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Adaptability analysis and spatial correlation characteristics of water-energy-food-ecology system in the Yellow River Basin from the perspective of symbiosis

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Based on the symbiosis theory, the concept of compatibility within the regional water-energy-food-ecology (WEFE) system was proposed. An indicator system for adaptability analysis was constructed from three subsystems: coordination, stability, and sustainability. Using the co-evolution model and partial autocorrelation analysis, the spatiotemporal evolutionary patterns and spatial correlation patterns of WEFE adaptability in the Yellow River Basin (YRB) from 2011 to 2022 were assessed. The results indicated that: (1) The order of subsystem weights was: stability > sustainability > coordination. (2) The absolute adaptability of the indicator was significantly higher than the relative adaptability. The adaptability degree of the three subsystems increased to varying degrees. Overall, the adaptability of the WEFE system in the middle and lower reaches of the YRB was obviously higher than in the upper reaches. (3) In terms of system coordination, the coordination and stability subsystems improved, whereas the coordination of the sustainability subsystem gradually declined. (4) The adaptability levels of the WEFE system in the YRB had a random distribution. In terms of local spatial autocorrelation, there were significant spatial disparities and path dependencies in the WEFE system adaptability across the YRB. This study enhances the understanding of the symbiotic adaptability development among water resources, food, energy and ecology in the YRB and provides important insights for regional multi-resource collaborative management.

Keywords Water-energy-food-ecology system, Adaptability analysis, Spatial autocorrelation analysis, Yellow river basin

Water, food, and energy are the core elements for human survival, and there are complex supply- demand cycles and a symbiotic relationship among these three elements[1–3]. However, due to urban population growth, dietary shifts, and climate change, water, energy, and food are increasingly in short supply, and the interconnections among these three elements are becoming increasingly fragile[4,5]. With the growing demands for human survival and production, competition for resources among the water, energy, and food sectors is becoming more intense. A series of challenges, including water quality deterioration, energy shortages, and ecological function degradation, are posing significant threats to water, energy, and food security[6]. The Bonn Conference in 2011 formally conceptualized the relationship between water, energy, and food as the WEF Nexus, a term that describes the complex and interconnected nature of these three subsystems[7,8]. Subsequently, a substantial body of research has emerged, which has not only explored the internal correlations within the WEF nexus system[9], but also analyzed its interactions between the linkage system and outside conditions[10].

Since 2014, the extensibility of the WEF Nexus has been explored. Consequently, the impacts of external factors—such as ecology, the environment, the economy, and society—on the system have become a new focus for both governments and scholars. Ecology, serving as both the source and carrier for these three resources, is often positioned at the center of the WEF Nexus[11]. First, ecosystems (e.g., wetlands, forests, and rivers) provide clean water and help regenerate and facilitate water regeneration and recycling through natural processes. Second, ecosystems provide renewable energy in the form of biomass (e.g., wood and crop residues)

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and positively impact energy use through climate regulation and carbon storage. Finally, healthy ecosystems support soil fertility and crop growth, thereby ensuring sustainable agricultural production. In this relationship, ecosystems not only provide the foundation for these resources but also ensure their long-term sustainability. Conversely, processes within the WEF system—such as water supply and treatment, energy production, and food production—generate carbon emissions that adversely affect the environment[12]. As the interrelationship between WEF and the environment deepens, these four elements—water, energy, food, and ecology (WEFE)—have become integrated into a complex and co-evolving system (Fig. 1).

The WEFE system is a complex structure primarily comprised of water resources, energy, food, and the ecology. The interactions and feedback among these four elements influence natural, social, and economic factors, thereby shaping the overall socio-economic-natural composite system. This system functions as a unified and organic whole, wherein its elements both compete and cooperate. The goal of WEFE system development is to achieve symbiotic coexistence among its various elements, thereby forming a more orderly system structure and enhancing its adaptability to changes in both internal and external conditions[13]. In recent years, an increasing number of studies have adopted symbiosis theory to examine the WEFE nexus[14]. The concept of symbiosis originates from biology and describes different organisms living together in a long-term, mutually dependent relationship that achieves a dynamic equilibrium[15]. As a fundamental ecological principle, symbiosis theory describes interdependent relationships between organisms. Given its explanatory power for complex ecosystems, this theory has been extended to socio-economic studies, where it is regarded as a foundation for multi-agent collaborative development[16].

In the socio-economic-natural complex system, there exists an interdependent and symbiotic relationship among WEFE system. Specifically, within the symbiotic environment of the socio-economic-natural system, the WEFE system constitutes heterogeneous symbiotic units that serve as the fundamental units for energy production and exchange. The quantity, quality, and structure of their internal resources are critical conditions for maintaining equilibrium within the symbiotic system[2,17]. The interdependent transformation between water-energy, water-food, water-ecology, energy-food, energy-ecology and food-ecology represent symbiotic relationships. These relationships are characterized by multiple couplings of competitive and cooperative processes (Fig. 1). This is an important attribute of the equilibrium in symbiotic systems. According to symbiosis theory, the WEFE system generates symbiotic energy, which drives it toward a state of symmetric reciprocity[1]. In other words, within the environmental capacity of a certain region, resource flow and transformation

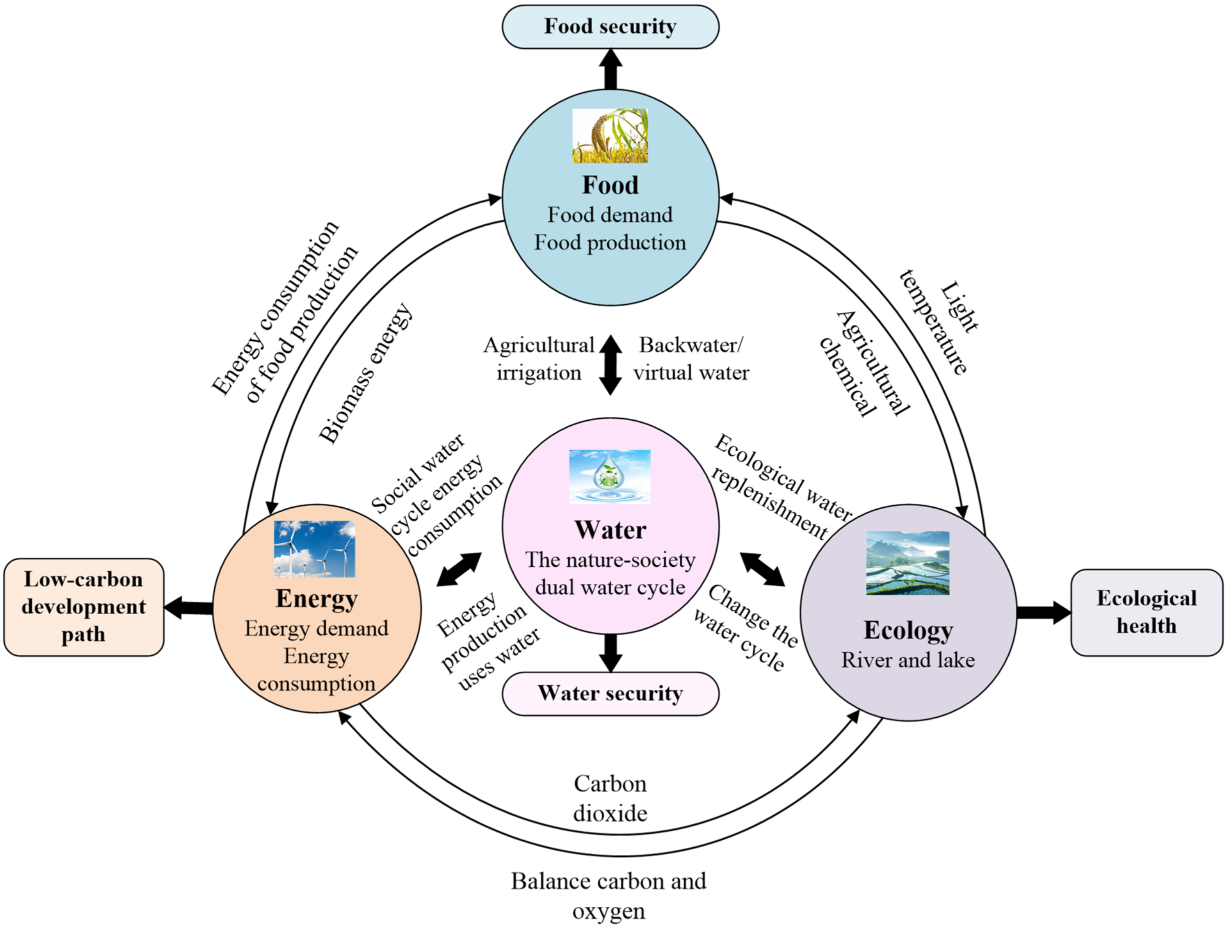


Fig. 1. WEFE system relationship.

efficiency can be improved by optimizing resource allocation within and between water resources, energy, and food systems. The goal of WEFE system symbiosis is to generate superior synergistic benefits across economic, social, and environmental dimensions. This is achieved by enhancing the system's adaptability to the external environment and promoting regional sustainable development.

With the interdependence and symbiosis of water, energy, food, and ecology, the traditional single-resource management mode is not able to effectively address the contradiction between resource supply and demand, which can easily lead to unbalanced resource development[17]. From a symbiosis perspective, there is a synergistic relationship between water, energy, food, and ecosystems, with resources being used and transformed among the subsystems. This synergy helps reduce the constraining effect of resource endowments on social development by optimizing resource allocation within the system and improving the efficiency of resource conversion. Improving the adaptability and matching relationship between the WEFE system and socio-economic-natural systems is an important part of multi-resource integrated management. In the WEFE system, the essence of system adaptability is to achieve optimal resource use and environmental protection through the interaction between water, energy, food, and ecology. In this process, the WEFE system should not only coordinate internal and external supply and demand, but also achieve local and global equilibrium. Ultimately, this would cyclically feed back into nature, society, and the economy by continuously enhancing the adaptability of the WEFE system, thereby supporting regional sustainable development.

