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Research article

Coupling efficiency and spatial dynamic evolution of urban water–energy–food in China–A case of evidence from 94 cities

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A R T I C L E I N F O

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A B S T R A C T

Quantifying and interpreting the water–energy–food (WEF) nexus is critical to achieve the sustainable development of urban resources. The mismatch between urban water, energy and food allocations is a prominent problem that is particularly acute in the Yellow River Basin (YRB) of China. In this study, models for the WEF coupling degree and coupling efficiency were constructed. The WEF coupling efficiencies of the 94 cities in the YRB from 2011 to 2020 were quantified using a data envelopment analysis (DEA) model. On this basis, the spatial distribution characteristics and evolutionary trends of different urban WEF coupling efficiencies were analysed and explored using an exploratory spatial data analysis (ESDA) model and a parametric kernel density estimation model. The results show that the energy subsystem constrain the development of the WEF nexus, and the food subsystem, in turn, regulates the development of the WEF nexus. In some years, the phenomenon of 'resource curse' occurred, in which the WEF coupling degree increased while the coupling efficiency decreased. Overall, the values of the urban WEF coupling efficiency were low, ranging from 0.5300 to 0.6300, which is not effective. Spatial clustering was detected in the urban WEF coupling efficiency. The clustering types were 'high–high' clustering areas in less developed regions and 'low–low' clustering areas in developed regions. The two clusters and the median contiguous group had different evolutionary trends. Both efficiency and polarisation increased in the high-clustering group, efficiency improved in the low-clustering group, and a new efficiency pole was formed in the median contiguous group. Among the three grouped cities, we discuss the potential of policies such as cross-city cooperation, intra-city multi-sectoral cooperation and cultivating new central growth cities to improve the WEF coupling efficiency in the YRB.

1. Introduction

Given unprecedented population growth, global climate change and environmental troubles, the demand and manage pressure on vital resources, such as water, energy and food, are increasing every day. The demand for food, energy and water will rise globally by 40 %, 50 % and 35 %, respectively, by 2030 compared to 2010 [1]. Furthermore, more than 5 billion people worldwide will confront

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water scarcity by 2050 [2]. Food waste is also a significant factor in food insecurity. The statistics show that dietary issues related to food security have resulted in 11 millions of deaths and 255 millions of disabilities [3]. The price of energy has increased significantly in many regions as the global oil crisis continues to worsen, and the number of people who are unable to pay their energy bills has increased [4]. Various items of evidence reveal that the hazards caused by the resource crisis threaten the sustainable development of cities and the survival of human beings. In the process of making social development policies, the research into the water–energy–food (WEF) nexus is crucial to balance the development of water, energy and food and the conflicts between the related authorities [5].

Traditional single-sector management of water, energy and food will further aggravate the crisis of resource shortages [6,7]. The WEF systems are interactive: the production of energy and food is inseparable from water, and the transportation of water and food is also inseparable from the use of energy. Hence, researchers and decision-makers are increasingly aware that a single resource management policy is inadequate for the current complex crisis of resource shortages and may even lead to the loss of these resources [6,8,9]. The appropriate consideration of the WEF nexus, therefore, becomes a crucial and hotly debated aspect of sustainable urban development [10–12]. Indeed, as early as 2008, at the World Economic Forum, the relationship between water, energy and food was determined. The Bonn Conference in 2011 helped humanity better understand the significance of the nexus between water, energy and food [13]. The relevance of the WEF nexus is also highlighted in the Asia-Pacific WEF, which was released by the United Nations Economic and Social Committee for Asia and the Pacific [11]. In addition, China discussed the importance of resource security in the report of the 20th National Congress of the Party in 2022. As the foundation of human survival and development, resources play an important role in research in the social and natural science spheres. Thus, the development of the WEF nexus will become a new driving force in cities looking to address the resource crisis and promote sustainable development [14].

It has become a consensus to quantify the WEF nexus to provide suggestions for systematic resource management [15]. Researchers have developed different framework models and tools to quantify the WEF nexus in different countries, provinces and cities [16]. Some scholars have measured and analysed the level of WEF coupling and collaboration in the region [17–22]. For instance, Li et al. have used the collaborative security index as a basis for evaluating the WEF security of China in time and space [23]. Some have focused on building footprint frameworks for water, energy and food to quantify them [24–27]. Lu et al. estimate the WEF footprint and virtual trade water flow in the Central China region by using a Modified Water Stress Index associated with virtual water outflows [28]. Others have studied the WEF nexus to provide a theoretical basis for the trade-offs between related industries [29–32]. Bakhshianlamouki et al. identify inter-sectoral trade-offs by using a system dynamics model to simulate the WEF nexus in the Lake Urmia basin as a holistic multi-sectoral system [33].

The WEF coupling reflects current quantitative relationships between water, energy and food. Deng et al. use the coupled coordination model and the grey model to evaluate and predict the WEF nexus in Jiangsu Province [34]. However, from a macro point of view, as a model reflecting the quality relations of WEF, the WEF coupling efficiency model is rarely used by scholars [8]. Therefore, it may not be possible to provide comprehensive policy guidance for regional WEF sectors. The existing research has contributed to the input–output efficiency of single resources such as water, energy and food [35–40]. Zheng et al. take the WEF nexus as an entry point to quantify China's food production efficiency and consider the direct and indirect inputs of water and energy in food production [41]. Zhang et al. systematically analyse the differences in energy efficiency in 13 countries [42]. Although these studies provide new theoretical references for the management and use of resources, they are not conducive to providing scientific strategies for cooperation between multi-resource departments [43]. Some scholars also analysed the input–output efficiency of the WEF nexus but did not consider the coupling relationships between its three elements [44]. It is, therefore, necessary to study WEF coupling and coupling efficiency from a macro perspective.

The Yellow River Basin (YRB) forms an important ecological barrier and economic belt in China. The YRB has strong economic foundations in agriculture and animal husbandry and is rich in energy resources. However, as a typical region with competing demands for water, energy and food resources, it is facing various challenges and opportunities. Economic and agricultural development in the basin has been disorganised, which has resulted in excessive resource consumption and environmental pollution, and the phenomenon of competing for water that exists between economic development and environmental protection has intensified. In the basin, the proportions of agricultural water and energy development water are 71 % and 13 %, respectively. In 2020, the total grain output of the basin was 239 million tons, accounting for 35.6 % of the total national grain output. The complex WEF nexus has become an important factor restricting the development of this region [45]. There are many resources in the basin, such as coal, oil, natural gas and nonferrous metals, among which coal accounts for more than 50 % of the total coal in China. Because of its single industrial structure and traditional energy surplus, it puts great pressure on the environmental governance and sustainable development of the basin [46]. The research shows that the exploitation rate of water resources in the basin has reached 80 %, which exceeds the ecological warning line of 40 %, and, in particular, the increase in water consumption in the middle reaches leads to the decrease of flow in the lower reaches by 60 %. The shortage of water resources has become an important factor restricting the development of this region. Hence, it is necessary to consider WEF coupling and coupling efficiency to provide more macroscopic and perfecting suggestions for the combined WEF departments in this region. As for how to improve the efficiency of urban resources, China's municipal government hopes to proceed from local advantages and actively explore resource allocation policies with regional characteristics [47]. However, there is a lack of research in this field, so it is necessary to analyse WEF coupling efficiency from a spatial perspective in the YRB [48,49].

