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Evaluation of the Provincial Carbon Neutrality Capacity of the Middle and Lower Yellow River Basin based on the Entropy Weight Matter-Element Model

Jian Xu [1], Haiying Wang [2,*] and Zhi Li [2]

[1] School of Management, Xi'an University of Science and Technology, Xi'an 710054, China
[2] School of Construction Machinery, Chang'an University, Xi'an 710064, China
* Correspondence: whying@chd.edu.cn; Tel.: +86-138-9195-8502

Abstract: In the process of promoting economic development, carbon peaks and carbon neutrality have gradually received more attention. The question of how to steadily and rapidly improve the carbon neutrality capacity of each province and excavate the key factors hindering the carbon neutrality capacity has become particularly important. In this study, the DPSIR (driving, pressure, state, influence, response) framework was used to construct an index system of the provincial carbon neutrality capacity of the middle and lower Yellow River Basin, which included 37 indices. Based on the entropy weight matter-element model, the time evolution, regional differences, and restriction indicators of the carbon neutrality capacity of four provinces in the middle and lower Yellow River Basin from 2008 to 2021 were analyzed. The results showed that the carbon neutrality capacity of the four provinces in the middle and lower Yellow River Basin has significantly improved over time and has gradually reached a grade of "good". Differences in carbon neutrality capacity among the provinces still exist but are gradually shrinking. the per capita car ownership, urban population density, and other factors have hindered the improvement of the carbon neutrality capacity in each province, but with the reduction in restriction indicators and increase in positive indicators such as urbanization rate, forest grass coverage, and others, the overall development direction tended to be promising.

Keywords: Yellow River Basin; carbon neutrality; DPSIR framework; entropy method; matter-element model

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1. Introduction

The Yellow River Basin is an important economic corridor in China's Belt and Road Initiative, as well as an important economic link that covers the eastern, central, and western provinces and regions and plays an important role in national economic and social development and ecological protection [1]. The middle and lower Yellow River Basin flows through the Shaanxi, Shanxi, Henan, and Shandong provinces. Its carbon neutrality capacity and social and economic development affect the economic development of the northern region as well as that of the country as a whole. There are many ecological, hydrological, and water resource-related problems in the Yellow River Basin, such as soil erosion, desertification, surface mining collapse, water shortage, and downstream flooding. There are also many economic and social development problems, such as lagging economic development, large regional gaps, and low-end industries. Therefore, the key to improving the coordinated development of regional carbon neutrality capacity and promoting relevant strategies lies in the following points. The first point is the need for a comprehensive understanding of the provincial carbon neutrality capacity in the middle and lower Yellow River basin. The second point is the need to find regional carbon neutral capacity-building barriers. The third point is to explore the path of carbon neutrality capacity optimization.

Carbon neutrality starts with reducing carbon emissions and improving carbon absorption. Research on reducing carbon emissions has mainly focused on both low-carbon transportation and low-carbon economic development. Fan, Zhou, Li, Wang, Zhou, and Su, taking Dalian city, Beijing city, Harbin city, Taiyuan city, and Shanxi Province as the research objects, applied the DPSIR framework to determine an index system for urban low-carbon transportation development, measure the level of urban low-carbon transportation, and put forward relevant suggestions for urban low-carbon and transportation development [2–7]. Dai, Li, Wang, Zhang, and Sun constructed a low-carbon economic index system in Shandong province as well as in Changsha and other cities based on the DPSIR framework. According to the relevant statistical data, the hierarchical analysis method and expert scoring method were used to quantitatively evaluate the change in low-carbon economic development, and they discussed the path of low-carbon economic development. The ecological environment and ecological security of cities and river basins are the main pathways to improving carbon absorption [8–12]. Ting Xu, Fu, and Ycab, based on the PSR model, used the Fuzzy matter element analysis and entropy weight methods to evaluate the urban ecological security of Lanzhou city and Hengyang city and the urban agglomerations of Jiangsu and Zhejiang, and discussed the impact of each index on their urban ecological security [13–16]. Li, Zhou, and Yanan established an index system for urban land ecological security from different perspectives and carried out a land ecological security analysis of the Yimeng Mountain area, Inner Mongolia Autonomous Region, and Urumqi city using the entropy weight and object methods, respectively [17–19]. Huang, Jiang, and Cao constructed an index system from the three aspects of water resources management, underground water quality, and water security. The comprehensive weight of the index was determined by coupling the hierarchical analysis (FAHP) and entropy weight methods, and the model was established using the material element theory [20–22]. Ru, Xue, and Pei evaluated the vulnerability of urban ecological environments and their carrying capacity using the entropy weight method [23–25]. Zhang, Xiong, Lu, and Sun studied the ecological environments of the middle reaches of the Yangtze River, the water resource carrying capacity of the Yellow River Basin, and the health of the lake ecological system and established an index system [26–29].

In summary, indexes based on the DPSIR framework and the data processing method based on the entropy weight method and object model have been widely used to evaluate ecological safety and low-carbon economic development. However, the research object has generally been a single area or field, and the results have not reflected regional differences. At the same time, most of the studies related to carbon emissions and absorption have remained at the low-carbon level, and discussions of carbon peak and carbon neutrality are still rare. Therefore, this study took the Shaanxi, Henan, Shanxi, and Shandong provinces in the middle and lower Yellow River Basin as the research objects, established a DPSIR carbon neutrality capacity framework, and used the entropy weight method to weight each index based on the corresponding index data for each province and city from 2008 to 2021. The matter-element model was used to evaluate the carbon neutrality capacity of each province in the middle and lower Yellow River Basin to improve its ecological environment and carbon neutrality capacity. Based on the DPSIR model, this study studied the carbon neutrality capacity level of the middle and lower reaches of the Yellow River basin from the dimensions of time and space. The entropy weight method was applied to assign weights to the index system. A matter element model was established to evaluate the carbon neutrality capacity of the middle and lower reaches of the Yellow River, and the indicators with "bad" and "poor" evaluation grades were listed as restrictive indicators.

2. Materials and Methods

2.1. DPSIR Framework for Carbon Neutrality Evaluation

The DPSIR framework was created by the European Environment Agency by integrating the strengths of the "press-state-response" and "driving-state-response" models. The DPSIR framework for carbon neutrality capacity evaluation in the middle and lower

Yellow River provinces is shown in Figure 1. Driving force represents the driving factor of carbon neutrality, which is mainly reflected in economic status, population distribution status, industrial development status, and other aspects. Stress represents the impact of social development on carbon neutrality, which is mainly reflected in three aspects: carbon emissions, ecological environment, and resource pressure. State represents the status quo of the main factors related to carbon neutrality capacity under the influence of pressure factors, which are mainly reflected in three aspects: carbon emission level, energy structure, and environmental status of the basin. Influence represents the feedback result and degree of the influence of stress factors and state factors on carbon neutrality capacity, which is mainly reflected in the two aspects of social and economic development and environmental optimization. Response represents various positive measures and countermeasures for the destruction of carbon neutrality capacity caused by economic development.

