then we referred to The Technical Specification HJ192-2015 for Eco-Environmental Status Assessment and the National Sustainable Development Plan for Resource-based Cities (2013-2020). Based on the above analysis and the characteristics of coal cities, we finally screened out 42 indexes to form the assessment indicator system of ECC (Table 2).

Normal Cloud Model

Calculative Process of Normal Cloud Model

Cloud model is a new mathematical model based on probability theory and diffusion mathematics theory, which can solve the problems of fuzziness and randomness of the system [26]. The model is developed from normal distribution and bell-shaped membership function and has wide applicability [27, 28].

Cloud model describes the numerical characteristics via three numbers: E_x(*Expected value*), E_n(Entropy), and H_e(Hyper entropy). It can conduct the uncertainty transformation from qualitative concept to quantitative characterization. E_x represents the central value of the domain of qualitative concept, E_n is the measure of the fuzzy degree of qualitative concept, and H_e reflects the randomness level of membership degree [29]. The specific calculative process of one-dimensional normal cloud model is as follows:

Firstly, a normal random number E_n' is obtained. Its expected value is E_n and its standard deviation is H_e.

Secondly, we can get a normal random number X_i, whose standard deviation is E_n', and the expected value is E_x.

Thirdly, according to equation (1), the determination of x_i to the qualitative concept is calculated.

$$y_i = exp\left[-(x_i - E_x)^2 / 2 {E_{n_i}}^2\right] \quad (1)$$

Fourthly, repeat the above steps until N cloud droplets (x_i,y_i) are generated to form the cloud image.

Construction of the Normal Model for ECC Evaluation

The index set $U = \{u_1, u_2, u_3, \dots u_n\}$ and the evaluation set $V = \{v_1, v_2, v_3, \dots v_n\}$ of the evaluation objects of ECC were constructed. The methods of entropy and AHP were used to calculate the weight of each index, and then took the mean value as the final weight, so as to get the weight set $W = \{w_1, w_2, w_3, \dots w_n\}$ of each index [30].

The fuzzy relation matrix R was formed according to the mapping of each index in the evaluation set. Factor r_{ij} was a number in R, which could represent the membership degree of the ith factor u_i relative to the level j i.e., v_j in the evaluation set V. If x_{ij}^1 and x_{ij}^2 represented the maximum value and the minimum value in level j(j = 1, 2, 3, ... m) corresponding to factor i(i = 1, 2, 3, ... n), then the qualitative concept of the level j corresponding to factor i could be described by cloud model as follows:

$$Ex_{ij} = \left(x_{ij}^1 + x_{ij}^2\right)/2 \quad (2)$$

$$En_{ij} = \left(x_{ij}^1 - x_{ij}^2\right)/6 \quad (3)$$

Table 2. Assessment indicator system of environmental carrying capacity.

Target layer	System layer	Criterion layer	Indicator layer	Indicator code
Environmental carrying capacity	Resource-environment	Resource utilization and environmental pollution	Energy consumption per unit of GDP	Z_1
			Electricity consumption per unit of GDP	Z_2
			Water consumption per unit of GDP	Z_3
			Regional traffic noise value	Z_4
			Industrial waste water discharge intensity	Z_5
			Industrial waste gas emission intensity	Z_6
			Industrial dust emission intensity	Z_7
			Industrial solid waste discharge intensity	Z_8
			Industrial COD emission intensity	Z_9
			Industrial SO_2 emission intensity	Z_{10}
		Resource and environmental status	Water resources per capita	Z_{11}
			Sown area of crops per capita	Z_{12}
			Coal reserves per capita	Z_{13}
			Reserve-production ratio of coal resources	Z_{14}
			Gas penetration rate	Z_{15}
			Proportion of built-up area	Z_{16}
			Proportion of subsidence area	Z_{17}
			Park and green land area per capita	Z_{18}
		Environmental governance	Control rate of industrial waste water discharge	Z_{19}
			Comprehensive utilization rate of industrial solid	Z_{20}
			Treatment rate of industrial dust	Z_{21}
			Harmless treatment rate of household garbage	Z_{22}
			Coverage rate of green belt in built-up area	Z_{23}
			Proportion of days with good air quality	Z_{24}
			Proportion of environmental protection spending	Z_{25}

Table 2. Continued.