Within the symbiotic environment of the socio-economic-natural system, urban development, economic growth, social progress, industrial structure adjustments, and other factors have led to an increased demand for water resources, energy, and food, exerting significant pressure on the ecosystem[18]. The WEFE system is tightly intertwined with natural resources, the economy, and society. The water, energy, food, and ecology (WEFE) subsystems continuously exchange matter, energy, and information with the surrounding environment, ensuring that development is coordinated and achieving stable and sustainable development for the socio-economic-natural system[19]. This process is referred to as absolute adaptation. On the other hand, in a high-pressure environment, the four subsystems of water, energy, food, and ecology face severe challenges and pressures from the socio-economic-natural system. To meet these challenges, these subsystems continue to integrate, communicate, and adapt to each other by adjusting their structures so that each subsystem is compatible with the others. This process is called relative adaptation[17]. The symbiosis of the WEFE system not only depends on subsystem adjustments but also on the interactions with the surrounding subsystems, forming a complex virtuous cycle that adapts to environmental changes. Under the influence of the socio-economic-natural system, water, energy, food, and ecology together form a highly interactive and interdependent symbiotic system. This system achieves overall positive development through interactions between the natural environment, social demands, and economic activities.

As crucial factors closely related to human survival and development, water, energy, food, and ecology are progressively displaying new characteristics of interdependence, interactive adaptation, and mutual constraints within the socio-economic-natural complex system. Analyzing the adaptation and matching relationships between water, energy, food, and ecology, as well as optimizing resource allocation within the system, are important aspects of multi-resource integrated management. Therefore, it is important to conduct adaptation research on the regional WEFE system. The main contributions of this study are as follows: (1) This research introduces symbiosis theory for analyzing WEFE system adaptability and constructs a symbiotic framework for holistic regional WEFE adaptability analysis. This framework helps expand the WEFE system research paradigm. (2) This study establishes an adaptability analysis indicator system for the WEFE system that encompasses stability, coordination, and sustainability systems. Additionally, a comprehensive adaptability evaluation model for the WEFE system is developed that considers both absolute and relative adaptabilities. (3) This research combines an exploratory spatial data analysis model with a spatial autocorrelation analysis model to explore spatial distribution characteristics and spatial correlation patterns of regional WEFE adaptability levels in a large research area.

Literature review

Since the Bonn Conference in 2011, many related research results have emerged[20]. From the perspective of research progress on the spatial relationships between WEF resources, scholars have not only explored the internal relationships within the WEF Nexus[21–23], but also analyzed their interactions with external systems[24,25]. In terms of research content, studies have mainly focused on the connotation and association mechanisms of the WEF Nexus[26–28], the theoretical framework[29], and the regional status quo[30,31]. Regarding research methods, studies have mainly used models such as the coupling coordination degree model[32], the spatial autocorrelation index[33], the input-output model[34], and the empirical research method[35]. As research has deepened, the content and scope of WEF Nexus studies have gradually diversified and the research perspective has continued to expand. Scholars have incorporated external factors such as land[36], carbon[37], and the environment[38] into the WEF Nexus framework.

Recently, scholars have used the nexus model to integrate concepts like ecosystem services, environmental governance, sustainable development, and climate change. As an important carrier for the interactions between water, energy, and food resources, ecosystems have interdependencies and mutual influences among the three components of the WEF Nexus[39]. The matching and coupling between ecosystems and WEF Nexus are crucial for regional development and stability. The matching and coupling relationship between ecosystems and WEF has attracted extensive attention[40]. Existing research has primarily explored ecosystem function based on the WEF Nexus. Scholars have used the WEF Nexus to consider the impacts of carbon emissions on the environment and discussed the relationship between WEF and ecosystem. Furthermore, the research perspective has been extended to the coupling synergistic effects of WEFE and the exploration of influencing factors[41,42].

Considering the coupling relationship of WEFE, the adaptability of the system to external factors such as climate change, economic development, and human disturbance has been a subject of widespread concern. From the perspective of sustainable development, Qin et al.[3] comprehensively evaluated the pressure and adaptability of the WEFE system based on the projection pursuit model, revealing the transmission pathways of pressure. Ling et al.[43] established a dynamic simulation model for the WEFE system using system dynamics and discussed the dynamic changes in resource demand and supply, as well as the adaptation of the ecosystem to resource transfer. By developing an integrated WEFE and economy-society-environment coupled system, Liu et al.[44] simulated the water, energy, and food supply-demand dynamics along with ecological changes in the Yangtze River Economic Belt during 2020–2030, while investigating the causal feedback and adaptability mechanisms between the WEFE nexus and the socio-economic-environmental system.

Given the factors that influence the WEFE system, scholars pay more attention to factors such as climate change[45], ecological service functions[46], resource endowments[47], and human activities[48]. Climate change, one of the factors most closely related to human production and life, can directly affect water resource conditions, energy consumption, and food security by regulating resource supply and changes in human demand. It also influences ecological carrying capacity and environmental self-purification capabilities[32]. Ecological functions influence regional runoff and precipitation, altering the seasonality of flow, which in turn affects water resource availability, crop growth conditions, and biomass supply[18]. Human activities also impact water resource extraction and utilization, energy transformation and applications, food production and processing, as well as ecological interventions[49]. All these factors would affect the adaptability level of the WEFE system.

The applicable research outcomes offer guidance for progressing the WEFE system. However, the interplay of internal and external environmental changes has significantly affected the eco-friendly development of the region. There is an urgent need to strengthen the adaptability of the regional WEFE system to meet new challenges. Yet, despite the significant research interest in analyzing the adaptability of multiple systems[16,17], several research gaps persist in this field. Firstly, the current adaptability analysis model of the WEFE system mainly discusses the relationship between the system and the external socio-economic-natural system. The symbiotic interactions between the WEFE system and the surrounding environment are overlooked. Secondly, existing studies analyze the influence of a single factor on the adaptability of the WEFE system, without integrating key systemic drivers such as human activities, climate change, and resource conditions. Finally, existing literature evaluates the WEFE system coupling by treating adaptability as a component within the evaluation framework. However, it fails to clearly illustrate the aggregation of positive benefits and the exacerbation of negative impacts among multiple subsystems from an overall adaptability perspective. Further study of spatial correlations of the adaptability level of the regional WEFE system is needed.

Study area and methodology

Study area

The YRB is an ecological geographic area influenced by the Yellow River system, covering an area of 745,100 square kilometers. Located in northern and central China, the YRB spans nine provinces. From east to west, these provinces are Shandong, Henan, Shanxi, Shaanxi, Inner Mongolia, Ningxia, Gansu, Sichuan, and Qinghai (Fig. 2). Approximately 46% of the basin is situated in arid and semi-arid regions, with per capita water resources amounting to less than one-fourth of the national average. The YRB is home to seven coal mine bases—five in the middle and upper reaches and two in the lower reaches, accounting for more than 70% of the country's coal production. The lower reaches of the YRB account for nearly 60% of the basin's grain production yet possess only 26% of its water resources. Disorderly and extensive resource development and utilization have had a significant impact on the environment of the YRB. The middle and upper reaches of the YRB feature a delicate ecology, experience high water consumption, and face heavy pollution through energy development, with desertification affecting more than one-fourth of the entire basin.

Indicator system

Indicator system establishment

According to symbiosis theory, the adaptability of the WEFE system can be divided into three aspects: stability, sustainability, and coordination. Of these, stability, based on the interactive characteristics of the WEFE system, emphasizes the system's ability to remain relatively stable in structure when faced with external disturbances or internal changes. At the same time, the system possesses self-repair and recovery capabilities to ensure its robust operation. Sustainability, from a holistic perspective, stresses the effective utilization of resources and environmental safeguarding, as well as the maintenance of ecological services. It focuses on the dynamic integration and synergistic development of the WEFE system with external economic, social, and natural environments. By promoting the recycling and mutual support of WEFE, the long-term stability and resilience of the entire system are maintained. Coordination starts from the independent characteristics of the system, emphasizing that water, energy, food, and ecology should be independently developed while forming complementary and synergistic relationships. This aims to maximize overall benefits and promote harmonious coexistence among the various systems. A series of interaction and adjustment mechanisms, such as the stability and coordination of the WEFE system, are shown in Fig. 3 in the process of adapting to complex environmental changes.