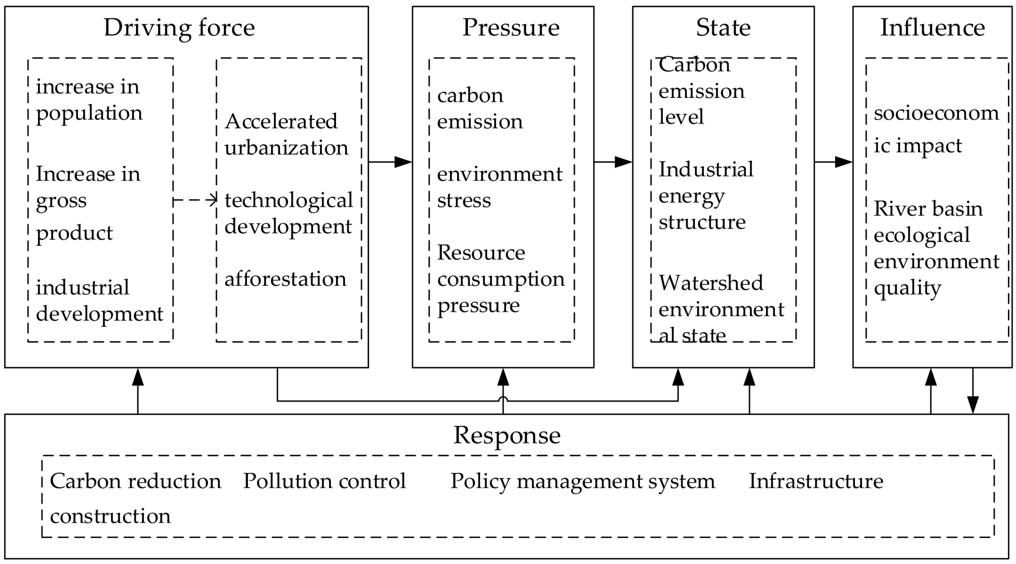

Figure 1. DPSIR framework of the provincial carbon neutrality capacity framework in the middle and lower Yellow River Basin.

2.2. Construction of a Carbon Neutrality Capacity Index System

The index system of carbon neutrality capacity is established based on the five standard levels of DPSIR framework: driving force, pressure, state, impact, and response. Population, economy, industrial structure, energy intensity, existing ecological environment, carbon emissions, and carbon absorption constraints are fully considered [3,9,11,19,24,27,30]. Based on the DPSIR model, the index system of provincial carbon neutrality capacity in the middle and lower reaches of the Yellow River was constructed with a total of 37 indicators, as shown in Table 1. Its properties represented the influence of the index on carbon neutrality capacity, with positive indicators expressed as "+" and negative indicators expressed as "–".

Table 1. Provincial carbon neutrality capacity index system in the middle and lower Yellow River Basin.

The Standard Layer	Index Layer	Variable	Description and Description	Attribute
Driving force D	Per capita GDP growth rate	d_1	Growth rate of regional economic development (%)	+
	Per capita GDP	d_2	Standard for measuring people's living standards (yuan)	+
	Natural population growth rate	d_3	Regional population growth rate (%)	–
	Urbanization rate	d_4	Degree of population aggregation in cities (%)	+
	Total resident population	d_5	Population distribution in the province (ten thousand people)	–
	Growth rate of industrial utput	d_6	Growth rate of industrial production in a certain period of time (%)	–
	Number of approved patents	d_7	Regional scientific and technological innovation capabilities (individual)	+
	Afforestation area	d_8	Regional ecological improvement capacity (ha/person)	+

Table 1. *Cont.*

The Standard Layer	Index Layer	Variable	Description and Description	Attribute
Pressure P	Urban population density	p_1	Density of the urban population (person/km^2)	−
	Per capita carbon emissions	p_2	Total carbon emissions per capita to the environment (ton/person)	−
	Energy consumption per capita	p_3	The ability to consume energy per person (ton of standard coal/person)	−
	The GDP proportion of the secondary industry	p_4	Total GDP of processing and manufacturing industry/regional GDP (%)	−
	Car ownership per capita	p_5	Degree of environmental carbon pollution caused by traffic (vehicle/person)	−
State S	Total water resources	s_1	Regional high-quality water source scale (100 million cubic meters)	+
	Per capita arable land area	s_2	Per capita farmland ownership (mu/person)	+
	Water consumption per capita	s_3	Water resources per capita (ton)	+
	Air quality compliance rate	s_4	The number of days that the air quality reaches the standard/365 (%)	+
	The proportion of renewable energy power generation	s_5	The district's commitment to renewable energy generation (%)	+
	Carbon absorption to carbon emissions ratio	s_6	Per capita farmland ownership (mu/person)	+
	Provincial health city proportion	s_7	The city that selected as the national health city/all cities in the province (%)	+
	The GDP proportion of the tertiary industry	s_8	Total GDP of services/regional GDP (%)	+
	Average flow rate of the main stream of the Yellow River	s_9	Water abundance in watershed basin (m^3/s)	+
Influence I	Area of woods	i_1	Regional forest coverage (ten thousand hectares)	+
	Green park area per capita	i_2	Urban green space per capita (square meters)	+
	Industrial waste water discharge volume	i_3	Annual total wastewater discharge (ton/year)	−
	Area of soil erosion	i_4	Soil erosion caused by environmental deterioration (thousand hectares)	−
	Total carbon dioxide emissions	i_5	Regional CO_2 production (million tons)	−
	Comprehensive water quality pollution index	i_6	Evaluation of the water quality	−
Response R	Soil erosion control area	r_1	The ability to restore the ecological environment (thousand hectares)	+
	Urban sewage centralized treatment rate	r_2	Meet emissions standards of sewage discharge/municipal sewage discharge (%)	+
	Forest grass coverage	r_3	The regional ecological improvement capacity (%)	+
	Public transport vehicles per 10,000 people	r_4	The environmental impact of carbon emissions generated by traffic (%)	+
	Comprehensive utilization rate of industrial solid waste	r_5	Ratio of comprehensive utilization of industrial solid waste to production of industrial solid waste (%)	+
	The proportion of solar power generation	r_6	Solar power generation/total power generation (%)	+
	Low-carbon economic development plan	r_7	To characterize the government's response to carbon neutrality	+
	Urban road area per capita	r_8	Characterize the congestion degree of urban traffic (m^2/human being)	+
	Hydropower station generating capacity	r_9	The utilization degree of water conservancy power generation (GW)	+

2.3. Determination of Index Weights Based on the Entropy Weight Method

The entropy weight method is an objective empowerment method that judges the entropy value of an indicator based on a comprehensive evaluation according to the information entropy value (i.e., weight), which provides a basis for the comprehensive evaluation of multiple indicators. The specific steps are as follows.