Our research has made the following contributions to the study of the WEF nexus. First, the previous literature mostly focused on the quantification of the comprehensive index of WEF coupling coordination in various regions [17,20,48]. Coupling efficiency is a key factor in measuring the effectiveness of various resource inputs under the current WEF coupling development level and measuring the optimal allocation and sustainable development of urban resources at the macro level. At present, however, only a few scholars have conducted in-depth research [8]. Existing WEF coupling efficiency, which only reflects the efficiency of each subsystem, does not include WEF as a holistic element in the category of sustainable development [39]. Some scholars also analyse the input–output efficiency of the WEF nexus but do not systematically study the coupling degree and coupling efficiency between the three elements at the same time [3]. Hence, our research on WEF coupling efficiency broadens the research horizon of the relationship between the urban WEF system and investment resources. We provide better policy suggestions for the combined departments of WEF. Second, in the previous studies, the research on the WEF nexus in the YRB was mostly concentrated in the provinces, and the research from the perspective of prefecture-level cities is scant. The existing literature only studies the characteristics of the WEF coupling degree but lacks data on WEF coupling efficiency. However, there are many cities in this basin and the development levels vary. The lack of water and energy, in particular, has caused uneven distribution and spatial and temporal dislocation of resources between cities. It is necessary to measure and analyse the difference in WEF coupling efficiency between cities within the YRB based on space. This study expands the research field scale of WEF coupling efficiency.

This study adopts a new framework to measure urban WEF coupling efficiency in the YRB. Meanwhile, taking the city's location advantages and resource endowments into account, we recommend policies to improve the efficiency of different regions, aiming at providing a macro and holistic reference for the current urban current WEF management department. To begin with, the coupling efficiency is calculated after the WEF degree of coupling is introduced into the model. In the overall model, many cities are involved, and it is self-evident that a large amount of data is collected. In addition, we use exploratory spatial data analysis (ESDA) and kernel density estimation to reveal the spatial distribution characteristics and evolutionary trends of urban WEF coupling efficiency. Finally, we formulate different policies to improve WEF coupling efficiency for different clustering areas in the YRB. From the macro level, this study provides a theoretical reference and policy basis for promoting the synergistic management of water, energy and food resources in the basin while safeguarding its ecological protection role and accelerating its high-quality development. The study of the WEF coupling efficiency in the YRB and the formulation of different clustering areas' development policies is a novel perspective on the urban sustainable development of resources, which can be useful and operational for research on the sustainable development of resources of other similar basins abroad. The study is organised as follows: Chapter 2 describes the methods and data used with respect to the WEF coupling level and coupling efficiency. Chapter 3 presents the results. Chapter 4 provides a discussion of the results. Finally, Chapter 5 presents the conclusions.

2. Materials and methods

2.1. Study area

The object of this study is the prefecture-level cities within the nine provinces of the YRB. Following the existing studies [50,51], two criteria are used to select the object of this study. First, when planning and implementing initiatives in the ecological, economic and cultural fields, policy-making can extend and consider the closely connected regions according to the actual situation, based on the principles of the integrity of ecosystems, the rationality of resource allocation and the relevance of cultural protection and promotion. Second, it follows the principles of the strategic layout of resources as outlined in the Outline of Ecological Protection and High Quality Development Plan for the YRB. Based on the above criteria, a total of 94 cities in nine provinces are selected (cities with serious data

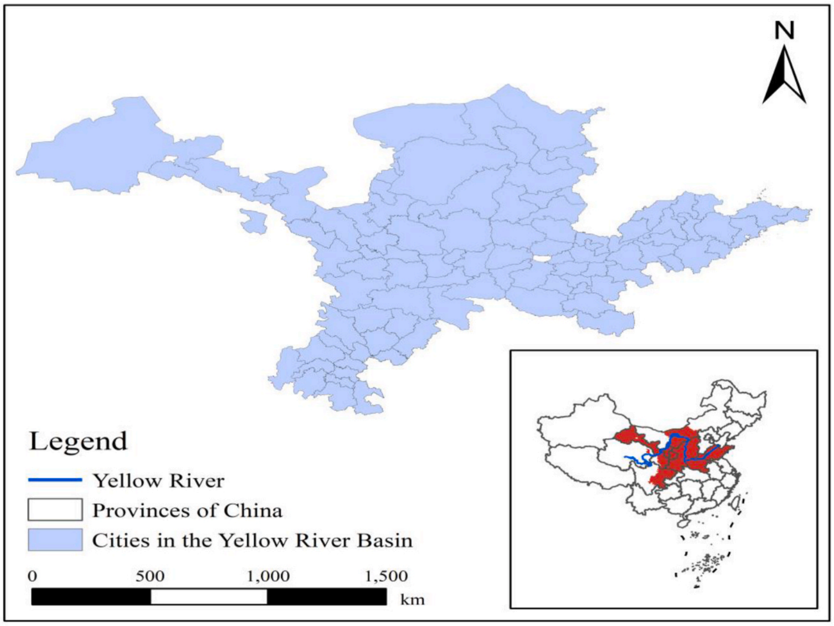

Fig. 1. Location of the study area.

deficiencies are excluded). This study period is from 2011 to 2020 and the location of the study area is shown in Fig. 1. A list of the specific cities in this study can be found in Appendix A.

2.2. Index system construction and data sources

The WEF system is a complex system consisting of three interacting subsystems: a water subsystem, an energy subsystem and a food subsystem. Referring to related research [52,53], according to the relationship between systems, this study establishes the architecture diagram of WEF coupling efficiency, as shown in Fig. 2. We divide the structure into two stages. The inner ring of the structure is the first stage. At this stage, based on the concept of the WEF system and the relationship between the three subsystems, the coupling model of the WEF system is established to calculate the coupling degree. All indicators of the water subsystem, the energy subsystem and the food subsystem are shown in Table 1. The outer ring of the structure is the second stage. At this stage, the WEF coupling degree in the first stage is taken as the desired output index, and the WEF coupling efficiency is calculated based on the data envelopment analysis (DEA) model. The input index involves many aspects such as society, economy and security, and the detailed index selection is shown in Table 2. For the input index, the data on urban food consumption are not available, so the food output is used instead of consumption as the food input index. Carbon dioxide emissions are calculated by the amount of natural gas and oil used in each city. Data used in this study are extracted from official data such as the China Urban Construction Statistical Yearbook, the Statistical Yearbook and the Statistical Yearbook of nine provinces. Data processing system software is used to estimate and supplement the missing data in some cities and years, to ensure the availability and reliability of the data. The data sources of each indicator are shown in Tables 1 and 2.