In terms of coordination, water, energy, food, and ecology were selected as factors, and 12 indicators such as the amount of water resources, per capita domestic water consumption, and the utilization rate of groundwater resources were selected to represent water resource status, energy consumption, food production, and environmental change[32]. In the stability dimension, the water-energy, water-food, water-ecology, energy-food, energy-ecology, and food-ecology layers were considered as essential factors. Twelve indicators were selected to represent the dependencies and interrelationships among the four elements of WEFE, including the

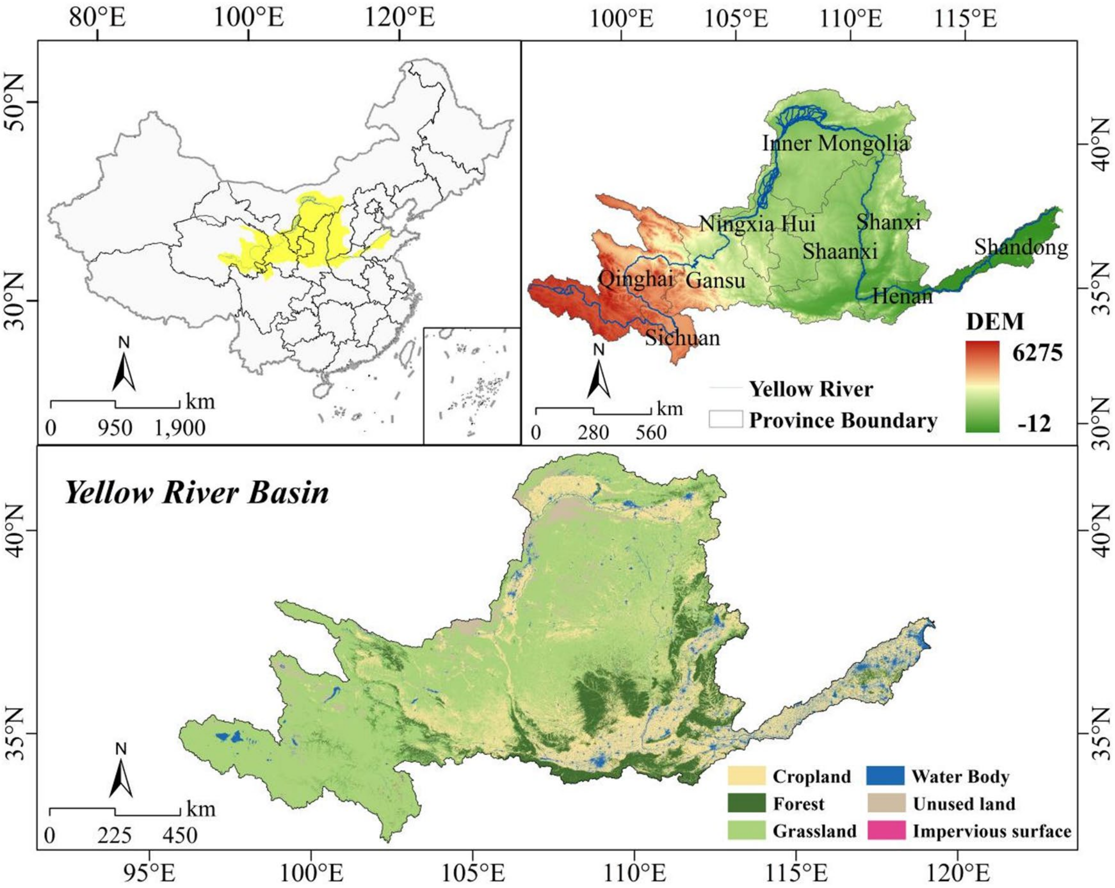


Fig. 2. Study area (created in ArcGIS 10.8; https://desktop.arcgis.com).

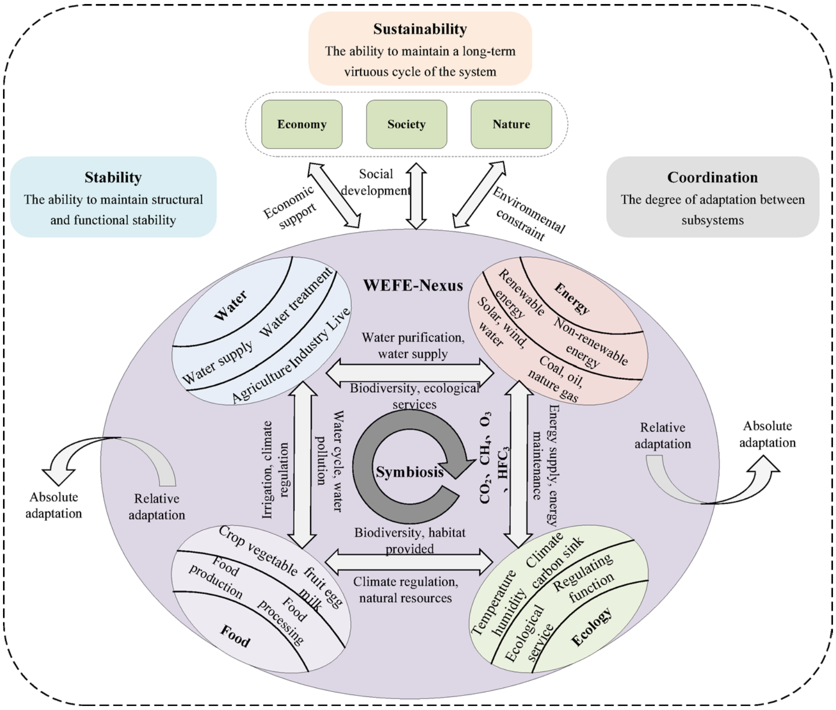


Fig. 3. Symbiotic relationship of WEFE system.

proportion of water used in the energy system, the proportion of energy used in the water resources system, and the proportion of water used for agricultural irrigation[17]. In the sustainability dimension, economic, social, and natural systems were the factors, and nine indicators were picked to represent the economic growth degree, human social activities, and the state of natural ecology, including per capita GDP, energy consumption per unit of GDP, and water consumption per unit of GDP. Finally, a total of 33 indicators were determined to evaluate the WEFE system adaptability, as shown in Table 1.

Datasets

In this study, data from various sources were used to diagnose the adaptability of WEFE systems in nine regions of the YRB. Data on the natural environment were sourced from the *China Eco-environment Bulletin*[50] and the *China Water Resources Bulletin*[51]. Data on food and energy were obtained from the *China Urban Statistical Yearbook*[52] and the *China Energy Statistical Yearbook*[53]. The energy carbon emission coefficient was derived from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* and *China Carbon Emission Accounting Database* (https://www.ceads.net.cn/data/). Data on economic and social development were taken from the *China Statistics Yearbook*[54]. The specific data sources for each indicator are detailed in Table S1. It is worth noting that the values of a small number of missing data were obtained through linear function interpolation[55].

Subsystem	Factor	Indicator	Unit	Character	Indicator connotation
Coordination	Water	C_1 Amount of water resources	10^8m^3	+	Water resources system supply ability
		C_2 Per capita domestic water consumption	liter	+	Carrying capacity of water resources system
		C_3 Utilization rate of groundwater resources	%	+	Safety of groundwater resource system
	Energy	C_4 The proportion of secondary and tertiary industries in GDP	%	+	Industrial structure state
		C_5 Industrial waste gas emission	t	–	Impact of energy consumption on air
		C_6 Total Primary Energy production	10^4t of SCE	–	Energy production status
	Food	C_7 Per capita food production	t/people	+	Carrying capacity of the food system
		C_8 Per capita arable land area	hm^2/people	+	Cultivated land resources for food production
		C_9Grain yield per unit area	kilogram/hectare	+	Food supply capacity of the food system
	Ecology	C_{10} Total amount of sewage treated	10^4m^3	+	Water ecological protection level
		C_{11} Harmless treatment rate of consumption wastes	%	+	Regional environmental protection level
		C_{12} Industrial smoke and dust removal	10^4t	+	Atmospheric environmental protection level
Stability	Water-Energy	S_1 Industrial water consumption ratio	%	–	Interdependence between energy and water resources
		S_2 Elasticity ratio of energy consumption	/	+	Interdependence between energy and water resources
	Water-Food	S_3 Proportion of water used for agricultural irrigation	%	–	Dependence of food on water resources
		S_4 Water consumption per unit of grain production	10^8m^3	–	Water support for food production
	Water-Ecology	S_5 Ecological water replenishment	10^8 m^3	+	Human coordination of water-ecology relationship
		S_6 Area of wetlands	10^4h	+	Water support for ecosystems
	Energy-Food	S_7 Total power of agricultural machinery	Kwh	–	Dependence of food production on energy
		S_8 Energy consumption in agricultural products processing	10^4t of SCE	–	Dependence of grain processing on energy
	Energy-Ecology	S_9 Carbon emissions from oil production	t	–	Impact of petroleum energy on ecology
		S_{10} Carbon emissions from natural gas production	t	–	Impact of natural gas energy on ecology
	Food-Ecology	S_{11} Consumption of chemical pesticides	10^4t	–	Impact of grain cultivation on ecology
		S_{12} The amount of fertilizer applied	10^4t	–	Impact of grain cultivation on ecology
Sustainability	Economy	D_1 Per capita GDP	10^4 Yuan	+	Economic development degree
		D_2 Energy consumption per unit of GDP	t/10^4Yuan	+	Pressure of economic development on energy
		D_3 Water consumption per unit of GDP	m^3/10^4Yuan	+	Pressure of economic development on water
	Society	D_4 Urbanization rate	%	+	Social development degree
		D_5 Population density	person/km^2	+	Dynamic population pressure
		D_6 Urban land area	km^2	+	Urban carrying capacity
	Nature	D_7 Average rainfall	mm	+	Climate change impact
		D_8 Forest coverage rate	%	+	Basic state of natural system
		D_9 Proportion of days with good air quality	%	+	Air quality status

Table 1. WEFE system adaptability evaluation indicator system.

Construction of the adaptability evaluation model

Indicator data standardization

To eliminate the dimensional and attribute differences among the various indicators, it is necessary to carry out standardization processing on the indicator data prior to analysis[56]. The data standardization model is used to standardize the original indicators and eliminate the influence of different dimensions[21]. All indicator data were normalized to a standardized [0, 1] scale using min-max transformation. The normalized matrix$X = (x_{ij})_{n*m}$ was formed.