The data of each index are standardized and normalized.

First, the index data $X_{\alpha ij}$ is standardized to remove the differences in attributes, units, and orders of magnitude from the data and transform it into dimensionless data $Z_{\alpha ij}$.

$$z_{\alpha ij} = \begin{cases} \frac{x_{\alpha ij} - x_{\alpha min}}{x_{\alpha max} - x_{\alpha min}} & \text{Positive index} \\ \frac{x_{\alpha max} - x_{\alpha ij}}{x_{\alpha max} - x_{\alpha min}} & \text{Negative index} \end{cases} \tag{1}$$

In the formula, $X_{\alpha ij}$ and $Z_{\alpha ij}$ represent the value of the α index of province j before and after standardized treatment in the year i, $j \in (1, 4)$, $i \in (1, 14)$, $\alpha \in (1, 37)$.

$X_{\alpha min}$ and $X_{\alpha max}$ represent the maximum and minimum values of the α index in all years and in all provinces.

Then, the standardized data $Z_{\alpha ij}$ is mapped to the range of 0~1 for normalization processing, and the normalized data $y_{\alpha ij}$ is obtained.

$$y_{\alpha ij} = \frac{z_{\alpha ij}}{\sum_{i=1}^{14} \sum_{j=1}^{4} z_{\alpha ij}} \tag{2}$$

(1) The index information entropy E_α is calculated

$$E_\alpha = -k \sum_{i=1}^{12} \sum_{j=1}^{4} y_{\alpha ij} \ln y_{\alpha ij} \tag{3}$$

In the formula, $k = 1/\ln 56$ when $y_{\alpha ij} = 0$, $y_{\alpha ij} \ln y_{\alpha ij} = 0$.

(2) The index scale redundancy D_α is calculated

$$D_\alpha = 1 - E_\alpha \tag{4}$$

(3) The index weight W_α is determined

$$W_\alpha = \frac{D_\alpha}{\sum_{\alpha=1}^{37} D_\alpha} \tag{5}$$

2.4. Construction of the Matter-Element Model

2.4.1. Matter Element Description

Matter-element analysis describes objects in terms of "things (N), characteristics (C), and values (V)" in the form of orderly triples. The element model of provincial carbon neutrality capacity in the middle and lower Yellow River Basin is given by Formula (6).

$$R = (N,\ C,\ V) = \begin{bmatrix} N_j & C_1 & V_1 \\ & C_2 & V_2 \\ & \vdots & \vdots \\ & C_\alpha & V_\alpha \end{bmatrix} = \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_j \end{bmatrix} \tag{6}$$

In the formula, N_j represents the evaluation object of the provincial carbon neutrality capacity of the middle and lower Yellow River Basin (i.e., Shaanxi, Shanxi, Henan, and Shandong provinces; j = 4), the feature C represents the index in the carbon neutrality capacity index system (α = 37), and V represents the value corresponding to the index C of evaluation object N_j.

2.4.2. The Matter-Element Matrix of the Classical and Nodal Domains

In the matter-element model, the object element to be tested has a value. The classical domain refers to the standard value interval of the selected evaluation object and index in the level corresponding to the index. The section domain refers to the sum of all grade standard value ranges of the selected evaluation objects and indicators.

Suppose that the grade of carbon neutrality capacity index is divided into m levels, or the α index C_α. The range of values under level m is denoted as $V_{m\alpha}$. The value range is $(a_{m\alpha}, b_{m\alpha})$. Then, the classical domain element matrix R_{mj} under rank m is expressed as:

$$R_{mj} = \begin{bmatrix} N_j & C_1 & V_{m1} \\ & C_2 & V_{m1} \\ & \vdots & \vdots \\ & C_\alpha & V_{m\alpha} \end{bmatrix} = \begin{bmatrix} N_j & C_1 & (a_{m1}, b_{m1}) \\ & C_2 & (a_{m2}, b_{m2}) \\ & \vdots & \vdots \\ & C_\alpha & (a_{m\alpha}, b_{m\alpha}) \end{bmatrix} \quad (7)$$

The union of the $\boldsymbol{\alpha}$ index C_α over the range of values of all m values is denoted as $V_{p\alpha}$. The value range is $(a_{p\alpha}, b_{p\alpha})$. Then, the node domain matter-element matrix R_{pj} is expressed as:

$$R_{pj} = \begin{bmatrix} N_j & C_1 & V_{p1} \\ & C_2 & Vp1 \\ & \vdots & \vdots \\ & C_\alpha & V_{p\alpha} \end{bmatrix} = \begin{bmatrix} N_j & C_1 & (a_{p1}, b_{p1}) \\ & C_2 & (a_{p2}, b_{p2}) \\ & \vdots & \vdots \\ & C_\alpha & (a_{p\alpha}, b_{p\alpha}) \end{bmatrix} \quad (8)$$

2.4.3. Determination of the Object Element Distance to Be Measured and the Classical Object Element Distance

The modulus of the bounded interval [a.b] of the index value V is defined as $|V| = |b - a|$. The distance from the value $V_{\alpha j}$ to V corresponding to the C_α index of the N_j evaluation object is:

$$\rho(V_{\alpha j}, V) = \left| V_{\alpha j} - \frac{1}{2}(a+b) \right| - \frac{1}{2}(b-a) \quad (9)$$

The distance $\rho(V_{\alpha j}, V_{p\alpha})$ of the object element to be measured represents the distance between the value $V_{\alpha j}$ corresponding to the index C_α of the evaluation object N_j and the node domain $V_{p\alpha}$. The distance $\rho(V_{\alpha j}, V_{m\alpha})$ of the classical matter element represents the distance between the value $V_{\alpha j}$ corresponding to the index C_α of the N_j evaluation object N_j and the *m* evaluation classical domain.

2.4.4. Calculation of Correlation Function and Degree

The correlation function $K_m(v_\alpha)$ was used to determine the degree of membership of the index C_α regarding the evaluation rank m. The value corresponding to the maximum value of the correlation function is the value to which the α index C_α belongs.

$$K_m(v_\alpha) = \begin{cases} \frac{-\rho(V_{\alpha j}, V_{p\alpha})}{|V_{m\alpha}|} \ V_{\alpha j} \in V_{m\alpha} \\ \frac{\rho(V_{\alpha j}, V_{p\alpha})}{\rho(V_{\alpha j}, V_{m\alpha}) - \rho(V_{\alpha j}, V_{p\alpha})} \ V_{\alpha j} \notin V_{m\alpha} \end{cases} \quad (10)$$

In the formula, $|V_{m\alpha}|$ is the length of the grade interval.