Environmental carrying capacity	Economy-society	Population growth and industrial development	Population density	Z_{26}
			Natural population growth rate	Z_{27}
			Urbanization rate	Z_{28}
			Proportion of output value of secondary industry	Z_{29}
			Proportion of coal industrial output value	Z_{30}
			Raw coal production per capita	Z_{31}
		Economic and social development	GDP per capita	Z_{32}
			Growth rate of GDP	Z_{33}
			Fixed asset investment per capita	Z_{34}
			Engel coefficient of urban residents	Z_{35}
			Per capita disposable income of urban residents	Z_{36}
			Proportion of output value of tertiary industry	Z_{37}
		Social security	Employment rate	Z_{38}
			Proportion of education spending	Z_{39}
			Proportion of R&D spending	Z_{40}
			Urban road area per capita	Z_{41}
			Number of beds in medical institutions per 10,000 people	Z_{42}

$$He_{ij} = k \tag{4}$$

Where, k is empirically set to 0.01 [31].

According to the values of the sample to be evaluated, the forward cloud generator and equation 1 were used to calculate the determinism of factor i to level j, which generated the membership matrix $U = (y_{ij})_{n*m}$. Then the fuzzy subset Z corresponding to evaluation set V was obtained by fuzzy transformation of weight set W and membership matrix U:

$$Z = W * U = (b_1, b_2, \dots b_m) \tag{5}$$

Where, $z_j = \Sigma^n_{i=1} w_{ij} y_{ij}$ j(j = 1, 2, 3, ... m). Finally, the level with maximum membership degree was considered as the evaluation result according to the principle of maximum membership degree in fuzzy mathematics.

BP-DEMATEL Mode

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 [32]. 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 relationship between factors [33]. 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 find out the main factors with the greatest influence on the ECC system. The specific steps are as follows:

1. Total weight vector

$$\omega = mean(|W| * |w|) = (\omega_1, \omega_2, \dots \omega_n) \tag{6}$$

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 $|W|$ * $|w|$ 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.

$$B = (b_{ij})_{n\times n} = \begin{bmatrix} b_{11} & b_{12} \cdots & b_{1n} \\ b_{21} & b_{22} \cdots & b_{2n} \\ \vdots & \vdots & \vdots \\ b_{n1} & b_{n2} \cdots & b_{nn} \end{bmatrix} \tag{7}$$

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.

Table 3. Levels of each indicator.

Indicator	Level 1	Level 2	Level 3	Level 4	Level 5
Z_1	(1.8,2.1)	(1.5,1.8)	(1.2,1.5)	(0.5,1.2)	(0.35,0.5)
Z_2	(1900,2300)	(1475,1900)	(1060,1475)	(645,1060)	(230,645)
Z_3	(240,320)	(155,240)	(70,155)	(50,70)	(30,50)
Z_4	(71,75)	(68,71)	(63,68)	(61,63)	(58,61)
Z_5	(3,4.5)	(0.2,3)	(0.15,0.2)	(0.10,0.15)	(0.08,0.10)
Z_6	(0.6,6.6)	(0.3,0.6)	(0.1,0.3)	(0.05,0.1)	(0.04,0.05)
Z_7	(11.5,14.5)	(9.5,11.5)	(6.5,9.5)	(3.5,6.5)	(0.25,3.5)
Z_8	(0.4,0.6)	(0.1,0.4)	(0.035,0.1)	(0.02,0.035)	(0.01,0.02)
Z_9	(0.8,2)	(0.3,0.8)	(0.08,0.3)	(0.05,0.08)	(0.03,0.05)
Z_{10}	(15.5,18)	(6.5,15.5)	(3,6.5)	(0.4,3)	(0.1,0.4)
Z_{11}	(100,500)	(500,800)	(800,1100)	(1100,1400)	(1400,2100)
Z_{12}	(0.065,0.085)	(0.085,0.105)	(0.105,0.125)	(0.125,0.165)	(0.165,0.185)
Z_{13}	(0.002,0.01)	(0.01,0.5)	(0.5,0.6)	(0.6,0.9)	(0.9,1.3)
Z_{14}	(30,100)	(100,200)	(200,300)	(300,400)	(400,750)
Z_{15}	(66,80)	(80,85)	(85,90)	(90,95)	(95,100)
Z_{16}	(1.9,2.3)	(1.5,1.9)	(1.1,1.5)	(0.7,1.1)	(0.3,0.7)
Z_{17}	(4.5,6.5)	(3.5,4.5)	(2.5,3.5)	(1,2.5)	(0.1,1)
Z_{18}	(6.5,9.5)	(9.5,12.5)	(12.5,14.5)	(14.5,15.5)	(15.5,19)
Z_{19}	(90,92)	(92,94)	(94,96)	(96,98)	(98,100)
Z_{20}	(20,36)	(36,52)	(52,68)	(68,84)	(84,100)
Z_{21}	(95,96)	(96,97)	(97,98)	(98,99)	(99,100)
Z_{22}	(35,40)	(40,55)	(55,70)	(70,85)	(85,100)
Z_{23}	(35,38)	(38,41)	(41,44)	(44,47)	(47,51)
Z_{24}	(35,48)	(48,61)	(61,74)	(74,87)	(87,100)
Z_{25}	(0.15,0.45)	(0.45,0.65)	(0.65,0.85)	(0.85,1.15)	(1.15,1.45)
Z_{26}	(600,780)	(450,600)	(300,450)	(150,300)	(100,150)
Z_{27}	(9,12)	(6,9)	(4,6)	(1,4)	(-2,1)
Z_{28}	(60,67)	(55,60)	(45,55)	(35,45)	(30,35)
Z_{29}	(64,70)	(56,64)	(48,56)	(40,48)	(30,40)
Z_{30}	(70,85)	(55,70)	(40,55)	(25,40)	(10,25)
Z_{31}	(40,50)	(30,40)	(20,30)	(10,20)	(0.5,10)
Z_{32}	(2,3)	(3,4)	(4,5)	(5,7)	(7,8)
Z_{33}	(-1.8,2.8)	(2.8,7.6)	(7.6,12.4)	(12.4,17.2)	(17.2,22)
Z_{34}	(1,2)	(2,4)	(4,6)	(6,9)	(9,13)
Z_{35}	(40,45)	(35,40)	(30,35)	(25,30)	(20,25)
Z_{36}	(1.5,2.1)	(2.1,2.7)	(2.7,3.3)	(3.3,3.9)	(3.9,4.5)
Z_{37}	(20,28)	(28,36)	(36,44)	(44,52)	(52,60)
Z_{38}	(50,54)	(54,58)	(58,62)	(62,66)	(66,70)
Z_{39}	(1.5,2.2)	(2.2,2.9)	(2.9,3.6)	(3.6,4.2)	(4.2,5.2)