(1) Standardization formula of forward indicators:

$$x_{ij}{=}(y_{ij} - \min\{y_i\}/(\max\{y_i\} - \min\{y_i\}) \tag{1}$$

(2) Standardization formula of inverse indicators:

$$x_{ij}{=}(\max\{y_i\} - y_{ij})/(\max\{y_i\} - \min\{y_i\}) \tag{2}$$

where y_{ij} is the original indicator value; and x_{ij} is the normalized value of y_{ij}, $y_{ij}\in$ [0, 1]. i and j represent evaluation objects and evaluation indicators, respectively.

Kantiray weighting method

Analyzing the adaptability of the WEFE system is an objective evaluation, which is not biased towards any category of indicators. An objective weighting method better reflects the objectivity of indicator weights. The Kantiray weighting method is an objective weighting method proposed by Kantiray, which uses the product of a correlation coefficient matrix and the standard deviation matrix for weighting[57]. The weight determination method combines both information content weighting and correlation weighting, which overcomes the disadvantages of ignoring data correlation in the entropy weight and deviation maximization methods, while also addressing the shortcomings of neglecting data information content in the factor analysis method. The Kantiray weighting method can fully reflect the dependency relationship among the four subsystems of WEFE and is suitable for determining the indicator weights of small sample data. The weight calculation process is as follows:

Step 1. Determine the correlation coefficient matrix R for indicators j and k.

$$r_{jk}{=}\frac{\sum\limits_{i=1}^{m}(x_{ij} - \bar{x}_j)(x_{ik} - \bar{x}_k)}{\sqrt{\sum\limits_{i=1}^{m}(x_{ij}-\bar{x}_j)^2}\sqrt{\sum\limits_{i=1}^{m}(x_{ik}-\bar{x}_k)^2}} \tag{3}$$

where, $\bar{x}_j$and $\bar{x}_k$are the normalized mean values of indicators j and k. r_{jk} is the correlation coefficient between indicators *j* and *k*.

The correlation coefficient matrix$R{=}(r_{ij})_{n*m}$can be obtained by inserting the correlation coefficient into the corresponding position of the matrix.

$$R{=}\begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{pmatrix} \tag{4}$$

where *n* and *m* are the number of evaluation objects and evaluation indicators, respectively.

Step 2. Calculate the standard deviation diagonal matrix S.

$$s_j{=}\sqrt{\sum_{i=1}^{m}(x_{ij} - \bar{x}_j)^2/m} \tag{5}$$

where $s_j$is the standard deviation of indicator *j* in the normalized matrix. The standard deviation matrix $S = (s_j)_{n*n}$can be obtained by including the corresponding standard deviation in the corresponding position of the diagonal of the matrix.

Step 3. Determine the eigenvector corresponding *b* to the maximum eigenvalue of the matrix $R \times S$.

$$(R \times S) \times b = \lambda \times b \tag{6}$$

Step 4. Determine the weight.

Let $b = (b_1, b_2, \cdots, b_j, \cdots b_n)$, and normalize the eigenvector values to obtain $b^* = ({b_1}^*, {b_2}^*, \cdots, {b_j}^*, \cdots {b_n}^*)$. The weight of indicator *j*, denoted as w_j, is the absolute value of the *j*th component of b^*.

$$|{b_j}^*| = \left| b_j / \sqrt{\sum_{j=1}^{n} b_j^2} \right| \tag{7}$$

$$w_j = |{b_j}^*| / \sum_{j=1}^{n} |{b_j}^*| \tag{8}$$

where $w_j$is the comprehensive weight value.

Adaptability analysis model
(1) Indicator adaptability analysis model.
Step 1. Calculate the absolute adaptability.

The absolute adaptability of indicators in the WEFE system can be calculated using grey correlation analysis[16]. *X* is selected as the initialization decision matrix. x_{0j} is selected as the optimal reference sequence, and x_{ij} is the comparison sequence according to the indicator attribute. The grey correlation factor matrix is dimensionless processed. For the forward indicators, the optimal reference sequence consists of the maximum values of the corresponding indicators of the evaluation objects. Conversely, for the negative indicators, the optimal reference sequence consists of the minimum values of the relevant indicators of the evaluation objects. According to $X_{ij} = \frac{x_{ij}}{x_{0j}}$, the decision matrix X_{ij}can be obtained. The correlation coefficient between the comparison sequence and the reference sequence at each point is:

$$\xi_{ij} = \frac{\underset{i}{\min}\,\underset{j}{\min}\,|x_{oj} - X_{ij}| + \frac{1}{2}\,\underset{i}{\max}\,\underset{j}{\max}\,|x_{oj} - X_{ij}|}{|x_{oj} - X_{ij}| + \zeta\,\underset{i}{\max}\,\underset{j}{\max}\,|x_{oj} - X_{ij}|} \tag{9}$$

$$\overline{\xi_{ij}} = \frac{1}{n} \sum_{i=1}^{n} \xi_{ij} \tag{10}$$

where $\overline{\xi_{ij}}$is the grey average correlation.

Let A_i indicate that X_{ij} is related to x_{0j}, that is, A_i=$(\xi_{i1}, \xi_{i2}, \cdots, \xi_{im})$, then the mutual proximity level of any two A_i and $A_l(i, l = 1, 2, \cdots, n)$is expressed as:

$$N(A_i, A_l) = 1 - \frac{1}{\sqrt{n}} \left[\sum_{i=1}^{n} (\xi_{ij} - \xi_{lj})^2 \times u_k^* \right]^{1/2} \tag{11}$$

Let $A_e = (1, 1, \cdots, 1)$indicate that X_{ij} has the greatest correlation with x_{0j}. The proximity between $A_i$and A_e is taken as the correlation level between X_{ij} and x_{0j}, that is:

$$\xi_{ij} = 1 - \frac{1}{\sqrt{n}} \left[\sum_{i=1}^{n} (\xi_{ij} - 1)^2 \times u_k^* \right]^{1/2} \tag{12}$$

Assuming that the fluctuation value of the correlation coefficient ζ_{ij} between the comparative series X_{ij} and the reference series x_{0j} at each point, relative to the weighted average$\overline{\zeta_{ij}}$ is $\varepsilon_{ij} = \zeta_{ij} - \overline{\zeta_{ij}}$, then:

$$\zeta_{ij} = \overline{\zeta_{ij}} + \varepsilon_{ij} \tag{13}$$

$$f_j^c = 1 - \left[\left(\overline{\zeta_{ij}} - 1\right)^2 + \sum_{j=1}^{m} \varepsilon_{ij}^2 \times u_k^* \right]^{1/2} \tag{14}$$

where f_j^c is the absolute adaptability of the indicator *j*.
Step 2. Calculate the relative adaptability.

The relative adaptability of each indicator in the WEFE system was calculated using the co-evolutionary algorithm[58].

$$HD_j = \sum_{k=1}^{n} (b_{jk}! = B_j) \tag{15}$$

$$AHD = \frac{1}{nm - 1} \sum_{j=1}^{m} \sum_{k=1}^{n} (b_{jk}! = B_j) \tag{16}$$

$$f_j^R = \frac{H + HD_j - AHD}{H + AHD} f_j^C \tag{17}$$

where HD_j represents the Hamming distance between the *j-th* indicator bjk of the *k-th* sample and the best indicator B_j. AHD represents the average Hamming distance between each indicator and its best indicator, H is the smooth protection factor, which is usually taken as 0.5 ($H = 0.5$)[59].

Step 3. Calculate the comprehensive adaptability.

The comprehensive adaptability of indicator j was calculated according to the absolute adaptability and relative adaptability of the indicator.

$$f_j^s = w_j \times f_j^C + (1 - w_j) \times f_j^R \tag{18}$$

where f_j^s is comprehensive adaptability of indicator.

(2) Subsystem adaptability analysis model.

The comprehensive adaptability of all indicators determines the adaptability of subsystems. The adaptability of the subsystem symbolizes the internal adaptability characteristics and trends of each subsystem in the WEFE system, and is the key to measuring the adaptability of the system.

$$A_s = \sum_{j=1}^{m} f_j^s \times \frac{x_{ij}}{\sum_{j=1}^{m} x_{ij}} \tag{19}$$

where A_s is the comprehensive adaptability of subsystem, $s = 1, 2, 3$.

(3) System adaptability analysis model.

The adaptability of the WEFE system is determined by the adaptability of the subsystems. The influence of each subsystem on system adaptability is determined by considering their relative importance. Therefore, the WEFE system adaptability is:

$$A = A_1 * w_1 + A_2 * w_2 + A_3 * w_3 \tag{20}$$

where *A* is the adaptability of WEFE system.

(4) Classify adaptability level.

The value of *A* can be used to judge the level of adaptability of the WEFE system. According to the relevant research results[16], the division standards and level of adaptability are shown in Fig. 4.

Coordination analysis model

The coordination index was used to describe the degree of coordination among subsystems and the adaptability of the WEFE system. The coordination index is calculated as shown below:

$$CI_S = \sqrt{\sum_{j=1}^{m} (f_j^s - A_s)^2 / A} \tag{21}$$

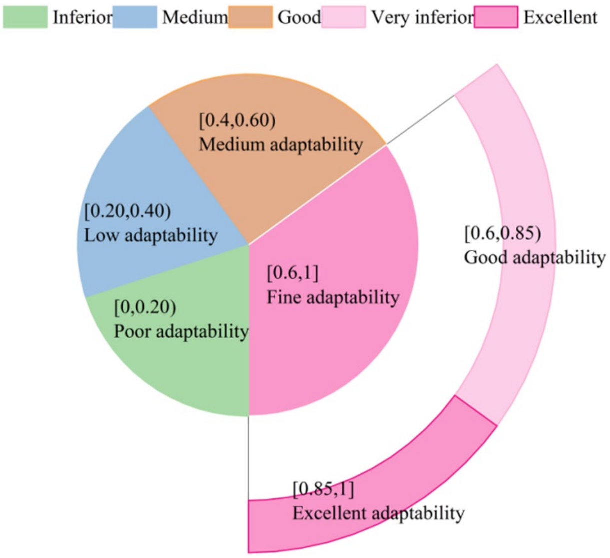


Fig. 4. The division standards and degree of adaptability level.

$$CI = CI_1 * w_1 + CI_2 * w_2 + CI_3 * w_3 \tag{22}$$

where CI_S is the coordination degree between the subsystem and the adaptability of the WEFE system adaptability. CIrefers to the overall coordination degree.