2.4.5. Determination of the Comprehensive Correlation Degree and Evaluation Level

The comprehensive correlation degree $K_m(N_j)$ is used to determine the attribution degree of evaluation object N_j to the evaluation level, and the level corresponding to the maximum comprehensive correlation degree value $\max K_m(N_j)$ is the value of the evaluation object.

$$K_m(N_j) = \sum_{\alpha=1}^{n} W_\alpha k_m(V_\alpha) \quad (11)$$

The evaluation grade corresponding to the maximum comprehensive correlation degree is the evaluation grade of the evaluation object.

$$K_m = \max K_m(N_j) \tag{12}$$

2.4.6. Determination of the Variable Feature Values

Variable eigenvalues are used to measure which level things are more inclined to. Assuming that the level is divided into five grades (e.g., excellent, good, medium, bad, and worse), the variable eigenvalue j * is expressed as:

$$j^* = \frac{\sum_{m=1}^{5} m \cdot \bar{k}_m(N_j)}{\sum_{m=1}^{5} \bar{k}_m(N_j)} \tag{13}$$

where

$$\bar{k}_m(N_j) = \frac{k_m(N_j) - \min k_m(N_j)}{\max k_m(N_j) - \min k_m(N_j)} \tag{14}$$

2.5. Data Source

Data from 2008–2021 for the Shaanxi, Shanxi, Henan, and Shandong provinces in the middle and lower Yellow River Basin were selected as research objects. The 2008–2020 index data mainly came from the China Statistical Yearbook, China Environmental Statistical Yearbook, China Forestry and Grassland Statistical Yearbook, China Industrial Statistical Yearbook, Shandong Statistical Yearbook, Henan Statistical Yearbook, Shanxi Statistical Yearbook, Shaanxi Statistical Yearbook, and Yellow River Yearbook as well as related documents. The 2021 data were predicted using a linear prediction model.

3. Results and Discussion

3.1. Determination of Weight of the Carbon Neutrality Capacity Index

Using Formulas (1)–(5), we calculated and assigned the provincial carbon neutral index system and obtained the weight of 37 variables in 2008–2021, as shown in Table 2.

Table 2. Weight of the provincial carbon neutrality capacity index system in the middle and lower Yellow River Basin.

Standard Layer	Index Layer	Variable	Weight
Driving force D	Per capita GDP growth rate	d_1	0.0791
	Per capita GDP	d_2	0.0781
	Natural population growth rate	d_3	0.0138
	Urbanization rate	d_4	0.0159
	Total resident population	d_5	0.0182
	Growth rate of industrial output value	d_6	0.0159
	Number of approved patents	d_7	0.0052
	Afforestation area	d_8	0.0139
Pressure P	Urban population density	p_1	0.0531
	Per capita carbon emissions	p_2	0.0786
	Energy consumption per capita	p_3	0.0588
	The GDP proportion of secondary industries	p_4	0.0795
	Car ownership per capita	p_5	0.0442
State S	Total water resources	s_1	0.0064
	Per capita arable land area	s_2	0.0051
	Water consumption per capita	s_3	0.0030
	Air quality compliance rate	s_4	0.0039
	The proportion of renewable energy power generation	s_5	0.0253
	Carbon absorption to carbon emissions ratio	s_6	0.0708
	Provincial health (city proportion)	s_7	0.0035
	The GDP proportion of tertiary industries	s_8	0.0568
	Average flow rate of the main stream of the Yellow River	s_9	0.0113

Table 2. *Cont.*

Standard Layer	Index Layer	Variable	Weight
Influence I	Wooded area	i_1	0.0127
	Green park area per capita	i_2	0.0174
	Industrial waste water discharge volume	i_3	0.0051
	Area of soil erosion	i_4	0.0196
	Total carbon dioxide emissions	i_5	0.0816
	Comprehensive water quality pollution index	i_6	0.0179
Response R	Soil erosion control area	r_1	0.0025
	Urban sewage centralized treatment rate	r_2	0.0150
	Forest grass coverage	r_3	0.0094
	Public transport vehicles per 10,000 people	r_4	0.0188
	Comprehensive utilization rate of industrial solid waste	r_5	0.0091
	The proportion of solar power generation	r_6	0.0125
	Low-carbon economic development plan	r_7	0.0143
	Urban road area per capita	r_8	0.0108
	Hydropower station generating capacity	r_9	0.0131

3.2. Determination of the Classical and Node Domains of the Carbon Neutrality Index

The evaluation of the middle and lower Yellow River Basin had five grades: excellent, good, middle, bad, and worse. The variables, d_8, s_7, i_1, i_2, and r_3 were divided according to the National Demonstration County and City Index of Ecological Civilization Construction, Evaluation Standard for Urban Landscaping, and the provincial ecological environment standards. The variables d_1, d_2, d_3, d_4, d_5, d_6, p_4, and s_8 were classified according to the 14th Five-Year Plan for National Economic and Social Development and the Outline of 2035 Long-term Goals of each province. The p_2, s_6, and i_5 indices were divided into evaluation equivalence according to the Chinese Carbon Accounting Database CEADs [31]. The variables p_3, s_5, r_6, and r_9 were classified according to China's Energy Big Data Report. Other indicators referred to the index value of the year and were graded according to the data sample.

An index data sample of 31 provinces was used, and the normal distribution and number of grades were used to determine the classical and node domains, as shown in Table 3.

Table 3. Classical and node domain value ranges of carbon neutrality capacity variables.

Variable	Unit	Classical Domain					Node Domain
		Excellent	Good	Middle	Bad	Worse	
d_1	%	(17, 25)	(13, 17)	(7.5, 13)	(0, 7.5)	(–5, 0)	(0, 25)
d_2	One thousand yuan	(65, 125)	(50, 65)	(40, 50)	(22, 40)	(0, 22)	(0, 125)
d_3	‰	(–5, 1.5)	(1.5, 3.8)	(3.8, 5.8)	(5.8, 8.7)	(8.7, 14)	(–5, 14)
d_4	%	(65, 80)	(57, 65)	(50, 57)	(40, 50)	(10, 40)	(10, 80)
d_5	Ten million people	(0, 2)	(2, 4)	(4, 6.5)	(6.5, 8.5)	(8.5, 13)	(0, 13)
d_6	%	(–10, 5)	(5, 10)	(10, 12)	(12, 15)	(15, 30)	(–10, 30)
d_7	per/person	(40, 60)	(20, 40)	(10, 20)	(1, 10)	(0, 1)	(0, 60)
d_8	Ten thousand mu	(560, 750)	(340, 560)	(170, 340)	(80, 170)	(0, 80)	(0, 750)
p_1	Hundred people/km^2	(0, 14.5)	(14.5, 22)	(22, 30)	(30, 40)	(40, 64)	(0, 64)
p_2	Tons of standard coal/person	(0, 3)	(3, 6)	(6, 8)	(8, 10)	(10, 20)	(0, 20)
p_3	Ton of standard coal/ ten thousand yuan	(0, 1.6)	(1.6, 4.2)	(4.2, 6.4)	(6.4, 7.5)	(7.5, 8.6)	(0, 8.6)
p_4	%	(18, 38)	(38, 43)	(43, 48)	(48, 53)	(53, 70)	(18, 70)
p_5	A car	(0, 0.08)	(0.08, 0.1)	(0.1, 0.12)	(0.12, 0.15)	(0.15, 0.36)	(0, 0.36)
s_1	Ten billion cubic meters	(14, 38)	(7, 14)	(3, 700)	(0.5, 3)	(0, 0.5)	(0, 38)
s_2	mu/person	(2.6, 5.6)	(1.6, 2.6)	(1, 1.6)	(0.16, 1)	(0, 0.16)	(0, 5.6)
s_3	ton	(0, 50)	(50, 60)	(60, 70)	(70, 90)	(90, 150)	(0, 150)
s_4	%	(90, 100)	(70, 90)	(50, 70)	(20, 50)	(0, 20)	(0, 100)
s_5	%	(18, 20)	(14, 18)	(6, 14)	(4, 6)	(0, 4)	(0, 20)
s_6	%	(1.2, 1.5)	(0.8, 1.2)	(0.45, 0.8)	(0.15, 0.45)	(0, 0.15)	(0, 1.5)
s_7	%	(40, 50)	(30, 40)	(20, 30)	(10, 20)	(0, 10)	(0, 50)