2.3. Methods

The WEF coupling efficiency of cities in the YRB from 2011 to 2020 is further calculated by using the calculation results of the WEF coupling degree. Based on the measurement results of urban WEF coupling efficiency, the spatial correlation analysis index of cities in the YRB is measured. Combining the results of the relevant analytical indices, we suggest resource sustainability strategies suitable for the different regions. Data on 94 cities in the YRB from 2011 to 2020 are analysed with MaxDEA, Geoda, ArcGIS 10.2.2 and Stata MP 17 using packages of 'super efficiency DEA based on undesired output', 'correlation analysis' and 'kernel density estimation'.

2.3.1. Urban WEF coupling degree

In the first step, the urban WEF coupling degree is measured as follows [54].

(1) Standardisation of indicators

By standardising the sample data, the effects caused by metrics of different magnitudes or orders of magnitude can be eliminated. The indicators of the WEF coupling degree index system are classified into two types according to their characteristics (positive or negative). If an indicator is positive, then the larger its value is, the better its impact on the WEF coupling degree is. Conversely, if an indicator is negative, then the smaller its value is and the better its impact on the WEF coupling degree is. The formula for indicator standardisation [46] for the WEF coupling degree index system can be described as follows.

When indicator j of the subsystem i is positive, the indicator standardisation formula is calculated as follows (Eq (1)):

$$d_{ij} = \left[x_{ij} - min\left(x_{ij}\right)\right] / \left[max\left(x_{ij}\right) - min\left(x_{ij}\right)\right] \tag{1}$$

When indicator j of the subsystem i is negative, the indicator standardisation formula is calculated as follows (Eq (2)):

$$d_{ij} = \left[max\left(x_{ij}\right) - x_{ij}\right] / \left[max\left(x_{ij}\right) - min\left(x_{ij}\right)\right] \tag{2}$$

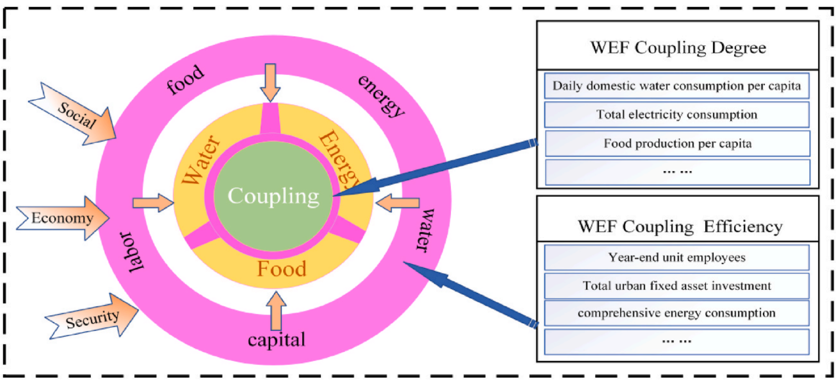

Fig. 2. WEF coupling efficiency frame diagram.

Table 1
WEF coupling degree index system.

Target layer	Indicator layer	Units	Attributes	Data resources
Water subsystem	Daily domestic water consumption per capita	L/person	–	China Urban Construction Statistical Yearbook
	Integrated water production capacity	m^3/day	+ +	China Urban Construction Statistical Yearbook
	Total water supply	10,000 m^3	+	China Urban Construction Statistical Yearbook
	Urban sewage treatment rate	%	–	China Urban Construction Statistical Yearbook
	Water consumption of million yuan GDP	m^3/10.000 ¥	–	China Urban Construction Statistical Yearbook/China Urban Statistical Yearbook/Statistical Yearbook of nine provinces
Energy subsystem	Total electricity consumption	10,000 kW h	–	China Urban Statistical Yearbook
	Natural gas supply per capita	m^3	–	China Urban Construction Statistical Yearbook/China Urban Statistical Yearbook
	Energy consumption of million yuan GDP	million tons of standard coal/ 10,000 ¥	–	Statistical Yearbook of nine provinces/China Urban Statistical Yearbook
	Energy consumption per capita	tons of standard coal/person	–	Statistical Yearbook of nine provinces/China Urban Statistical Yearbook
	Natural gas penetration rate	%	+	China Urban Construction Statistical Yearbook
Food subsystem	Food production per capita	t/person	+	Statistical Yearbook of nine provinces/China Urban Statistical Yearbook
	Power of agricultural machinery per capita	kWh/person	+	Statistical Yearbook of nine provinces
	Grain yield per ha	t/ha	+	Statistical Yearbook of nine provinces
	Food production volatility	%	–	Statistical Yearbook of nine provinces

Table 2
Level of WEF coupling efficiency index system.

Target layer		Indicator layer	Units	Data resources
Input		Urban year-end unit employees	million people	China Urban Statistical Yearbook
		Total urban fixed asset investment	million yuan	China Urban Statistical Yearbook
		Total water resources use	million tons	China Urban Statistical Yearbook
		Comprehensive energy consumption	million tons of standard coal	Statistical Yearbook of 9 provinces
		Total food production	million tons	Statistical Yearbook of 9 provinces
Output	desired output	Urban WEF coupling degree	/	Appendix A
	undesired output	Total urban wastewater discharge	million m^3	China Urban Statistical Yearbook
		Urban CO_2 emissions	million tons	China Urban Statistical Yearbook

where x_{ij} is the value of indicator j of subsystem i; max (x_{ij}) and min (x_{ij}) are the maximum and minimum values of indicator j of subsystem i during the calculation period, respectively; and d_{ij} is the efficacy index of indicator j of subsystem i. The range of values is $0 \leq d_{ij} \leq 1$; the larger the value is, the more satisfactory the index is.

(2) Subsystem efficacy index calculation

The water, energy and food subsystem efficacy index U_i is a composite consideration of the efficacy of the indicators within each subsystem. Its calculation [2] is shown as follows (Eq (3)):

$$U_i = \sum_{J=1}^{m} w_{ij} * d_{ij} \tag{3}$$

where w_{ij} is the weight coefficient of indicator j within subsystem i ($w_{ij} > 0, \sum_{J=1}^{m} w_{ij} = 1$).