Spatial correlation feature analysis

Moran's I can be used to explore the spatio-temporal distribution patterns of WEFE system adaptability from both global and local aspects[55]. The adaptability of the WEFE system is related to the natural geographical elements of spatial layout, socio-economic conditions, and resource distribution. These factors exhibit spatial randomness and structure, with measurable spatial autocorrelation. The global Moran's I represents the overall spatial correlation degree and regional differences in the adaptability development of the WEFE system. The local Moran's I reflects the spatial correlation between a given region and its adjacent regions. It is calculated as follows:

$$GlocalMoran'sI = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} w_{ij}(f_i^s - \overline{f_i^s})(f_j^s - \overline{f_m^s})}{Sd^2 \sum_{i=1}^{m}\sum_{j=1}^{n} w_{ij}} \tag{23}$$

$$LocalMoran'sI = \frac{m(f_i^s - \overline{f_i^s}) \sum_{i \neq j}^{m} w_{ij}(f_j^s - \overline{f_m^s})}{\sum_{i=1}^{m} (x_i - \overline{f_i^s})^2} \tag{24}$$

where $f_i^s$and $f_j^s$is the coordination index.

In the formula, f_i^s and $f_j^s$are the adaptability values for regions i and j, respectively. $\overline{f_m^s}$ is the mean value of regional adaptability; Sd is the standard deviation of the regional adaptability of WEFE system. w_{ij} is the spatial weight matrix, with a value of 1 or 0.

Results and analysis

WEFE system adaptability weight results

The weight calculation results for the subsystems and indicators of WEFE adaptability for the YRB are shown in Table 2. The stability subsystem had the highest weight (50.5%), indicating that it occupied a significant portion of the assessment process for WEFE system adaptability. Next was the sustainability subsystem, which accounted for 26.5% of the total weight, suggesting that sustainability was also an important factor. The coordination subsystem had the lowest weight, only 23.0%, implying that its importance was relatively minor in the overall assessment. The indicator level weight results showed that there were significant differences in the importance of each indicator. Among them, the indicator weight values of C10, S7, and S12 exceeded 0.055, reaching 0.0590, 0.0570, and 0.0557, respectively. This indicated that these factors were crucial for system adaptability analysis. These high-weight indicators were mainly related to water resource utilization, energy use, and fertilizer application. In contrast, indicators such as C4, C6, C12, and S2 had lower weight values that were all less than 0.01. This suggests that they have a relatively smaller impact on the overall assessment results.

Changes in the WEFE system adaptability

Indicator adaptability results

The absolute, relative, and comprehensive adaptability values of each indicator in the WEFE system for the YRB were obtained according to formulas (1) to (17), as shown in Fig. 5. The relative adaptability of the indicators

Subsystem	Indicator	Subsystem	Indicator	Subsystem	Indicator
Coordination (0.230)	C1(0.0118)	Stability (0.505)	S1(0.0364)	Sustainability (0.265)	D1(0.0222)
	C2(0.0121)		S2(0.0013)		D2(0.0473)
	C3(0.0347)		S3(0.0501)		D3(0.0456)
	C4(0.0038)		S4(0.0524)		D4(0.0065)
	C5(0.0105)		S5(0.0323)		D5(0.0132)
	C6(0.0029)		S6(0.0257)		D6(0.0457)
	C7(0.0023)		S7(0.0570)		D7(0.0451)
	C8(0.0246)		S8(0.0475)		D8(0.0357)
	C9(0.0490)		S9(0.0479)		D9(0.0039)
	C10(0.0590)		S10(0.0471)		
	C11(0.0187)		S11(0.0512)		
	C12(0.0006)		S12(0.0557)		

Table 2. Weight results for subsystems and indicators.

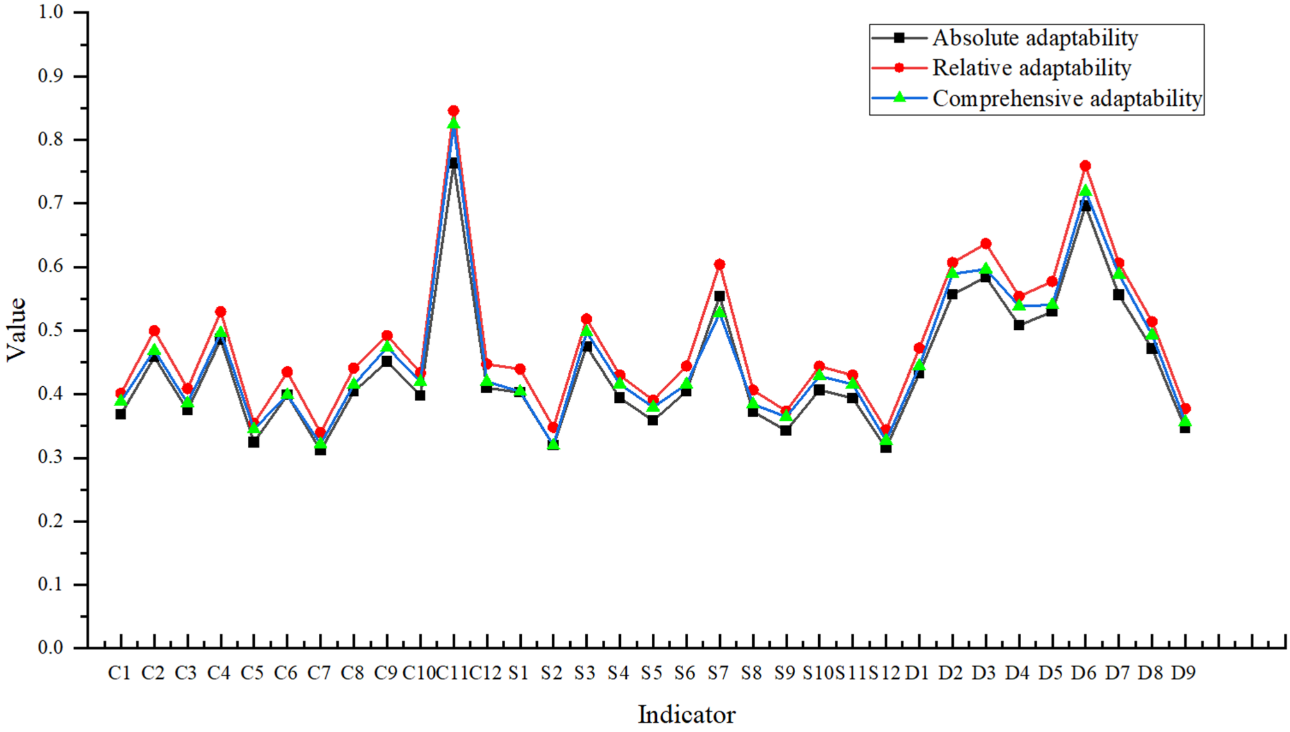


Fig. 5. Adaptability values of each indicator in the WEFE system adaptability analysis.

was obviously higher than their absolute adaptability. The comprehensive adaptability values of most indicators were in the range of [0.35, 0.60]. However, the comprehensive adaptability values of indicators C11, D3, and D6 were greater than 0.6. This indicated that: (1) The harmless treatment rate indicator of consumption waste (C11) reflected the efficiency and environmental standards of waste management. The higher adaptability value of C11 in the YRB indicated that the region had a strong waste treatment capacity, effectively reducing the negative impact of waste on the WEFE system. (2) The water consumption per unit of GDP indicator (D3) measures the degree of dependence on water resources and the efficiency of water use in economic development. A higher adaptability value suggested that the water resource utilization in the YRB was relatively efficient. This indicated that the region can promote economic growth while reducing excessive water consumption, which helps maintain the balance and sustainability of the WEFE system. (3) The urban land area indicator (D6) reflects the use of land resources in urbanization. A higher adaptability value indicated that urban land use planning and management in the YRB were relatively reasonable, effectively protecting and utilizing land resources during urban development.

Subsystem adaptability results

According to Formula 18, adaptability change trends for the three subsystems (coordination, stability, sustainability) of the WEFE system in the YRB from 2011 to 2022 were obtained, as shown in Fig. 6. The adaptability levels of the three subsystems in the nine provinces of the YRB increased overall. However, the degree of improvement varied among different provinces. Shandong and Shaanxi Provinces were prominent, showing significant increases in adaptability across all three subsystems, while the three subsystems in Ningxia exhibited limited growth in adaptability, and those in the remaining six provinces experienced a more gradual increase.

Data analysis revealed that the adaptability of the coordination subsystem in the YRB experienced stable development from 2011 to 2022. In 2011, Qinghai and Shaanxi Provinces had higher adaptability values in the coordination subsystem. By 2022, Shaanxi and Henan Provinces had higher adaptability values in the coordination subsystem. During this period, Gansu Province exhibited the most significant growth, with its adaptability value increasing from 0.624 to 0.710. In contrast, the adaptability value for Qinghai Province increased from 0.709 to 0.719, which was the smallest increase.