Table 3. *Cont.*

Variable	Unit	Classical Domain					Node Domain
		Excellent	Good	Middle	Bad	Worse	
s_8	%	(50, 75)	(45, 50)	(40, 45)	(35, 40)	(15, 35)	(15, 75)
s_9	One hundred million cubic meters	(330, 480)	(270, 330)	(250, 270)	(150, 250)	(0, 150)	(0, 480)
i_1	One million hectares	(10, 25)	(7.5, 10)	(4.5, 7.5)	(1, 4.5)	(0, 1)	(0, 25)
i_2	square meter	(16, 20)	(14, 16)	(12, 14)	(8, 12)	(0, 8)	(0, 20)
i_3	One hundred million tons/year	(0, 3.6)	(3.6, 3.8)	(3.8, 6)	(6, 10)	(10, 20)	(0, 20)
i_4	One million hectares	(0, 1.8)	(1.8, 3.5)	(3.5, 5.5)	(5.5, 9)	(9, 13)	(0, 13)
i_5	Ten thousand tons	(0, 150)	(150, 300)	(300, 400)	(400, 600)	(600, 900)	(0, 900)
i_6	/	(0, 1)	(1, 2)	(2, 3)	(3, 4)	(4, 5)	(0, 5)
r_1	One million hectares	(9, 13)	(5.4, 9)	(3.6, 5.4)	(2, 3.6)	(0, 2)	(0, 13)
r_2	%	(90, 100)	(80, 90)	(70, 80)	(50, 70)	(30, 50)	(30, 100)
r_3	Ten thousand mu	(8, 12)	(6.5, 8)	(5.5, 6.5)	(4.5, 5.5)	(0, 4.5)	(0, 12)
r_4	A car	(13, 20)	(11, 13)	(9.5, 11)	(8, 9.5)	(0, 8)	(0, 20)
r_5	%	(0.8, 1)	(0.7, 0.8)	(0.5, 0.7)	(0.3, 0.5)	(0, 0.3)	(0, 1)
r_6	%	(18, 20)	(15, 18)	(13, 15)	(10, 13)	(0, 10)	(0, 20)
r_7	Individual	(60, 90)	(35, 60)	(20, 35)	(15, 20)	(0, 15)	(0, 90)
r_8	Square meters/person	(16, 28)	(14, 16)	(12, 14)	(10, 12)	(0, 10)	(0, 28)
r_9	TWh	(650, 1000)	(350, 650)	(150, 350)	(25, 150)	(0, 25)	(0, 1000)

3.3. Analysis of Grades and Characteristic Values of Carbon Neutrality Capacity

Using the matter-element calculation process described in Sections 2.2–2.4, the grades and variable eigenvalues of carbon neutrality capacity in the middle and lower Yellow River Basin from 2008 to 2021 were calculated, as shown in Table 4.

Table 4. Grades and characteristic values of carbon neutrality capacity in the middle and lower Yellow River Basin from 2008 to 2021.

Year	Shaanxi			Henan			Shanxi			Shandong		
	Grade	MCCD	Eigenvalue j *	Grade	MCCD	Eigenvalue j *	Grade	MCCD	Eigenvalue j *	Grade	MCCD	Eigenvalue j *
2008	worse	0.080	3.747	worse	0.107	3.799	worse	0.085	4.008	worse	0.080	4.238
2009	bad	0.084	3.569	worse	0.097	3.865	worse	0.060	3.993	worse	0.076	3.784
2010	bad	0.103	3.422	bad	0.090	3.756	bad	0.093	4.156	worse	0.066	3.674
2011	bad	0.085	3.334	bad	0.112	3.944	bad	0.129	4.141	worse	0.072	3.632
2012	middle	0.089	3.485	bad	0.126	3.843	bad	0.126	3.953	bad	0.087	3.820
2013	middle	0.121	3.564	bad	0.133	3.683	bad	0.135	3.878	middle	0.074	3.404
2014	middle	0.118	3.615	bad	0.103	3.693	bad	0.128	3.302	good	0.069	3.215
2015	middle	0.090	3.465	bad	0.127	3.661	bad	0.103	3.138	middle	0.071	3.315
2016	good	0.105	3.280	middle	0.121	3.146	middle	0.080	3.059	middle	0.076	2.646
2017	good	0.113	2.856	middle	0.113	3.041	bad	0.086	3.384	middle	0.080	2.547
2018	middle	0.087	2.665	good	0.092	3.275	middle	0.082	3.234	good	0.067	2.423
2019	good	0.092	2.373	good	0.122	3.063	middle	0.091	3.125	good	0.121	2.460
2020	good	0.110	2.425	good	0.085	3.001	good	0.060	3.370	good	0.083	2.448
2021	good	0.078	2.399	good	0.126	2.885	good	0.086	3.152	good	0.080	2.360

* MCCD is the abbreviation of maximum comprehensive correlation degree.

It can be seen that from 2008 to 2021, the grades of the four provinces fluctuated along a trend from worse to bad to medium to good. The eigenvalues generally showed a decreasing trend, which indicated that the carbon neutrality capacity of the four provinces has generally improved. The value of the highest comprehensive correlation degree constantly fluctuated, which in turn created fluctuations in the grades of the four provinces in their transformation processes.