(3) Weighting of indicators

The normalised entropy value assignment method [53] is used to determine the weights of each indicator w_{ij}. Assuming that there are K cities to be evaluated, n subsystems, m indicators in any subsystem and a calculation period of y years, the weighting process is divided into three steps. First, standardised indicators are transformed through normalisation, and the formula is calculated as follows (Eq (4)):

$$p_{ij}^{k} = x_{ij}^{k} \Big/ \sum_{k=1}^{K} x_{ij}^{k} \tag{4}$$

Second, the formula for calculating the indicator entropy value e_{ij} is shown as follows (Eq (5)):

$$e_{ij} = -1 / \ln(K * y) * \sum_{k=1}^{K} p_{ij}^{k} * ln\left(p_{ij}^{k}\right) \tag{5}$$

Finally, the formula for calculating indicator weights is shown as follows (Eq (6)):

$$w_{ij} = \left(1 - \exp_{ij}\right) \Big/ \sum_{j=1}^{m} \left(1 - \exp_{ij}\right) \tag{6}$$

where w_{ij} is the indicator weight of the j^{th} indicator in subsystem i.

(4) WEF coupling degree calculation

In this study, water, energy and food subsystems are involved, so the WEF coupling degree model is constructed. Referring to the model of coupling degree [55], the calculation formula is as follows (Eq (7)):

$$C = n * (U_1 * U_2 * \ldots * U_n)^{1/n} \Big/ (U_1 + U_2 + \ldots + U_n) \tag{7}$$

where C is the coupling degree and n is the number of subsystems. The range of possible C values is [0, 1]. The larger the value of C, the stronger the WEF coupling degree is. When $C = 0$, the subsystems are unrelated and moving towards disorder; when $C = 1$, the systems have achieved benign resonant coupling degree and tend to a new ordered structure.

2.3.2. Urban WEF coupling efficiency

In the second step, the WEF coupling efficiency is calculated. The evaluation of urban WEF coupling efficiency refers to the high or low level of efficiency indicators of urban WEF system in resource allocation and use, and it reflects the relative positions of regions in resource sustainable development. Using the results of the first step as the desired output index, we measure the urban WEF coupling efficiency using the DEA model based on undesired output.

The DEA model is a widely used analytical method to study the efficiency of input indicators and output indicators of decision units. It was first proposed by Charnes et al. [56] and after a series of improvements, this method gradually evolved into a system containing multiple model evaluation methods. In this study, the super-efficient DEA model based on an undesired output model is used to account for the redundancy of undesired output indicators and to avoid the problem of not being able to make cross-sectional comparisons when multiple decision units have the value of 1. The model's [57] calculation formula is shown as follows (Eq (8)):

$$\rho = min\ 1 \Big/ m \sum_{i=1}^{m} s_i^- \Big/ x_{ik} \Big/ \left[1 / (s_1 + s_2) * \left(\sum_{r=1}^{s_1} s_r^q \Big/ y_{rk}^q + \sum_{r=1}^{s_2} s_t^f \Big/ y_{tk}^f \right) \right]$$

$$s.t. \begin{cases} x_{ik} \geq x_{ij}\, \lambda_j - s_i^- \\ y_{rk}^q \leq \sum_{j=1, j \neq k}^{n} y_{rj}^q\, \lambda_j - s_r^q \\ y_{tk}^f \leq \sum_{j=1, j \neq k}^{n} y_{tj}^f\, \lambda_j - s_t^f \\ s_i^-, \lambda_j, s_r^q, s_t^f \geq 0 \end{cases} \tag{8}$$

where ρ is the efficiency value of the decision-making unit (*DMU*). The number of input indicators is m. The number of desired output indicators is s_1, and the number of undesired output indicators is s_2. The number of decision units *DMU* is n. The slack variables for the i^{th} input indicators, the r^{th} desired output indicators and the r^{th} undesired output indicators are s_i^-, s_r^q and s_t^f, respectively. The optimal number of combinations of *DMU* input indicators, desired output indicators and undesired output indicators for k decision units improved by slack variables are x_{ik}, y_{rk}^q and y_{tk}^f, respectively, where $k = 1, 2, 3, \ldots, n$. The input, desired output and undesired output indicator quantities for i, r and t of the individual decision units are x_{ij}, y_{rj}^q and y_{tj}^f, respectively; λ_j is the weight vector.

2.3.3. ESDA and classification

Based on the correlation and degree analysis of spatial sample values, the ESDA model can be used to explore the distribution characteristics of spatial correlation [58]. This study measures the global Moran's I and local Moran's I spatial correlation indices of urban WEF coupling efficiency. Spatial clustering characteristics are analysed and classified using ArcGIS 10.2.2 and Geoda.

The spatial correlation test is performed using the global Moran's I. Typically, the global Moran's I t values are in the range of [−1, 1]. When the global Moran's I > 0, it indicates a positive spatial correlation; when the global Moran's I < 0, it indicates a negative spatial correlation; and when the global Moran's I = 0, the space is random.

Global Moran's I formula [59] calculation is shown as follows (Eq (9)):

$$I_g = \sum_{i=1}^{n} \sum_{j \neq 1}^{n} W_{ij}\ z_i z_j \Big/ \sigma^2 \sum_{i=1}^{n} \sum_{j \neq 1}^{n} W_{ij} \tag{9}$$

Local Moran's I can verify the presence of spatial clustering types in the study samples [60]. When the local Moran's I > 0, it implies that 'high–high' (HH, cities with high WEF coupling efficiency are surrounded by neighbouring cities with high WEF coupling efficiency) or 'low–low' (LL, cities with low WEF coupling efficiency are surrounded by neighbouring cities with low WEF coupling efficiency) attribute values of the same type are adjacent; when the local Moran's I < 0, it indicates that 'high–low' (HL, cities with high WEF coupling efficiency are surrounded by neighbouring cities with low WEF coupling efficiency) or 'low–high' (LH, cities with low WEF coupling efficiency are surrounded by neighbouring cities with high WEF coupling efficiency) attribute values of the same type are adjacent. This adjacency creates a spatial cluster. The larger the absolute value of the index is, the clearer the cluster effect is.

Local Moran's I formula [3] calculation is shown as follows (Eq (10)):

$$I_l = z_i \sum_{j \neq 1}^{n} W_{ij}\, z_j \tag{10}$$

where W_{ij} denotes the weight matrix. x_i denotes the WEF coupling efficiency value for the i city in the YRB; n is the number of cities; z_i is the standardised transformation of x_i, $z_i = (x_i - \overline{x})/\sigma$, $\overline{x} = 1/n\sum_{i=1}^{n} x_i$, $\sigma^2 = 1/n \sum_{i=1}^{n} (x_i - \overline{x})^2$; and z_j is a similar denotation to z_i.

Table 3
Group category classification criteria.