The adaptability of the stability subsystem in the YRB increased slowly from 2011 to 2022, with the degree of increase varying across different provinces and years. The adaptability value for the stability subsystem in Shandong Province increased from 0.639 to 0.834, showing the biggest improvement. In contrast, the stability value of Inner Mongolia changed the least, increasing from 0.617 to 0.617. Regionally, in 2011, 2015, 2019, and 2022, the stability subsystem for Shandong Province consistently showed the highest adaptability values. In 2011 and 2022, the adaptability values of the stability subsystem for Ningxia were the lowest, whereas in 2015 and 2019, the adaptability values of the stability subsystem for Shanxi were the lowest.

The adaptability of the sustainability subsystem in the YRB rapidly increased during the study period. Most provinces exhibited a consistent increase. For example, the adaptability value of the sustainability subsystem

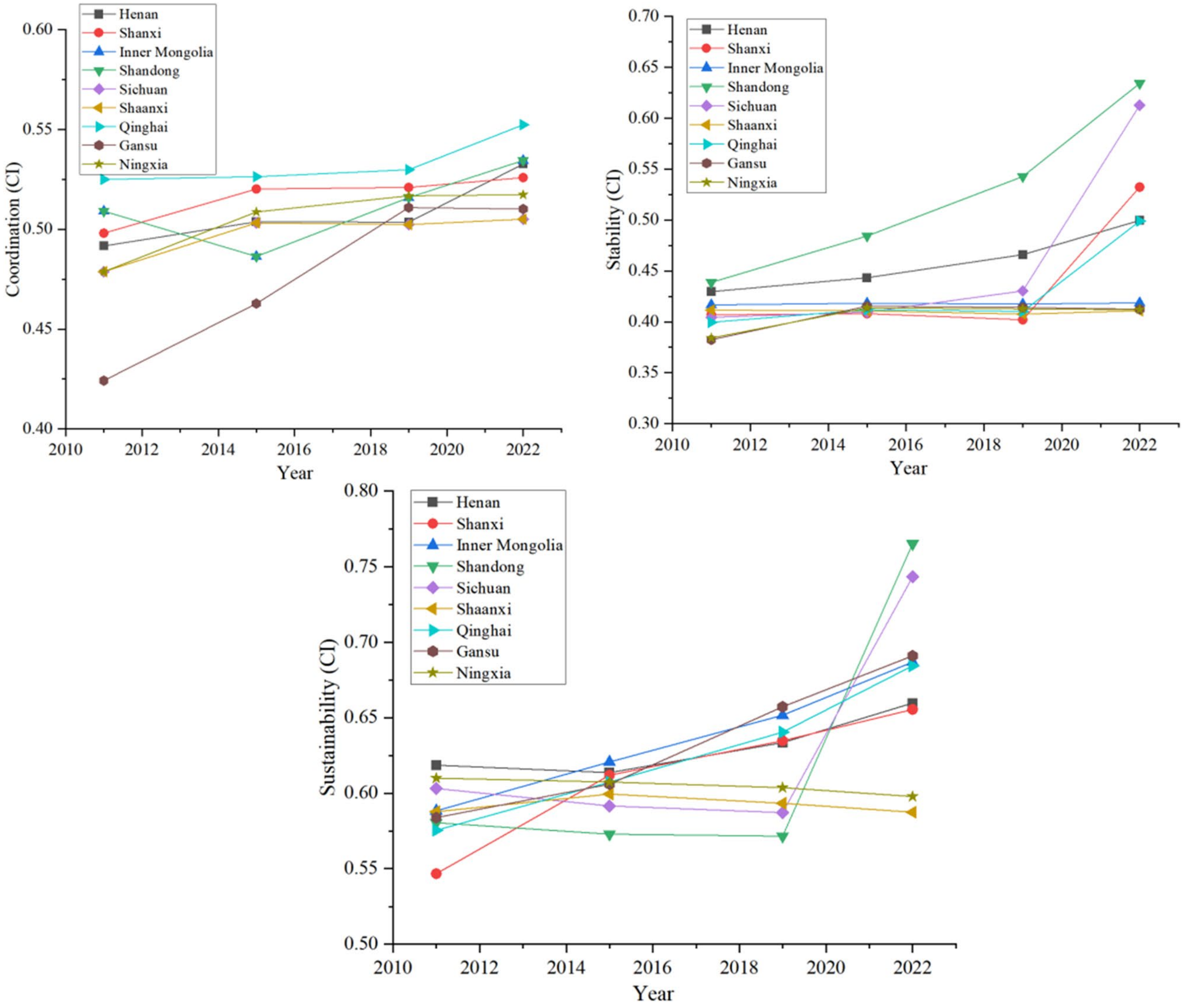


Fig. 6. The subsystem adaptability values for the WEFE system in YRB.

for Shandong Province increased significantly from 0.781 to 0.965, showing the largest growth trend among all provinces. The adaptability values of the sustainability subsystem in Sichuan and Gansu Provinces saw notable improvements, increasing from 0.803 to 0.784 in 2011 to 0.943 and 0.891 in 2022, respectively. The adaptability values of the sustainability subsystem for other provinces, such as Henan, Shaanxi, and Ningxia, also increased, but the increments were relatively smaller.

WEFE system adaptability results

The adaptability values for the WEFE system in the YRB from 2011 to 2022 were obtained according to formula (19). The adaptability trends for the WEFE system in nine provinces are shown in Fig. 7. In general, the adaptability values of the WEFE system in different provinces of the YRB increased by varying degrees during this period. Among them, the adaptability of Henan Province increased from 0.664 in 2011 to 0.818 in 2022, and that of Shandong Province increased from 0.680 in 2011 to 0.784 in 2022, showing a significant improvement in adaptability. However, some provinces such as Shaanxi and Gansu showed relatively little change during the 12-year period, from 0.488 to 0.424 in 2011 to 0.590 and 0.505 in 2022, respectively, indicating a slow improvement in adaptability. In addition, adaptability values in some provinces (Henan, Shandong, and Shanxi) generally declined in 2013, reflecting some degree of challenge or adjustment in these provinces during the year. Comparative data showed that the adaptability of the WEFE system in nine provinces of the YRB increased significantly during 2018–2022. In particular, the adaptability of Inner Mongolia and Sichuan Provinces increased by 9.3% and 6.9%, respectively, compared to 2017.

WEFE system coordination analysis

Figure 8 depicts the changes in the coordination indices of the three subsystems and the overall system across the nine provinces within the YRB from 2011 to 2022. Of the three subsystems, the coordination subsystem showed

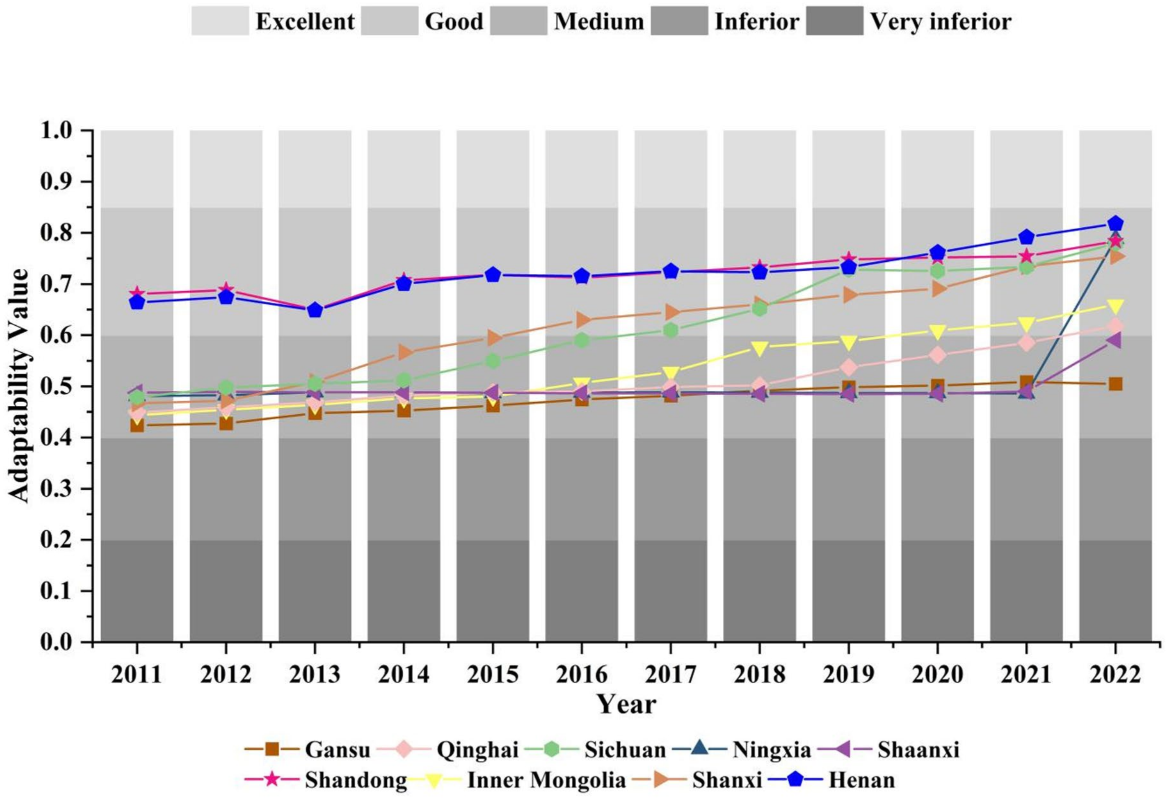


Fig. 7. The adaptability values for the WEFE system in the YRB from 2011 to 2022.

the best coordination, while the sustainability subsystem exhibited the poorest. There were obvious differences in the coordination levels among the three subsystems. The coordination index of coordination subsystem increased overall across the nine provinces of the YRB. The coordination index of stability subsystem showed some volatility. However, the coordination index of sustainability subsystem decreased in most provinces (except Shanxi Province). Except for Shandong and Gansu Provinces, the overall coordination of the WEFE system increased steadily. Among the provinces showing growth, Sichuan Province had the largest growth.