Table 3. Continued.

Z_{40}	(0.1,0.5)	(0.5,1.5)	(1.5,2.5)	(2.5,3.5)	(3.5,4)
Z_{41}	(9,12)	(12,15)	(15,20)	(20,28)	(28,36)
Z_{42}	(30,40)	(40,50)	(50,60)	(60,70)	(70,75)

Table 4. The center degree and the cause degree of each indicator.

Indicator	City H		City C		City N		City S		City J	
	m_i	r_i	m_i	r_i	m_i	r_i	m_i	r_i	m_i	r_i
Z_1	0.276	-0.045	1.611	1.266	1.124	0.131	0.987	-0.162	0.882	-0.766
Z_2	0.362	-0.239	1.011	0.108	1.141	0.238	1.063	0.428	0.473	-0.162
Z_3	0.278	-0.053	1.008	-0.079	1.181	0.387	1.324	-0.901	0.649	-0.476
Z_4	1.128	1.010	1.013	0.123	1.117	0.012	1.068	0.441	0.516	0.263
Z_5	0.292	-0.104	1.011	0.111	1.118	0.053	0.983	0.130	0.447	0.043
Z_6	0.321	0.171	1.013	0.129	1.151	-0.280	1.010	-0.268	0.453	0.084
Z_7	0.274	-0.031	1.541	1.175	1.122	-0.108	1.046	0.382	0.453	-0.083
Z_8	0.277	0.048	1.093	-0.433	1.212	0.475	1.527	1.183	0.494	0.216
Z_9	0.276	0.043	1.008	-0.076	1.145	0.253	0.991	0.180	0.750	0.607
Z_{10}	0.302	0.130	1.010	0.098	1.120	0.080	1.563	1.229	0.446	-0.031
Z_{11}	0.277	0.051	1.057	0.331	1.132	0.189	1.121	0.559	0.452	0.081
Z_{12}	0.275	0.039	1.006	0.042	1.165	0.334	0.979	-0.099	0.457	-0.106
Z_{13}	0.343	-0.210	1.030	-0.229	1.270	-0.608	1.440	1.067	0.461	-0.122
Z_{14}	0.274	-0.025	1.008	-0.083	1.176	-0.371	1.288	0.848	0.446	0.021
Z_{15}	0.273	0.010	1.203	0.666	1.286	0.641	1.006	-0.254	0.461	0.120
Z_{16}	0.273	-0.001	1.203	0.666	1.373	-0.804	2.341	-3.206	0.448	0.053
Z_{17}	0.393	-0.285	1.418	-1.006	1.436	-0.909	1.282	-0.839	0.621	-0.436
Z_{18}	0.281	0.068	1.158	-0.578	1.122	-0.111	1.011	0.270	0.728	0.579
Z_{19}	0.288	-0.095	1.085	0.412	1.273	-0.616	1.035	-0.351	0.525	0.281
Z_{20}	0.279	0.058	1.031	-0.233	1.272	0.613	1.281	0.837	0.575	0.366
Z_{21}	0.298	-0.121	1.200	-0.660	1.159	0.312	1.094	0.501	0.492	-0.210
Z_{22}	0.296	0.115	1.099	-0.447	1.560	-1.095	1.045	0.380	0.714	0.561
Z_{23}	0.282	0.072	1.018	0.162	1.120	-0.086	0.975	-0.041	0.448	-0.053
Z_{24}	0.282	0.072	1.187	-0.635	1.141	-0.235	1.031	0.339	0.446	0.023
Z_{25}	0.285	0.083	1.128	0.515	1.194	0.426	0.988	-0.165	0.528	0.285
Z_{26}	0.287	-0.090	1.363	-0.927	1.150	0.274	0.999	0.223	0.476	0.169
Z_{27}	0.282	0.072	1.049	0.304	1.710	1.303	0.984	0.137	0.450	-0.064
Z_{28}	0.430	0.335	1.332	-0.880	1.247	-0.559	1.556	-1.219	0.868	-0.749
Z_{29}	0.280	-0.066	1.118	-0.493	1.138	0.223	0.975	0.030	0.448	-0.052
Z_{30}	0.275	-0.033	1.227	0.708	1.129	-0.170	1.064	0.431	0.445	-0.008
Z_{31}	0.275	-0.036	1.014	-0.133	1.124	-0.126	1.005	0.247	0.467	0.141
Z_{32}	0.300	-0.125	1.320	0.862	1.345	0.755	1.447	-1.076	0.615	-0.427
Z_{33}	0.273	0.011	1.060	-0.338	1.360	-0.782	1.005	0.250	0.476	0.170