Group category	Explanation
High-clustering group	Cities with HH attribute values
Low-clustering group	Cities with LL attribute values
Median contiguous group	Other cities that are not part of the HH and LL attribute values

Local Moran's I clustering attribute [61] values of WEF coupling efficiency of 94 cities in the YRB are used to classify their clustering group categories into different groups. Following the method of Cheng [2], 94 cities in the YRB are classified into a high-clustering group, low-clustering group and a median contiguous group (Table 3).

2.3.4. Kernel density estimation

Kernel density estimation dynamic evolution is analysed using Stata MP 17.

The kernel density estimation model is a nonparametric estimation method, which has outstanding advantages compared to parametric estimation. This estimation method can study the characteristics and distribution of data itself, without using prior knowledge of data distribution and other assumptions, so it is highly valued in statistical theory and application fields. Generally, this method [62] assumes that the density function of random variable X is as follows (Eq (11)):

$$f(x) = 1 / (nh) * \sum_{i=1}^{n} K((X_i - x) / h) \tag{11}$$

where n denotes the number of samples, h denotes the bandwidth, k denotes the core density, X_i denotes the coupling efficiency value of urban WEF and x denotes the average value of WEF coupling efficiency. Meanwhile, the core density function needs to meet the following conditions (Eq (12)):

$$s.t. \begin{cases} \lim_{n\to\infty} K(x) * x = 0 \\ K(x) \geq 0 \int_{-\infty}^{+\infty} K(x)dx = 1 \\ \sup K(x) < +\infty \int_{-\infty}^{+\infty} K^2(x)dx < +\infty \end{cases} \tag{12}$$

The Gaussian kernel density estimation model is used in this study. Generally, the larger the bandwidth is, the smoother the kernel density distribution curve is, but the accuracy is lower. In contrast, the smaller the bandwidth is, the less smooth the kernel density distribution curve is, but the accuracy is higher. Therefore, to maintain high accuracy, this study uses a smaller bandwidth. The distribution curve obtained by the kernel density estimation model can be used to observe the characteristics of the urban WEF coupling efficiency, such as distribution shape, extension degree and location.

3. Results

3.1. Urban WEF coupling degree in the YRB

According to Eqs. (1)–(6), the efficacy of the water subsystem (WD), the energy subsystem (ED) and the food subsystem (FD) are calculated. Then the water–energy system coupling degree (WED), the water–food system coupling degree (WFD), the energy–food system coupling degree (EFD) and the WEF system coupling degree (WEFD, Appendix A) are calculated by Eq. (7). The annual average value results are shown in Fig. 3.

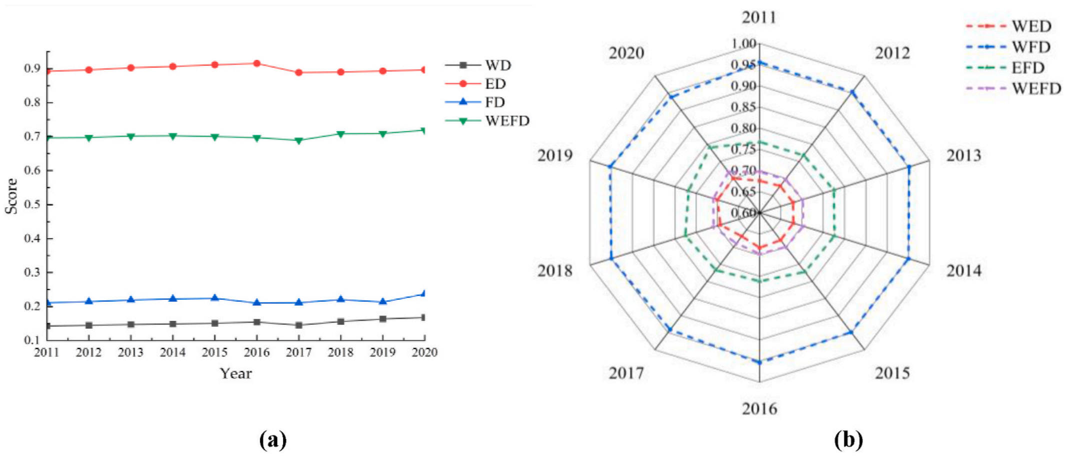

Fig. 3. Changing trend of (a) the water subsystem (WD), the energy subsystem (ED), the food subsystem (FD) and the WEF coupling degree (WEFD) and (b) the water–energy system coupling degree (WED), the water–food system coupling degree (WFD), the energy–food system coupling degree (EFD) and the WEF system coupling degree (WEFD).

3.2. Urban WEF coupling efficiency in the YRB

3.2.1. Evolution of urban WEF coupling degree and coupling efficiency

According to the WEF coupling efficiency model, the WEF coupling efficiency (WEFCE) of cities in the YRB is calculated (Appendix B). The annual average value change trend of the WEF coupling degree (WEFD) and the WEF coupling efficiency is shown in Fig. 4. The urban WEF coupling efficiency in the YRB has been improved, but it is still not optimal.

3.2.2. Changing trends of urban WEF coupling efficiency

The development speed of urban WEF coupling efficiency in the YRB is not consistent. As shown in Fig. 5, Appendix B, there are significant differences in the efficiency of different cities. The maximum efficiency value appears in Chengdu (0.2007) in 2016, and the minimum value appears in Jincheng in 2019 (1.5000). Likewise, the urban WEF coupling efficiency also presents different development trends. The WEF coupling efficiency of Ankang, for example, decreased from 0.6771 in 2011 to 0.6755 in 2020, while the WEF coupling efficiency of Anyang and Bayannaoer is on the rise. Different socioeconomic, geographical and resource conditions have affected the urban WEF coupling efficiency in the YRB. The annual average of the WEF coupling efficiency in 2011, 2014, 2017 and 2020 are 0.5756、0.0.5623、0.5836 and 0.6016, with a 4.52 % rate of change (Fig. 5(a–d)). The annual average change rate of WEF coupling efficiency in 94 cities from 2011 to 2020 is about 7.65 %. However, the annual change rate of efficiency in different cities ranges from −53.10 % to 75.22 %, and the absolute difference exceeds 1. Thus, it is necessary to explore the spatial correlation of cities.

3.3. Spatial correlation analysis of WEF coupling efficiency and its classification

3.3.1. Global Moran's I

Based on the geographic coordinates of cities in the YRB, the linear distance weight matrix is constructed. Then, we calculate the global Moran's I of coupling efficiency of 94 cities from 2011 to 2020 (Table 4). Global Moran's I is positive at a significance level of 1 % and reaches a maximum in 2012 (0.369), indicating that urban WEF coupling efficiency in the YRB has a positive spatial clustering effect. Cities with high coupling efficiency tend to be close to other cities with high coupling efficiency; similarly, cities with low coupling efficiency tend to be close to other cities with low coupling efficiency.