The nine provinces showed an overall increase in the coordination degree of the three subsystems. Among them, Shaanxi Province exhibited the most significant growth, with its coordination level rising from 0.754 in 2011 to 0.913 in 2022. In contrast, Inner Mongolia showed the least growth, with the coordination level increasing from 0.843 in 2011 to 0.861 in 2022. Shandong and Qinghai Provinces had fluctuating increases. The coordination trends of the stability subsystem varied across the nine provinces along the Yellow River. Most provinces experienced steady improvement in their coordination levels, with Sichuan Province displaying the most significant growth, increasing from 0.446 in 2011 to 0.658 in 2022. In contrast, Shanxi, Shandong, and Gansu Provinces exhibited slight declines in their coordination levels. The coordination of the sustainability subsystem showed a fluctuating decline in the nine provinces along the YRB. The coordination degree of the sustainability subsystem in Gansu Province decreased from 0.896 in 2011 to 0.761 in 2022, showing a significant decline. Henan, Inner Mongolia, and Qinghai showed a fluctuating decrease, characterized by an initial rise followed by a decline.

Adaptability spatial distribution patterns of the WEFE system

Global correlation feature

The changes in global Moran's I for the YRB from 2011 to 2022 are documented in Fig. 9. As shown in Fig. 9, the P value was greater than 0.1 for the timeframe from 2011 to 2022, which indicated that Moran's I value for adaptability analysis of the WEFE system within the YRB did not attain statistical significance during this period. This means that the adaptability level of the WEFE system was distributed randomly across the region during these years and there was no spatial clustering effect.

Local correlation feature

According to the research method of spatial autocorrelation analysis[16,55], the local spatial distribution characteristics of regions are usually classified into four categories: High-High aggregation, High-Low aggregation, Low-Low aggregation, and Low-High aggregation[60]. These four types of aggregation areas reveal different correlation patterns in attribute values between the area and its surrounding areas. The local spatial distribution of WEFE system adaptability in the YRB is shown in Fig. 10. The spatial local autocorrelation of nine provinces in the YRB during 2011, 2015, 2019, and 2022 showed two significant characteristics: path

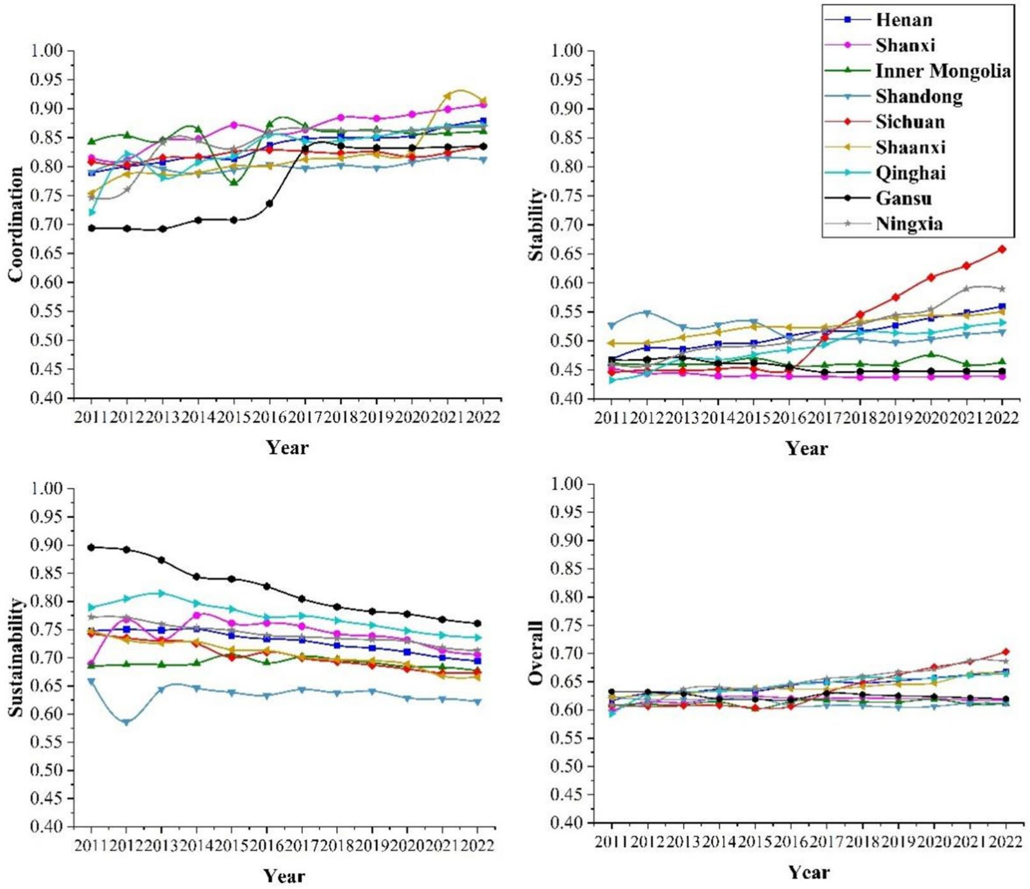
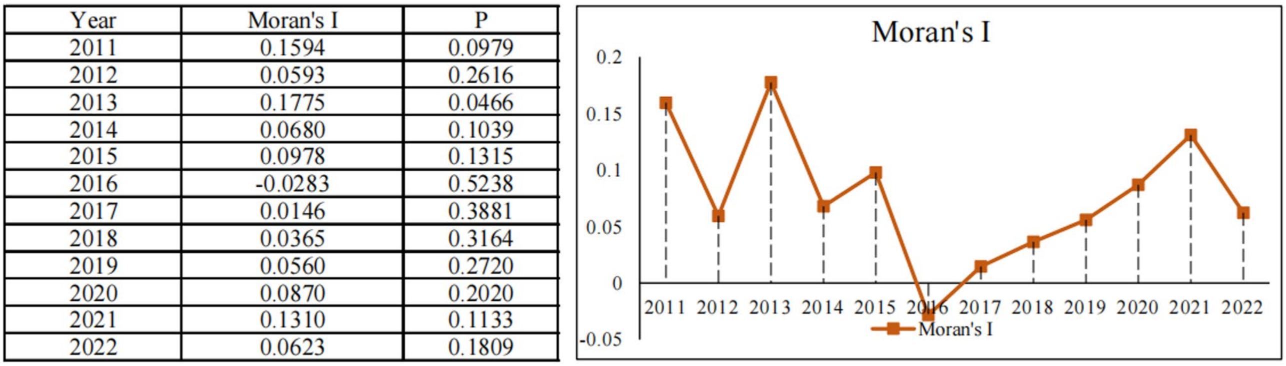


Fig. 8. Variability in the coordination degrees of adaptability between subsystems and the WEFE systems.



Year	Moran's I	P
2011	0.1594	0.0979
2012	0.0593	0.2616
2013	0.1775	0.0466
2014	0.0680	0.1039
2015	0.0978	0.1315
2016	-0.0283	0.5238
2017	0.0146	0.3881
2018	0.0365	0.3164
2019	0.0560	0.2720
2020	0.0870	0.2020
2021	0.1310	0.1133
2022	0.0623	0.1809

Fig. 9. The Global Moran's I results.

dependence and spatial disequilibrium. On the one hand, the adaptability spatial trajectory of the WEFE system in the YRB was stable, and there was clear path dependence. Initially, in 2011, provinces such as Henan, Qinghai, Shandong, and Shaanxi were in the High-High agglomeration zone, and by 2022, only Qinghai remained outside the High-High agglomeration zone. The Low-High agglomeration zone primarily included provinces like Ningxia, Shaanxi, and Sichuan. The Low-Low agglomeration zone, which mainly included Gansu, Inner Mongolia, Shanxi, and Sichuan in 2011, shifted to Gansu and Inner Mongolia by 2015, to Shandong and Sichuan by 2019, and finally settled in Inner Mongolia, Ningxia, and Shandong by 2022. The High-Low agglomeration zones featured Qinghai and Shanxi in 2015, Henan and Ningxia in 2019, and Gansu in 2022. Overall, the changes among the provinces were minor, with Qinghai, Gansu, and Shanxi shifting between the High-High and High-Low agglomeration zones across different years.