Table 4. Continued.

Z_{34}	0.372	-0.255	1.079	0.396	1.121	0.099	1.030	0.337	0.738	-0.592
Z_{35}	0.416	-0.316	1.006	0.048	1.119	-0.074	1.076	-0.460	0.486	0.195
Z_{36}	0.303	-0.132	1.383	-0.955	1.119	-0.064	1.443	-1.070	1.215	1.136
Z_{37}	0.273	-0.006	1.128	-0.516	1.126	0.147	1.030	-0.337	0.467	-0.140
Z_{38}	0.291	0.103	1.068	0.362	1.306	-0.681	1.091	-0.493	0.618	-0.432
Z_{39}	0.273	-0.010	1.015	0.142	1.151	0.280	1.172	0.655	0.446	0.021
Z_{40}	0.275	0.032	1.023	0.191	1.125	0.140	1.047	0.385	0.489	0.204
Z_{41}	0.407	-0.304	1.069	0.367	1.316	0.702	1.090	-0.493	0.572	-0.362
Z_{42}	0.274	-0.028	1.114	-0.484	1.181	-0.388	0.975	-0.031	0.564	-0.348

$$X = (x_{ij})_{n\times n} = \frac{B}{max_{1\le i\le n}\sum_{j=1}^{n} b_{ij}} \quad (8)$$

$$T = X(I - X)^{-1} \quad (9)$$

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.

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

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

$$r_i = a_i - b_i(i = 1,2, \dots, n) \quad (10)$$

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.

Results and Discussion

Evaluation of ECC

Levels of Each Indicator for ECC Evaluation

Based on the related evaluation standards of China, previous research and the situation of the study area, the ECC levels were divided into five grades, the greater the number meant the higher the level of ECC. The level grading of each indicator was shown in Table 3.

The Normal Cloud Model of Each Indicator

According to the level grading of each indicator in Table 3 and normal cloud model, the characteristic parameters of the standard normal cloud model of each indicator were obtained, as shown in Table 4. Then we got the cloud mode diagram of normal membership of each indicator by MATLAB 2016a software and the cloud model parameters of the indicator. For example, Fig. 2 is the cloud mode diagram of normal membership of energy consumption per unit GDP.

Calculating the ECC Level

The data of the indicators from 2010 to 2019 were substituted into the forward cloud generator to get the cloud determinism of each level corresponding to each indicator and establish the membership matrix U. Then the fuzzy transformation of the membership degree matrix U and the weight set W was done according to equation (5) to obtain the corresponding fuzzy subset Z of the evaluation set V, thus getting the membership degree of each indicator in each level. Finally, in accordance with the principle of maximum membership degree, the jth level with the maximum membership degree was taken as the evaluation result of this indicator.