3.3.2. Local Moran's I scatter plots

The local Moran's I of the WEF coupling efficiency for cities in 2011, 2014, 2017 and 2020 are 0.277, 0.264, 0.335 and 0.315, respectively ($p < 0.01$) (Fig. 6(a–d), where the first, second, third and fourth quadrants represent HH, LH, LL and HL clustering areas, respectively). The corresponding points are mostly concentrated in quadrants one (high–high clustering, HH) and three (low–low clustering, LL). The data indicate that cities and their neighbouring cities show similar clustering characteristics and cities with high coupling efficiency are adjacent to each other in space (The calculation results and specific city code are shown in Appendix C).

3.3.3. Local LISA cluster and classification

The local Moran's I spatial autocorrelation (LISA) cluster map demonstrates the spatial clustering of urban WEF coupling efficiency in the YRB. (Fig. 7). Fig. 7(a–d) shows that the number of both HH cluster and LL cluster are 41, 43, 48 and 46 in 2011, 2014, 2017 and 2020 respectively. Among them, the HH clusters are mainly distributed in Ningxia and Gansu Provinces of upper YRB, which is a less developed region. The LL cluster is distributed in Shandong and Henan provinces, which is a developed region. Based on spatial clustering characteristics, three different groups of urban WEF coupling efficiencies are formed. The first group is the high-clustering area of urban WEF coupling efficiency surrounded by multiple HH cities. The second group is the low WEF coupling efficiency clustering area surrounded by multiple LL cities. The third group is a median contiguous area of multiple other cities excluding HH and

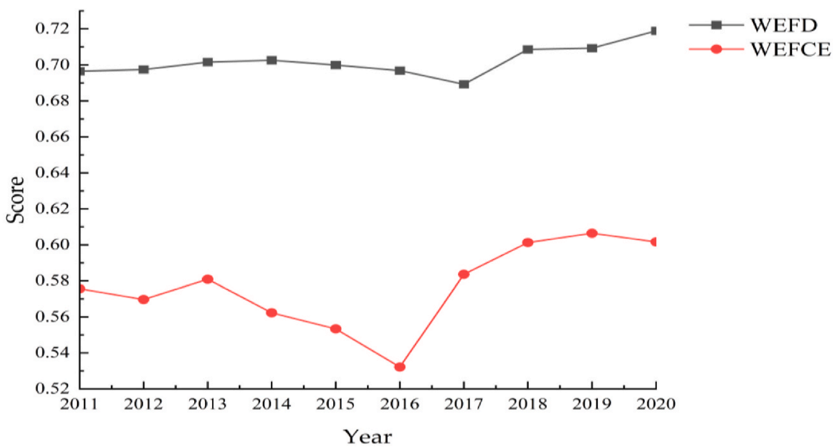

Fig. 4. Changing trend of urban WEF coupling degree and coupling efficiency in the YRB.

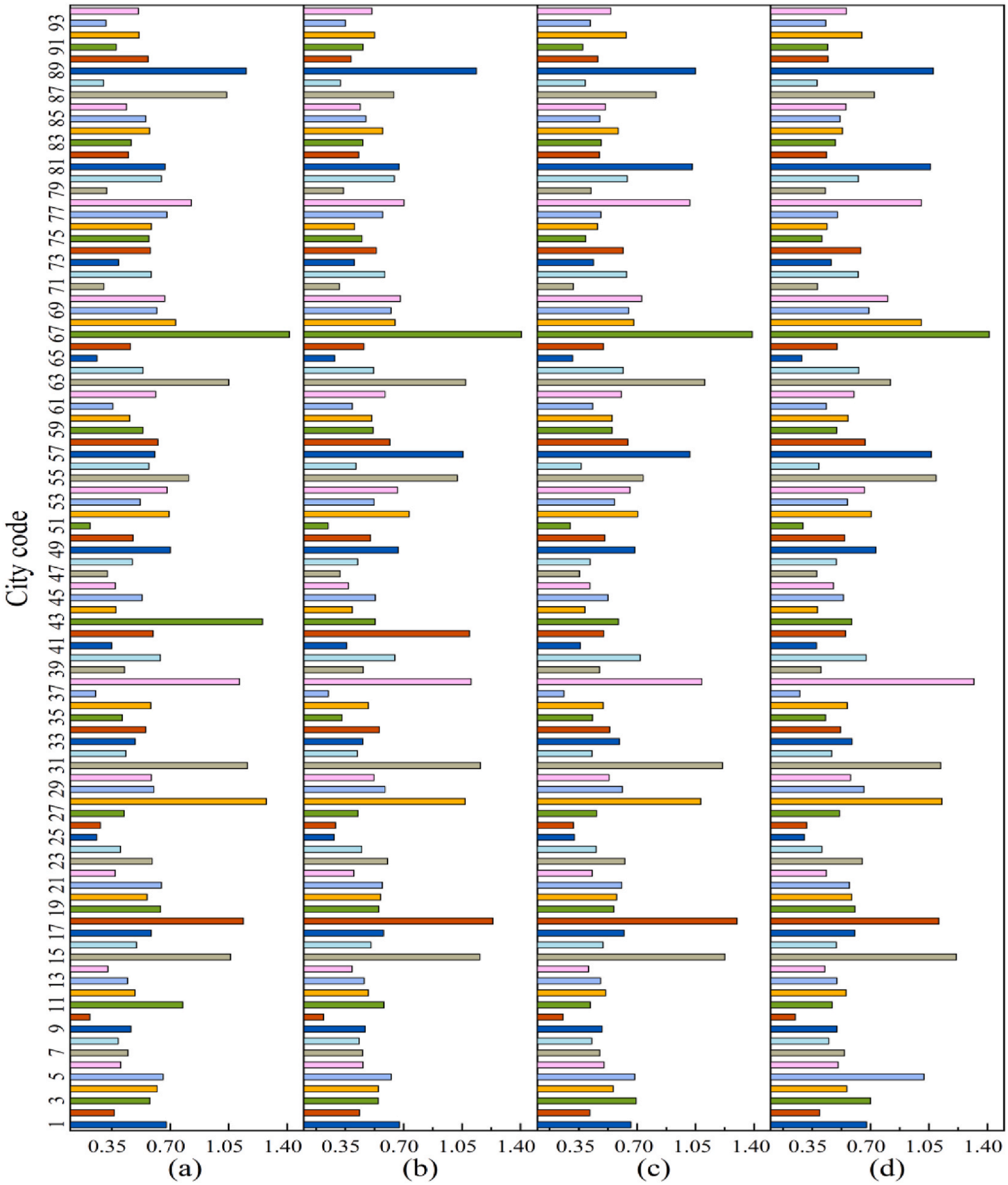

Fig. 5. Values of urban WEF coupling efficiency in (a) 2011, (b) 2014, (c) 2017 and (d) 2020.
*Note: owing to the position limitation in the figure, the city codes in the vertical axis only show cardinal items, not even items. See Appendix A for the cities represented by all codes.