3.4. Analysis of Provincial Carbon Neutrality Capacity-Limiting Indicators

The matter-element model was used to calculate the correlation function of each index, and the indices with grades of "worse" and "bad" were identified as the main limiting factors of carbon neutrality capacity, as shown in Table 5. It can be seen that the main limiting indicators of carbon neutrality capacity in all provinces in the middle and lower Yellow River Basin were significantly reduced, and their carbon neutrality capacity has improved. The total permanent resident population (d_5), urban population density (p_1), per capita carbon emissions (p_2), per capita automobile ownership (p_5), carbon absorption to carbon emissions ratio (s_6), and power generation capacity of hydropower stations (r_9) were the common factors hindering the improvement of carbon neutrality capacity. While promoting economic development, we should continuously adjust the industrial structure, promote scientific and technological innovation, advocate for green transportation, and further improve the carbon neutrality capacity.

Table 5. Main limiting indices of provincial carbon neutrality capacity of the middle and lower Yellow River Basin.

Year	Shaanxi	Henan	Shanxi	Shandong
2008	$d_2, d_4, d_7, p_1, p_4, s_4, s_6, s_7, s_8, s_9, i_2, i_4, r_2, r_3, r_5, r_7, r_9$	$d_2, d_4, d_5, d_6, d_7, p_1, p_4, s_2, s_4, s_5, s_6, s_7, s_8, s_9, i_1, i_2, i_3, i_5, i_6, r_4, r_7, r_8, r_9$	$d_2, d_4, d_6, d_7, p_2, p_4, s_1, s_2, s_4, s_5, s_6, s_7, s_8, s_9, i_1, i_2, i_4, r_4, r_6, r_7, r_8, r_9$	$d_2, d_4, d_5, d_6, d_7, p_4, s_2, s_4, s_5, s_6, s_8, s_9, i_1, i_3, i_5, r_7, r_9$
2009	$d_2, d_4, d_6, d_7, p_1, p_4, s_4, s_6, s_7, s_8, s_9, i_2, i_4, r_2, r_3, r_5, r_7, r_9$	$d_2, d_4, d_5, d_7, p_1, p_4, s_2, s_3, s_4, s_5, s_6, s_7, s_8, s_9, i_1, i_2, i_3, i_5, i_6, r_4, r_8, r_9$	$d_2, d_4, d_6, d_7, p_2, p_4, s_1, s_2, s_4, s_5, s_6, s_7, s_8, s_9, i_1, i_2, i_4, r_4, r_6, r_7, r_8, r_9$	$d_2, d_4, d_5, d_6, d_7, p_4, s_2, s_4, s_5, s_6, s_8, s_9, i_1, i_3, i_5, r_7, r_9$
2010	$d_2, d_4, d_6, d_7, p_1, p_4, s_4, s_6, s_7, s_8, s_9, i_2, i_4, r_3, r_5, r_9$	$d_2, d_4, d_5, d_7, p_1, p_4, s_2, s_3, s_4, s_5, s_6, s_7, s_8, i_1, i_2, i_3, i_5, i_6, r_4, r_8, r_9$	$d_2, d_4, d_6, d_7, p_2, p_4, s_1, s_2, s_4, s_5, s_6, s_7, s_8, s_9, i_1, i_2, i_4, r_4, r_6, r_8, r_9$	$d_5, d_6, p_4, s_2, s_4, s_5, s_6, s_8, s_9, i_1, i_3, i_5, r_7, r_9$
2011	$d_2, d_4, d_6, d_7, p_1, p_4, s_2, s_4, s_6, s_7, s_8, i_2, i_4, r_3, r_9$	$d_2, d_4, d_5, d_7, p_1, p_4, s_2, s_3, s_4, s_5, s_6, s_7, s_8, i_1, i_2, i_3, i_5, r_4, r_8, r_9$	$d_2, d_4, d_6, d_7, p_2, p_4, s_1, s_2, s_4, s_5, s_6, s_7, s_8, i_1, i_2, i_4, r_4, r_6, r_8, r_9$	$d_5, p_2, p_4, s_2, s_4, s_5, s_6, s_9, i_1, i_3, i_5, r_7, r_9$
2012	$d_2, d_6, d_7, p_1, p_4, s_2, s_4, s_6, s_8, i_2, i_4, r_3, r_9$	$d_2, d_4, d_5, d_7, p_1, p_4, s_2, s_3, s_4, s_5, s_6, s_8, i_1, i_2, i_3, i_5, r_4, r_8, r_9$	$d_2, d_6, d_7, p_2, p_4, s_1, s_2, s_4, s_5, s_6, s_7, s_8, i_1, i_2, i_4, r_6, r_8, r_9$	$d_5, p_2, p_4, s_2, s_4, s_5, s_6, i_1, i_3, i_5, r_9$
2013	$d_6, d_7, p_1, p_4, s_2, s_4, s_6, s_8, i_2, i_4, r_3, r_9$	$d_2, d_4, d_5, d_7, p_1, p_4, s_2, s_3, s_4, s_5, s_6, s_8, i_1, i_2, i_3, i_5, r_8, r_9$	$d_2, p_2, p_4, s_1, s_2, s_4, s_5, s_6, s_7, i_1, i_2, i_4, r_6, r_8, r_9$	$d_5, p_4, s_2, s_4, s_5, s_6, i_1, i_3, i_5, r_9$
2014	$d_7, p_1, p_4, s_2, s_6, s_8, i_4, r_3, r_9$	$d_2, d_4, d_5, d_7, p_1, p_4, s_2, s_3, s_4, s_5, s_6, s_8, i_1, i_2, i_3, i_5, r_9$	$d_2, p_2, s_1, s_2, s_4, s_5, s_6, i_1, i_2, i_4, r_6, r_9$	$d_5, p_2, p_4, s_2, s_4, s_5, s_6, i_1, i_3, i_5, r_9$
2015	$p_1, p_4, p_5, s_2, s_6, i_4, r_3, r_9$	$d_2, d_4, d_5, p_1, p_4, s_2, s_3, s_4, s_5, s_6, i_1, i_2, i_3, i_5, r_9$	$d_2, p_2, s_1, s_2, s_4, s_5, s_6, i_1, i_2, i_4, r_6, r_9$	$d_5, p_2, p_4, s_2, s_4, s_5, s_6, i_1, i_3, i_5, r_9$
2016	$p_1, p_4, p_5, s_2, s_6, i_4, r_3, r_9$	$d_4, d_5, p_1, s_2, s_3, s_4, s_5, s_6, i_1, i_2, i_3, i_5, r_9$	$d_2, p_2, p_5, s_1, s_2, s_4, s_6, i_1, i_2, i_4, r_6, r_9$	$d_5, p_2, p_4, s_2, s_4, s_5, s_6, i_1, i_3, i_5, r_9$
2017	$p_1, p_4, p_5, s_2, s_6, i_4, r_3, r_9$	$d_5, p_1, p_5, s_2, s_3, s_4, s_5, s_6, i_1, i_2, i_5, r_9$	$p_2, p_5, s_1, s_2, s_4, s_6, i_1, i_2, i_4, r_6, r_9$	$d_5, p_4, p_5, s_2, s_4, s_5, s_6, i_1, i_3, i_5, r_9$
2018	$p_1, p_4, p_5, s_2, s_6, i_4, r_3, r_9$	$d_5, p_1, p_5, s_2, s_3, s_6, i_1, i_5, r_9$	$p_2, p_5, s_1, s_2, s_4, s_6, i_1, i_4, r_6, r_9$	$d_5, p_2, p_4, p_5, s_2, s_4, s_5, s_6, i_1, i_3, i_5, r_9$
2019	$p_1, p_5, s_2, s_6, i_4, r_3, r_9$	$d_5, p_1, p_5, s_2, s_3, s_6, i_1, i_5, r_9$	$p_2, p_5, s_1, s_2, s_4, s_6, i_1, i_4, r_6, r_9$	$d_5, p_2, p_4, s_2, s_4, s_5, s_6, i_1, i_3, i_5, r_9$
2020	$p_1, p_5, s_2, s_6, i_4, r_3, r_9$	$d_5, p_1, p_5, s_2, s_6, i_1, i_5, r_9$	$p_2, s_1, s_2, s_4, s_6, i_4, i_6, r_6, r_9$	$d_5, p_2, p_5, s_2, s_4, s_5, s_6, s_9, i_1, i_3, i_5$
2021	$p_1, p_5, s_2, s_6, r_3, r_9$	$d_5, p_1, p_5, s_2, s_6, i_1, i_5, r_9$	$p_2, s_1, s_2, s_4, s_6, i_4, r_6, r_9$	$d_5, p_2, p_5, s_2, s_4, s_5, s_6, s_9, i_1, i_3, i_5$