Temporal Variation of ECC

Temporal Variation of ECC of the Whole System

The ECC level from 2010 to 2019 was calculated by the calculation procedure above and the temporal variation of ECC of each city was shown in Fig. 3. It could be known that there were differences in the change trend of ECC level of each city in 2010-2019. In terms of the level of ECC in 2019, City N and J were the best, followed by City H and S, and City C was the worst. From the perspective of the change trend of ECC, the ECC of City N remained at level 3 - 5, and the curve of ECC showed a U shape. It's ECC was at level 3 in 2012-2014, and it kept at level 5 in other years.

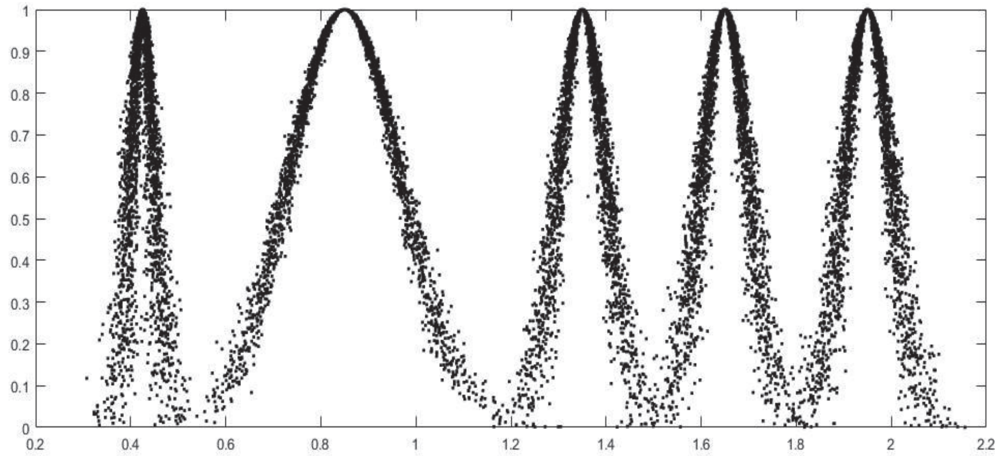

Fig. 2. The cloud mode diagram of the indicator belonging to different carrying capacity levels.

The ECC level of City H and J showed a continuous upward trend. The ECC of City H changed from level 2 to level 3, and the ECC of City J included three levels: level 2- level 3- level 4. The ECC level of City S fluctuated greatly. Its curve of ECC level showed an M-shaped trend from 2010 to 2014, fluctuating between level 2 and level 4, and remained at level 4 since 2015. The fluctuation of ECC level of City C was extremely obvious: the curve of ECC level showed a W-shaped from 2010 to 2015, and the ECC level decreased and remained at level 3 in 2016-2018, then further went down to level 1 in 2019.

These showed that the ECC level of most cities kept at the comparatively high level after fluctuation, or had been improved continually. It's worth noting that the ECC level of these cities improved significantly since 2015. The main reasons were as follows: On the one hand, China enacted a revised environmental protection law in 2015 and continuously improved the environmental quality monitoring system. On the other hand, the demand for transformation of mature coal cities became more urgent, these cities were committed to adjusting industrial structure, reducing coal production capacity and strengthening environmental protection measures. On the contrary, the ECC level of City C presented a downward trend. This city had the largest raw coal output in the five cities. The raw coal output had been increased since 2014 and exceeded 111 million tons in 2019. In addition, the main industries of City C were industries with high energy consumption and high pollution, such as coal, electricity, coal chemical industry and so on. According to relevant data, energy consumption per unit GDP of the city was still at a high level, and the discharge of industrial waste gas and industrial solid waste was large. The average proportion of days with good air quality was only 67.8% from 2010 to 2019. Meanwhile, coal industrial output value still accounted for a large proportion in GDP, economic growth was relatively slow.