LL cities. Among the 94 cities in the YRB, 17 in the high-clustering group account for 18.09 % of all cities, while 32 (34.04 %) are in the low-clustering group and 45 (47.87 %) are designated as median contiguous group cities (Table 5, Appendix C).

3.4. Dynamic spatial evolution of WEF coupling efficiency

We use the Stata MP 17 to produce the spatial dynamic evolution of urban WEF coupling efficiency for different groups in 2011, 2014, 2017 and 2020 (Fig. 8). The curves in Fig. 8(a) and (b) shift to the right, while the curve in Fig. 8(c) remains stable. Fig. 8(a) clearly shows that the height of the main peak decreases with time and the height of the secondary peak increases with time. In contrast, the height of the main peak in the curves in Fig. 8(b) and (c) increases with time. Notably, the curve in Fig. 8(c) shows a secondary peak in 2020.

Table 4
Global Moran's I for the urban WEF coupling efficiency, 2011–2020.

Year	Moran's I	Z
2011	0.268***	7.544
2012	0.369***	10.363
2013	0.275***	7.591
2014	0.241***	6.814
2015	0.294***	8.470
2016	0.326***	9.389
2017	0.303***	8.697
2018	0.236***	0.996
2019	0.284***	8.095
2020	0.280***	8.149

Note: *, ** and *** denote significance at the 10 %, 5 % and 1 % levels, respectively.

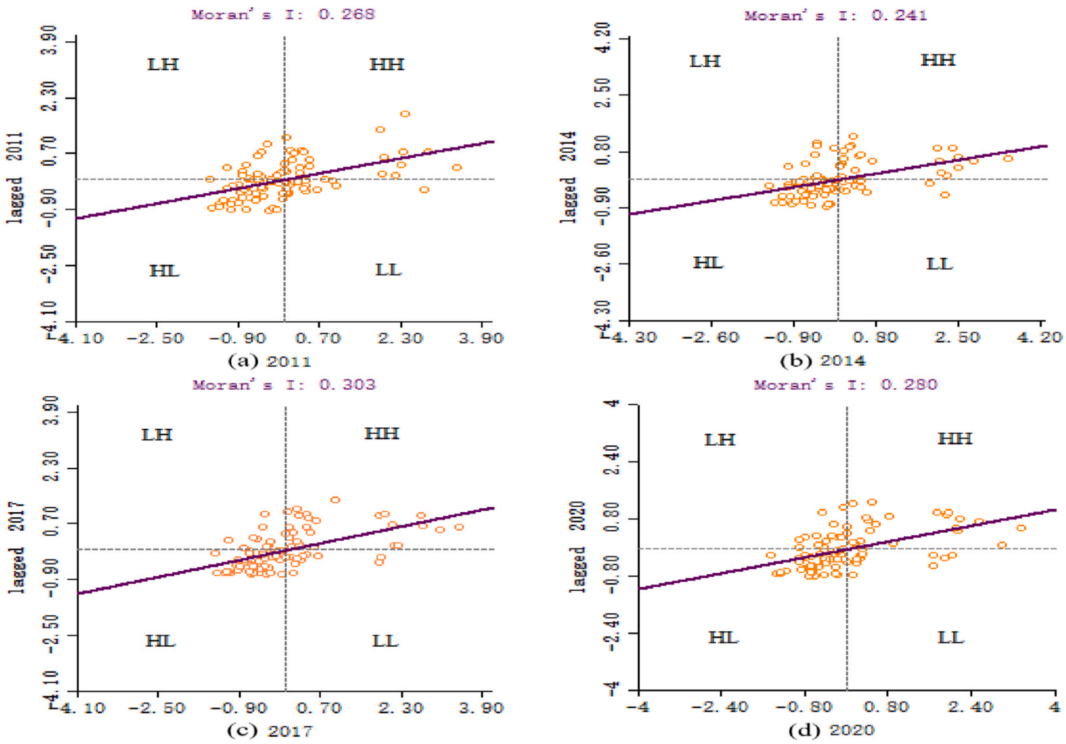

Fig. 6. Moran's I scatter plots of urban WEF coupling efficiency in (a) 2011, (b) 2014, (c) 2017 and (d) 2020.

4. Discussion

Fig. 3(a) shows that the energy subsystem has the highest efficacy score, followed by the food subsystem and the water subsystem, which has the lowest score. Fig. 3(b) shows that WFD has the highest score, followed by EFD and WED, which has the lowest score. According to the coupling degree model, the coupling degree depends on the relationship between subsystem efficacy scores. The closer the subsystem efficacy score is, the higher the coupling degree of the system is. Similarly, the greater the efficacy gap between subsystems is, the lower the coupling degree of the system is. We can conclude that the water and food subsystems develop synchronously, but the WEF system is destroyed. The competition index of energy development and food production for water in the YRB is at a high level (0.8), and this competition contradiction is severe [63]. Meanwhile, the shortage of sewage-absorbing bodies in coal and oil areas in the basin has caused the problem of water resources replenishment. As a result, food, as a social product, is more flexible in regulating the relationship between water and energy [18]. The increase in the WEF coupling degree shows that this contradiction has eased, and energy has become a factor restricting the WEF system of cities in the YRB.

WEF coupling efficiency reflects the effectiveness of various resources under the current coupling degree, that is, the quality relations of WEF. In individual years, the coupling degree increases but the efficiency decreases, that is, the phenomenon of resource curse appears (Fig. 4). This shows that excessive dependence on resources will adversely affect the decision-making development of

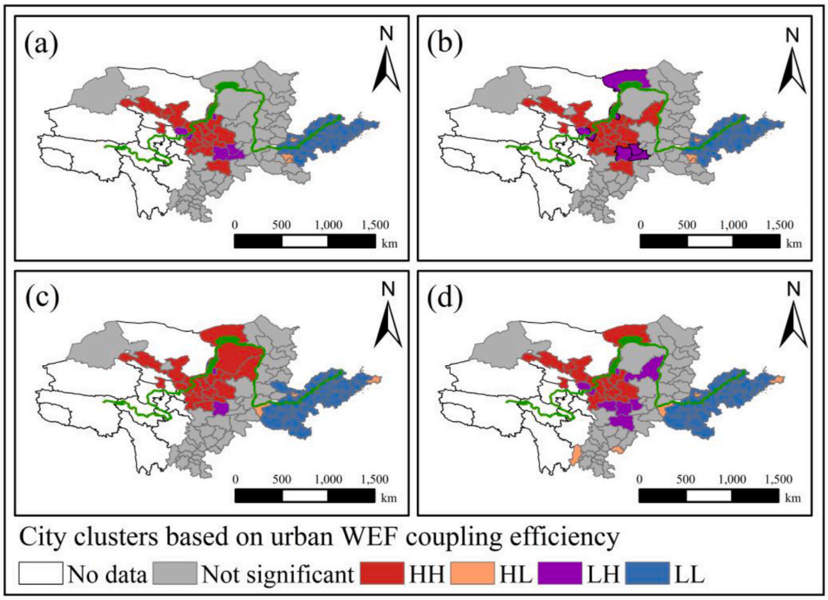

Fig. 7. LISA cluster map of urban WEF coupling efficiency in (a) 2011, (b) 2014, (c) 2017 and (d) 2020.