3.5. Analysis of Regional Differences in Provincial Carbon Neutralization Capacity

The temporal and spatial difference curves of the provincial carbon neutrality capacity of the middle and lower Yellow River Basin are shown in Figure 2. It can be seen that the provincial carbon neutrality capacity has significantly improved with time, while there were persistent regional differences. According to the changing characteristics of carbon neutrality capacity over time, it could be divided into a stagnation stage (2008–2012), a rapid improvement stage (2013–2017), and an oscillating improvement stage (2018–2021). The regional differences in each stage were analyzed according to the data in Tables 4 and 5.

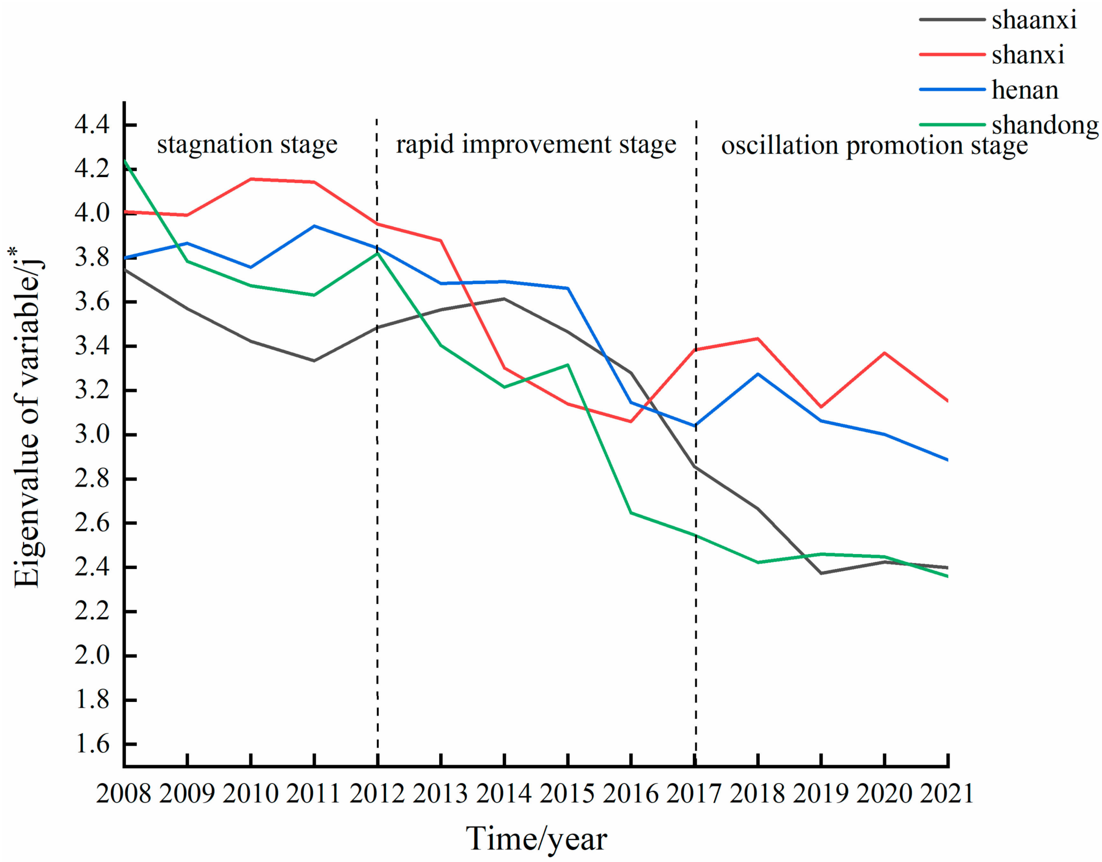

Figure 2. Regional differences in provincial carbon neutrality capacity of the middle and lower Yellow River Basin.

In the stagnation stage (2008–2012), which was characterized by the adjustment of energy consumption and changes to the industrial structure, the carbon-neutral pressure in the four provinces was at a high level, and the regions showed slight fluctuations. The variable values decreased steadily but remained high, the improvement of restrictive indicators was not obvious, and the carbon neutrality capacity treatment stagnated. Factors such as single and fragile industrial structures, urban distribution, insufficient economic development, and insufficient application of low-carbon technologies led to the persistence of restrictive indicators in this period, for example, per capita GDP (d_2), urbanization rate (d_4), GDP ratio of secondary industry (p_4), per capita cultivated land area (s_2), success rate of air quality (s_4), renewable energy capacity (s_5), carbon absorption and carbon emission (s_6), hydropower capacity (r_9), etc.