Temporal Variation of ECC of Subsystems

Fig. 4 indicated the change of ECC level of two subsystems of each city. The ECC level of each subsystem of City H all improved, changing from level 2 to level 3 or level 4. The ECC of resource-

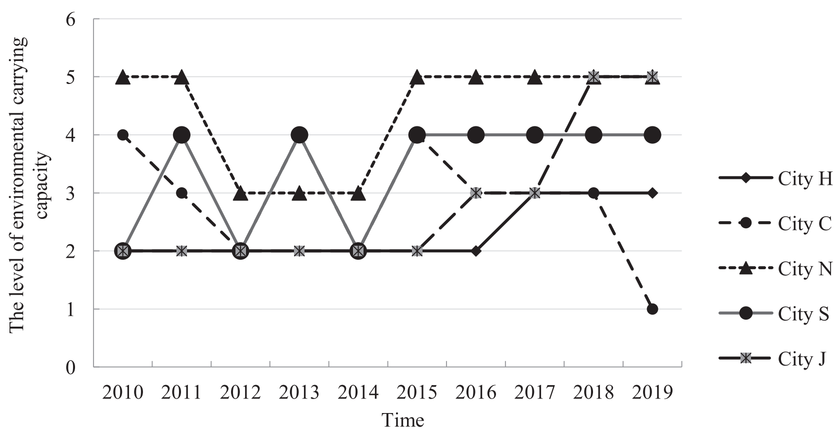

Fig. 3. Change of environmental carrying capacity of the case cities from 2010 to 2019.

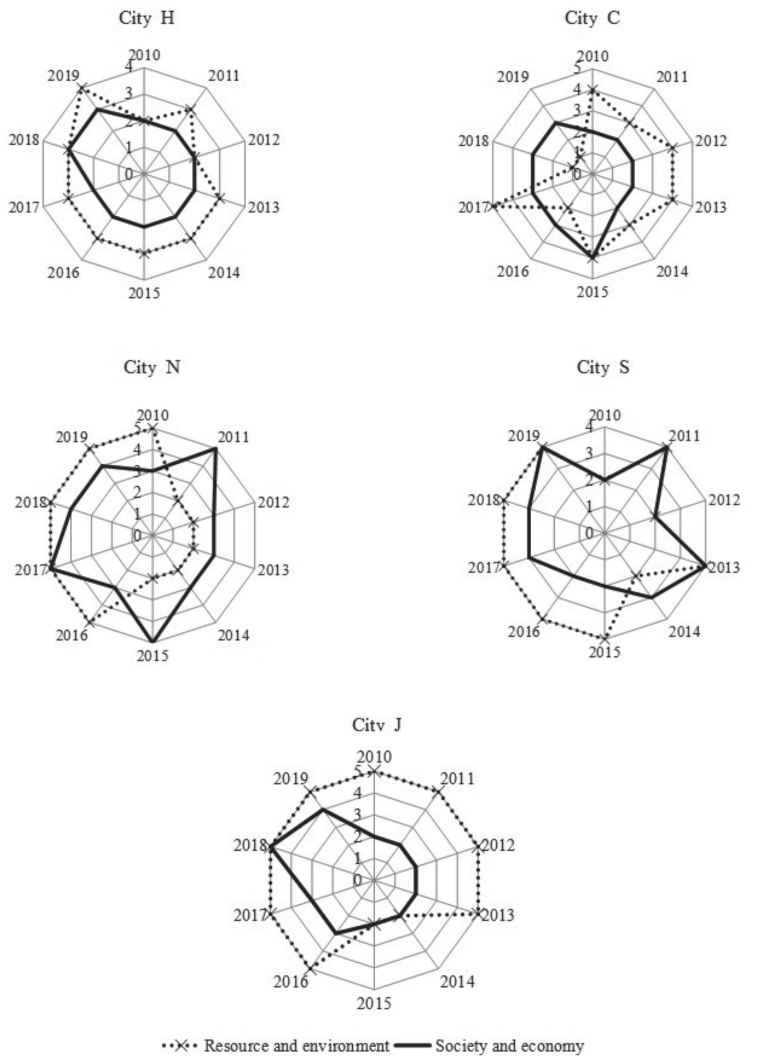

Fig. 4. Change of levels of environmental carrying capacity of resource-environmental system and socio-economic system in study area from 2010 to 2019

environment subsystem was higher than that of economy-society system except 2010, 2012 and 2018. The ECC level of economy-society system of City C had been slightly promoted. However, the ECC level of resource-environment subsystem fluctuated greatly, which became level 1 in 2019. These led to the reduction of the whole ECC level. City N's ECC of resource-environment subsystem kept at level 5 since 2016. But the ECC of economy-society system fluctuated between level 3 and level 5 in 2011-2017, then it stayed at level 4. It could be seen that resource-environment system had a more obvious driving effect on comprehensive ECC. The change trend of ECC of the two subsystems in City S was the same from 2010 to 2013. And the ECC level of resource-environment system was higher than that of economy-society system in 2014-2018 on the whole. The two subsystems' ECC level improved to level 4 in 2019. Overall, the ECC level of resource-environment system of City S was superior to that of economy-society system. The ECC level of the two subsystems of City J was obviously different. In 2014, 2015 and 2018, the ECC level of the two subsystems was the same. However, in other years, the ECC of resource-environment system remained at level 5, while the ECC of economy-society system was lower than that of resource-environment system although it had improved. Based on the above analysis, it could be seen that the ECC level of subsystems of these cities was unbalanced, and the driving effect of resource-environmental system on the improvement of ECC was more obvious. This indicated that it is very important for these cities to promote the social and economic transformation and development.