On the other hand, there were significant regional differences and obvious imbalances. High-High spatial concentration zones were chiefly concentrated in Henan, Shandong, and Shaanxi. These areas are part of the

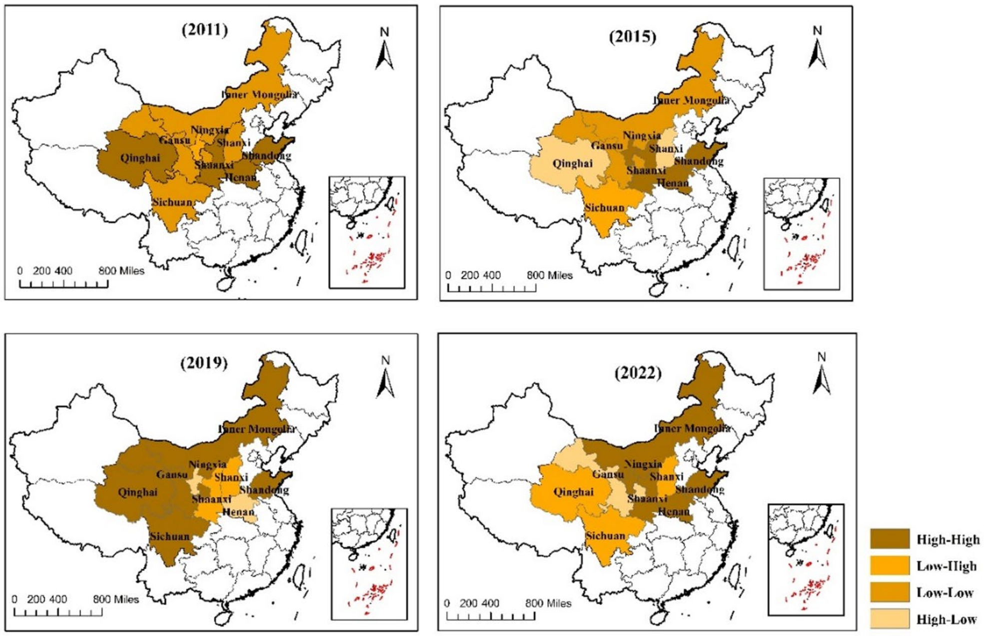


Fig. 10. Adaptability local spatial distribution map of the WEFE system in the YRB (created in ArcGIS 10.8; https://desktop.arcgis.com).

middle and lower reaches of the YRB, characterized by higher levels of economic development and superior technological conditions. The Low-Low agglomeration zones were primarily located in provinces with relatively underdeveloped economies and weak industrial bases. For example, in 2019, Gansu, Inner Mongolia, and Qinghai were in Low-Low concentration areas that belonged to the upper reaches of the YRB. The Low-High and High-Low concentration zones were mainly located in the middle reaches of the YRB. Overall, the adaptability level of the WEFE system in the YRB varied remarkably between provinces, showing a gradient structure of "downstream > middle > upstream".

Discussion

System adaptability level

From 2011 to 2022, the adaptability values of the coordination and stability subsystems of the WEFE system in the nine provinces of the YRB were within the range of (0.6, 0.85]. According to the adaptability classification criteria, these two subsystems had a good adaptability level. The adaptability level of the sustainability subsystem in the nine provinces of the YRB was also within the interval of (0.6, 0.85] from 2011 to 2020. However, by 2021–2022, the adaptability level of this subsystem exceeded 0.85, an excellent adaptability level. This indicated that the coordination and stability subsystems of the YRB maintained a good adaptability level over a 12-year span, reflecting the relatively stable and coordinated implementation of various environmental policies and infrastructure maintenance within the region. This improvement in the sustainability subsystem for 2021–2022 suggests that the YRB implemented more effective strategies in environmental management, resource utilization, and economic development during this period. The research findings of this paper are in line with the existing research outcomes[61]. Progress can be attributed to the introduction of the national strategy of "Ecological Protection and High-Quality Development of the YRB" in 2021.

The adaptability levels of the nine provinces in the YRB significantly improved during the study period. Specifically, the middle and lower reaches had notably higher adaptability levels compared to the upper reaches. Among these provinces, Henan and Shandong consistently maintained good adaptability levels throughout the entire study period. In contrast, the adaptability levels of the other seven provinces improved from medium to good. However, the adaptability evaluation results for the WEFE system in the YRB areas were not ideal and there was still much room for improvement in the overall adaptability level. The research findings of this paper are consistent with other research outcomes[17], which highlights the uneven distribution of natural resources such as water, energy, and food in the YRB. In particular, the upper reaches had relatively abundant water resources but low economic development levels, resulting in inefficient resource utilization[62]. Conversely, the downstream regions experienced rapid economic development but faced water scarcity, causing pronounced resource supply-demand contradictions. These factors collectively contributed to how adaptability levels in the WEFE system for the YRB fell short of what was desired.

System coordination discussion

Comparing the coordination results of the three subsystems in the YRB, the order was coordination subsystem > sustainability subsystem > stability subsystem. The coordinated relationship among the three subsystems has evolved from competition to sustainable and balanced development. Over the study period, the coordination degrees of the coordination and stability subsystems increased. This can be largely credited to the promotion of high-quality development, with an emphasis on ecological prioritization and eco-friendly development in the YRB[63]. This approach has strengthened the sharing and management of water resources, energy, and food, facilitating the coordinated operation of resources within the WEFE system. Consequently, the coordination levels of both the coordination and stability subsystems were significantly improved. Moreover, the cooperation and coordination mechanisms among various departments and stakeholders in the YRB have become more effective[64]. However, the coordination of the sustainability subsystem decreased, indicating that despite remarkable progress in resource management and economic development in the YRB, balancing long-term environmental protection and social sustainable development is still a challenge. On the one hand, the problems of ecological fragility and spatial and temporal inequality of resource distribution are still prominent in the YRB[65]. On the other hand, the YRB's water resources capacity is declining amid severe challenges, including difficult restoration of water ecosystems, imperfect agricultural subsidy policies, and a lack of effective ecological compensation mechanisms[66].

Spatial correlation feature

The spatial features of WEFE system adaptability in the YRB showed a random distribution across the region during these years, and there was no spatial clustering effect. The four types of local autocorrelation clusters reflected the characteristics of path dependence and spatial disequilibrium. The spatial dispersion of WEFE system adaptability in the YRB may have been due to the following: (1) The YRB encompasses a wide range of geographical features across multiple provinces. There are significant differences in geographical conditions and climate in the YRB. The YRB spans from the Qinghai-Tibet Plateau to the North China Plain, encompassing diverse topography and climate[63]. This variation led to marked discrepancies in the distribution of water resources, energy resources, and ecosystem adaptability across regions. (2) The impact of human activities in the YRB varies across the basin. The agricultural, industrial, and urbanization processes are varied across the YRB, which directly affect water resource utilization, energy consumption, and food production[55]. These differences, in turn, influence the adaptability of the system. (3) Relevant studies indicate that key factors such as land use, wastewater discharge, and economic development pose significant barriers to urban sustainable development[67]. The long-term over-exploitation and improper management of resources in the YRB, such as excessive irrigation and mining, have rendered resources and ecological systems vulnerable in certain areas. The cumulative spatial effects of these issues exacerbate the imbalance in WEFE system adaptability.

Conclusion

Research conclusion

Based on the symbiosis theory, the adaptability levels and grades of the WEFE system in the YRB from 2011 to 2022 were analyzed using a co-evolution model, and spatial correlation characteristics of WEFE system adaptability were explored. The core findings of this study are as follows:

(1) The stability subsystem had the highest weight, followed by the sustainability subsystem, while the coordination subsystem had the lowest weight. The indicators of total amount of sewage treated (C10), total power of agricultural machinery (S7), and the amount of fertilizer applied (S12) were the key factors for WEFE system adaptability analysis.
(2) The absolute adaptability of the indicators was obviously higher than their relative adaptability. From 2011 to 2022, the adaptability of the coordination subsystem was stable. Meanwhile, the adaptability of the stability subsystem exhibited a gradual increase. During the same period, the adaptability of the sustainability subsystem experienced a marked and rapid increase. According to the adaptability evaluation of the WEFE system, the adaptability levels of the nine provinces in the YRB significantly improved over the study period. Additionally, the adaptability levels in the middle and lower reaches were notably higher than those in the upper reaches.
(3) The coordination levels between the three subsystems and the WEFE system varied. Specifically, the coordination and stability subsystems improved, while the coordination of the sustainability subsystem declined.
(4) The adaptability level of the YRB's WEFE system was randomly spatially distributed. In terms of local spatial autocorrelation, there were significant spatial disparities and path dependencies in the adaptability level of the YRB's WEFE system.

Recommendations

Considering the results of this research, the following policies and suggestions are proposed:

(1) A regional management model for urban ecological environment governance should be adopted. For regions with low adaptability in the upper reaches of the YRB, future urban planning should focus on strengthening regional ecological protection and restoration and improving agricultural technology and management levels to enhance the adaptability of the urban WEFE system. These regions in the middle and lower reaches should emphasize industrial upgrades and transformation, reducing the environmental impact of high-emission enterprises.
(2) The provincial governments should develop and implement stricter environmental regulations and policies, particularly regarding water and energy use. They should encourage the development of eco-friendly technologies and clean energy to lessen dependence on fossil fuels. This would enhance the adaptability of sustainability subsystems in the YRB, ensuring the long-term sustainability of resource use.
(3) The provincial governments should optimize the regional system structure and material and energy flows by adjusting inter-regional industrial and trade structures. By improving the efficiency of resource and

energy use, the spatial adaptability of the WEFE system in the YRB can be improved through region-wide co-construction, development, and sharing.

(4) The provincial governments should further promote and introduce advanced sewage treatment technologies and processes, such as biological treatment technology, membrane technology, and ultraviolet purification, which can enhance sewage treatment efficiency and water quality compliance. Additionally, to reduce environmental pollution caused by industrial fertilizers, the use of new and bio-organic fertilizers should be increased.

Based on the symbiosis theory, this paper constructed an adaptability evaluation framework for the WEFE system, with coordination, stability, and sustainability as its subsystems. With climate change and economic development, the connotation of the WEFE system adaptability will continue to expand. Integrating energy ecological footprint, energy flow, and information flow into the evaluation framework will be a direction worth studying in the future.

Data availability

The data that support the findings of this study are not openly available due to reasons of data confidentiality requirements and are available from the corresponding author.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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