In the rapid improvement stage (2013–2017), the regional industrial structure was gradually clear, and the fluctuation was significantly reduced. The variable values decreased rapidly, and the restrictive indicators decreased significantly. Restrictive indicators such as per capita cultivated land area (s_2) and renewable energy generation ratio (s_5) were improved, and regional carbon neutrality capacity was significantly improved. However, the Yellow River basin has a dense population, a concentrated industrial structure, relatively insufficient carbon sink resources, and a weak power generation capacity. The above factors were still the main factors restricting the improvement of its carbon neutrality capacity. At this stage, due to adjustments to the energy structure of its secondary industries and an accelerated implementation of the industrial energy replacement policy, the variable values were significantly reduced, and the carbon neutrality capacity significantly improved, which was an improvement over the trends observed in the other three provinces. As an important coal-producing area, Shanxi Province's energy structure limited the speed with which carbon neutrality capacity could be improved and thus it remained relatively underdeveloped. It should therefore further adjust its industrial structure, promote the replacement of old and new energy sources, and promote the application of low-carbon technologies to industrial development.

In the oscillating stage (2018–2021), the carbon neutrality capacity of Shaanxi and Shandong provinces was further enhanced and stabilized, while Shanxi and Henan were in their bottleneck stage of development. The levels of the main restrictive indicators were not significantly reduced, and those of the new restrictive indicators, such as per capita automobile ownership (p_5), became the main restrictive indicators. Regulating the urban and rural populations, giving priority to the development of primary and tertiary industries, and maintaining the ecological environment in the middle reaches of the Yellow River Basin are the keys to continuously improving the carbon neutrality capacity of Henan Province. Optimizing environmental protection standards, adjusting the energy structure, and promoting the replacement of old enterprises are the keys to achieving the same in Shanxi Province.

3.6. Discussion

(1) The DPSIR-model based carbon neutrality capacity evaluation system for the Yellow River Basin had some limitations. The indicators and factors affecting carbon neutrality will change with the change in the spatio-temporal relationship. The index systems affecting the carbon neutrality capacity of the same region in different time periods were different, and the index systems of the carbon neutrality capacity of different regions in the same time period were also different. The 37-index system established in this study was only applicable to the carbon neutrality capacity evaluation of the Yellow River Basin from 2008 to 2021. With the change in time, the index system that affects the carbon neutrality capacity of the Yellow River Basin will also change.

(2) When determining the classical and node domain value ranges of each index, this study discussed, calculated, and developed the classical and node domain value ranges under the corresponding index system of the Yellow River Basin based on the data of 31 provinces and autonomous regions in China. In the process of determining classical and node domain value ranges, the mathematical statistical method of normal distribution was used to divide the matter-element domain, and the conclusions in Table 3 were finally determined. The above methods were used to make the classical and node domain value ranges more objective as far as possible. However, due to policy changes in different regions, force majeure, and people's response degree to environmental protection, there were certain subjective factors in the process of determining the classical and node domain value range of the matter-element model.

4. Conclusions and Policy Recommendations

4.1. Conclusions

(1) Based on the DPSIR framework, the carbon neutrality capacity framework of the middle and lower reaches of the Yellow River was constructed from the five aspects of driving force, pressure, state, impact, and response. The carbon neutrality capacity model was constructed based on the entropy weight method and the factor model [13–25]. The index data from 2008 to 2021 proved that the model had a good applicability.

(2) In 2008–2021, the provincial carbon neutrality capacity of the middle and lower Yellow River Basin went through a stagnation stage, a rapid improvement stage, and an os-

cillating stage. The value trended from worse to bad to medium to good, and its correlation with good values continuously improved until it became stable. The restrictive indicators of carbon neutrality capacity were significantly reduced. The current restrictive indicators, such as carbon absorption to carbon emissions ratio and per capita vehicle ownership, show regional consistency and universality. The adjustment should be to accelerate industrialization, promote clean energy to replace traditional fossil energy, develop new modes of public transportation [2–7], and improve the ecological environment [13–16]. Regional variation has always existed, especially as carbon neutrality capacity has increased. At present, the Shanxi and Henan provinces are in their bottleneck stage, and policies and measures should be formulated with respect to the restrictive indicators.

(3) According to the carbon neutrality capacity levels, restriction indices, time, and region differences, it is necessary to change the mode of industrial development, promote the low-carbon transformation of traditional industries, develop modern services, and accelerate the transformation of old and new driving forces in the economy of the Yellow River Basin. It is also necessary to protect its ecological environment [13–16], enhance its carbon sink capacity, and vigorously develop its green industrial chain while strengthening innovation in green science and technology, stepping up the research and development of low-carbon and environmental protection technologies, increasing new energy exploration, increasing the proportion of renewable energy consumption, and promoting the low-carbon transformation of traditional industries in the Yellow River Basin.

(4) This study analyzed the evolution process of regional carbon neutrality capacity over time and space, and deeply explored the specific influencing index factors of regional carbon neutrality capacity. Corresponding improvement methods and policy suggestions were put forward for each influencing factor. The specific evaluation grade of carbon neutrality capacity in the basin was given to provide help for the self-understanding of carbon neutrality capacity of each province. The problems faced by carbon neutrality are of great diversity and particularity. This study also identified deficiency aspects in the current carbon neutrality capacity of the studied provinces and provides directions for future policy making.

4.2. Policy Recommendations

Combined with the above analysis, the restrictive indicators that limit the carbon neutrality capacity of the provinces in the Yellow River Basin in different time periods and regions were obtained from 2008 to 2021. At the same time, the carbon neutrality level of the provinces in the basin was also evaluated. Accordingly, some policy suggestions to promote the carbon neutrality capacity of provinces in the Yellow River Basin are put forward as follows:

(1) Provinces have actively developed emerging industries, strengthened ecological and environmental protection in the Yellow River basin, formulated and implemented low-carbon development plans, and effectively eliminated obstructive indicators. The carbon neutrality status of most provinces in the Yellow River Basin is relatively severe, and the resource and environmental problems in the middle reaches are prominent. To improve the carbon neutrality capacity of the Yellow River basin, the resources and environment in the Yellow River basin need to be further rationally utilized, managed, and protected. It is necessary to establish a reasonable resource and environmental utilization mechanism, strictly control the emission of industrial pollutants, advocate for public transportation, promote the implementation of low-carbon economic development plans, and improve the comprehensive capacity of carbon neutrality in the provinces along the Yellow River Basin.

(2) The distribution of the middle and lower reaches of the Yellow River's provincial carbon neutral pressure is generally larger, strengthens the response and the implementation of policy, and increases the factors of flow across the land. Digging in the middle and lower reaches of the Yellow River and Yangtze River along the banks of the leading types of carbon neutral city gives full play to their ability to experience a carbon neutral spillover effect, which is a progressive effect, and the formation of the carbon cycle in the Yellow

River urban agglomeration will drive the improvement of the provincial carbon neutrality capacity in the form of urban agglomeration. Based on the development advantages of each region, the differences in factors hindering carbon neutrality shown by each region should be solved.

(3) While dredging economic development, the government should constantly coordinate the contradiction between environmental protection and economic development, improve the overall coordinated development level at the material level, such as industrial support and the accumulation of development factors, and formulate relevant policies according to local conditions.

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