Main Influencing Factors

As shown in Table 4, the center degree (m_i) and the cause degree (r_i) of each indicator were calculated via BP-DEMATEL model. Then we could analyze the similarities and differences of ECC of each city by the main driving influencing factors and the main characteristic influencing indicators.

The Main Driving Influencing Factors

"Proportion of environmental protection spending (Z_{25})" was the main driving influencing factors of City H, City C, City N, and City J. The data indicated that the proportion of environmental protection spending of the four cities was on the rise on the whole. And indicator Z_{25} had a significant effect on follow indicators: "treatment rate of industrial dust (Z_{21})" "proportion of days with good air quality (Z_{24})" "control rate of industrial waste water discharge (Z_{19})" "harmless treatment rate of household garbage (Z_{22})". These showed that the increase of environmental protection funds was effective to improve the pollutant control level. "Comprehensive utilization rate of industrial solid (Z_{20})" was the main driving influencing factor of City N, City S and City J. The utilization rate of industrial solid of these cities increased gradually and this reduced the intensity of industrial solid waste discharge. "Industrial SO_2 emission intensity" was the main driving influencing factor of City H and City S. The SO_2 emissions of the two cities were the largest in the five cities from 2010 to 2019, which influencing the atmospheric quality greatly.

The other main driving influencing factors of each city were as follows: "Regional traffic noise value (Z_4)" "urbanization rate (Z_{28})" "industrial waste gas emission intensity (Z_6)" "harmless treatment rate of household garbage (Z_{22})" and "employment rate (Z_{38})" were the main driving influencing factors of City H. "Regional traffic noise value (Z_4)" and "urbanization rate (Z_{28})" reflected the impact of population gathering in cities on environmental system. "Employment rate (Z_{38})" had a significant impact on disposable income of urban residents and Engel coefficient. "Industrial waste gas emission intensity (Z_6)" and "harmless treatment rate of household garbage (Z_{22})" meant that the treatment capacity of pollutants was relatively inadequate. The main driving influencing factors of City C included "energy consumption per unit of GDP (Z_1)" "industrial dust emission intensity (Z_7)" "proportion of coal industrial output value (Z_{30})" and "GDP per capita (Z_{32})". Considering the degree of association of the indicators, the factors above greatly impacted the factors of "proportion of output value of secondary industry (Z_{29})" "proportion of subsidence area (Z_{17})" and "per capita disposable income of urban residents (Z_{36})". The large-scale coal industry of this city's had resulted in high energy intensity and serious environmental damage. "Natural population growth rate (Z_{27})" and "GDP per capita (Z_{32})" were the main driving influencing factors of City N. The city's good location and diversified industrial structure made the economy grow stably, and also provided relatively sufficient employment opportunities. However, rapid population growth led to the expansion of built-up areas and a surge in household garbage discharge. The main driving influencing factors of City S were "industrial SO_2 emission intensity (Z_{10})" "industrial solid waste discharge intensity (Z_8)" "coal reserves per capita (Z_{13})" and "reserve-production ratio of coal resources (Z_{14})". The coal reserves per capita and the reserve-production ratio of coal resources in this city decreased significantly, and the advantage of coal resources gradually weakened. "Per capita disposable income of urban residents (Z_{36})" "industrial COD emission intensity (Z_9)" "park and green land area per capita (Z_{18})" and "harmless treatment rate of household garbage (Z_{22})" were the main driving influencing factors of City J. The proportion of coal industry of this city was relatively small; steel, electric power, manufacturing developed rapidly; the economic development momentum was sound and the income level of residents was relatively high. The emission intensity of industrial COD decreased a lot, but the park and green land area per capita reduced significantly, and the harmless treatment rate of household garbage was unstable.

The Main Characteristic Influencing Factors

"Proportion of subsidence area (Z_{17})" was the common characteristic influencing factor of City H, City C and City N. After a long period of high-intensity coal mining, the area of subsidence in these cities had been expanding, accounting for more than 3 percent of the total area. The expansion of subsidence area had caused a series of ecological and environmental problems, which was one of the key environmental problems to be solved in these cities. "Urbanization rate (Z_{28})" was the characteristic influencing factor of City C, City S and City J. Due to the large proportion of primary industry, or limited by mountainous terrain, the urbanization of these cities was relatively slow and the urbanization level was low. "Energy consumption per unit of GDP (Z_1)" was the characteristic influencing factor of City J and City H. The energy consumption intensity of the two cities was still high although it decreased overall. The characteristic influencing factor of City N and City S was "proportion of built-up area (Z_{16})". It could be known from the interaction of the factors that the expansion of built-up area in the two cities was influenced by the large population scale and high natural population growth rate.

Besides, the characteristic influencing factors of City H included "Engel coefficient of urban residents (Z_{35})" "urban road area per capita (Z_{41})" and "fixed asset investment per capita (Z_{34})". These factors were mainly influenced by urbanization rate, employment rate and economic growth level. "Per capita disposable income of urban residents (Z_{36})" and "population density (Z_{26})" were the characteristic influencing factors of City C. The factors which impacted those cities were "GDP per capita (Z_{32})" and "natural population growth rate (Z_{27})". The GDP per capita of the city was relatively high, and residents' income maintained at a high level. At the same time, the wide area, small population base and low natural population growth rate made the change of population density small. The other characteristic influencing factors of City N were "harmless treatment rate of household garbage (Z_{22})" and "growth rate of GDP (Z_{33})". The former factor was closely related to the city's large population density and rapid population growth. Moreover, the total economic output of this city was large, and the industrial structure had been continuously optimized in recent years, so the economy developed rapidly and the GDP increased significantly. "GDP per capita (Z_{32})" was the characteristic influencing factor of City S. In view of the relationship between factors, the growth of GDP per capita was mainly affected by GDP and population growth rate. The characteristic influencing factor of City J also included "fixed asset investment per capita (Z_{34})". This factor was strongly correlated with GDP growth rate and population density. GDP growth of City J was strong from 2010 to 2019, which boosted fixed asset investment. Meanwhile, the change in population density was small, resulting in a large increase in fixed asset investment per capita.

This study chose five typical mature coal cities in China as the case study and constructed the multidimensional comprehensive evaluation system. Then we used normal cloud model to evaluate the change trend of ECC. With the help of BP-DEMATEL model, the main influencing factors of ECC were found out, and the reasons for the similarities or differences of ECC of these cities were analyzed.

Results showed that the ECC level of most cities improved in 2010-2019 and the improvement became large since 2015 and 2016. On the contrary, the ECC of City C presented a downward trend. In 2019, the status of ECC of City N and City J was at level 5, City S and City H' ECC level was 4 and 3 respectively, but the ECC level of City C declined to level 1. From the point of view of the ECC of subsystems, the ECC level of resource-environment system was inversely related to the scale of coal industry on the whole. The ECC level of resource-environment system of most cities had improved, but the ECC level of this system of City C fluctuated significantly and fell to level 1 in 2018-2019. The ECC of society-economy system of each city was lower than that of resource-environment system although it had increased.

As for the main influencing factors of ECC of each city, "proportion of environmental protection spending (Z_{25})" "comprehensive utilization rate of industrial solid (Z_{20})" and the indicators related to emissions of air pollutants were the main driving influencing factors with the highest frequency. Moreover, factors of resource-environment system accounted for a larger proportion of the main driving influencing factors, and had a stronger effect on the ECC system. "Proportion of subsidence area (Z_{17})" and "urbanization rate (Z_{28})" were the main characteristic influencing factors with the highest frequency. In addition, among the main characteristic factors of each city, factors of society-economy system accounted for 70%, indicating that the society-economy system was greatly influenced by resource-environment system.

Conclusions

The research results can reflect the ECC of typical mature coal cities in China to some extent and provide theoretical reference for their subsequent development model. Compared with the traditional evaluation methods, the normal cloud model overcomes the fuzziness and randomness when judging the level of indicators and carrying capacity, so that the evaluation results are more objective and accurate. BP-DEMATEL model can not only identify the main influencing factors, but also analyze the relationship between the factors, which is helpful to clarify the action path of the influencing factors of ECC system. These methods provide a new way for ECC assessment. The sample size can be increased to make the research results more representative in future study. In addition, different methods could be compared to reflect the change of ECC level better.

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Conflict of Interest

The authors declare no conflict of interest.

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