Table 5
Group category classification criteria.

Group category	Numbers	Proportion	Explain
High-clustering group	17	18.09 %	HH clustering city
Low-clustering group	32	34.04 %	LL clustering city
Median contiguous group	45	47.87 %	HH clustering city

combined WEF departments. The key to breaking the resource curse is to adjust the distribution and optimisation of regional resource elements [64]. The spatial characteristics and evolution trend of efficiency value are very important to understanding the flow of resource elements. The development trend of WEF coupling efficiency and self-efficiency among YRB cities is different (Fig. 5). This difference is caused by geographical location, resource endowment and economic development level [65]. This has been confirmed by previous studies. Morán-Valencia et al. hold that the low efficiency of the water system in Oaxaca, Mexico is related to the local socioeconomic characteristics [66]. Furthermore, Zhang et al. indicate that water efficiency varies greatly with forest types, environmental conditions and management practices [67].

Global Moran's $I > 0$ ($p < 0.01$; 0 means the space is random), which indicates that the urban WEF coupling efficiency of the YRB has a positive spatial clustering effect. That is, cities with high coupling efficiency are often close to other cities with high coupling efficiency, and cities with low coupling efficiency are often close to other cities with low coupling efficiency. Previous studies have pointed out that the WEF nexus in the YRB has obvious spatial correlation characteristics [49,52]. We can use the distribution pattern of space and resource endowment to put forward targeted measures for sustainable urban development [48]. In Fig. 6, the number of cities with an HH cluster and an LL cluster is relatively large, showing positive spatial autocorrelation. There are 38 cities and 43 cities in the first and third quadrants in 2011 and 2020, respectively. The proportion of samples increases from 40.43 % to 45.74 %. The data show that cities and neighbouring cities present similar clustering characteristics, and cities with high coupling efficiency are adjacent in space. In space, the urban WEF coupling efficiency forms two different clustering areas (Fig. 7). Based on the characteristics of spatial clustering, cities are divided into three groups. First, the high-clustering group including Zhongwei, Baiyin and Guyuan is mainly distributed in the economically underdeveloped areas in the upper basin. Second, the low-clustering group, including Jinan, Kaifeng and Heze, is mainly distributed in the economically developed lower basin. Third, the median contiguous group including Changzhi, Datong and Jincheng is mainly concentrated in the middle basin. The characteristics of spatial clusters show that the WEF coupling efficiency of cities in the YRB is not completely determined by random factors, and the spatial spillover effect plays a role in its formation [68]. For different coupling efficiency clusters, the policies to improve WEF coupling efficiency, optimise resource allocation and realise sustainable development are different. The evolution trend of different groups from 2011 to 2020 is shown in Fig. 8. The evolution trend varies between groups. Among them, the differentiation of efficiency values among cities in the high-clustering group is increased, and the polarisation is serious, while that in the low-clustering group is the opposite. The WEF coupling efficiency of the middle contiguous group remains stable, the difference in efficiency values between cities narrows and a new efficiency growth point appears in 2020.

These results have confirmed that there are differences in the WEF nexus between regions in the YRB. However, most of the results

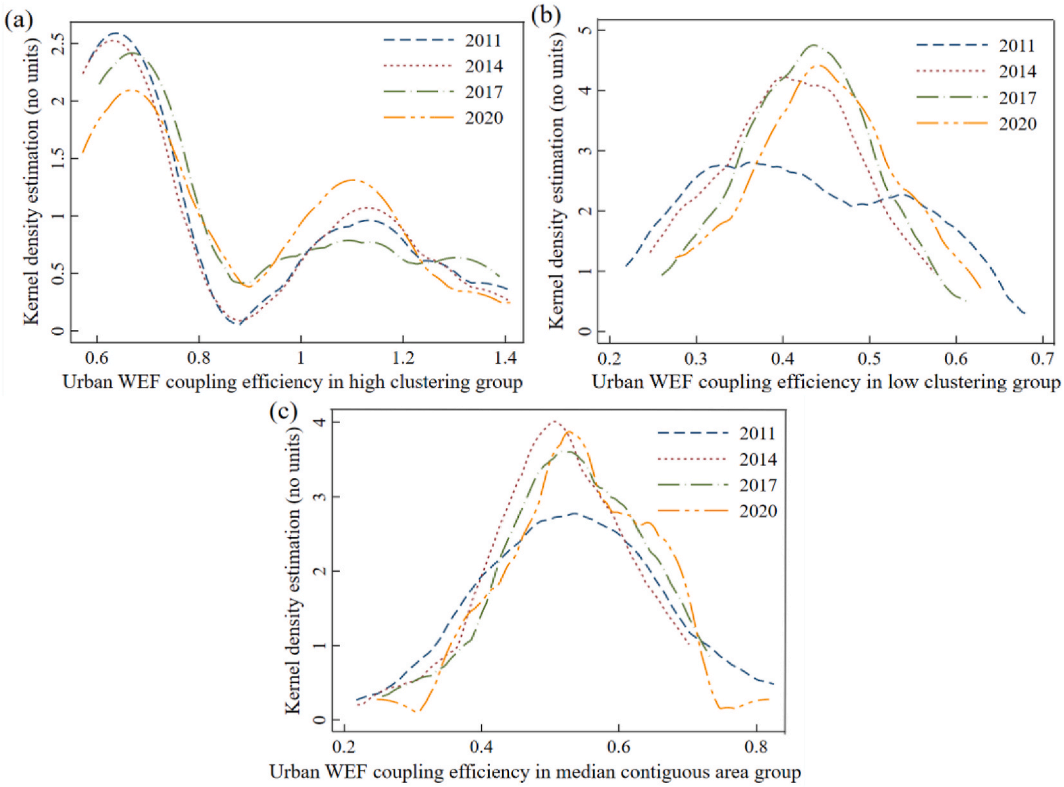

Fig. 8. Spatial dynamic evolution of urban WEF coupling efficiency in (a) the high-clustering group, (b) the low-clustering group and (c) the median contiguous group.

focus on the study of the interaction and trade-off between subsystems and almost ignore the effect of resource factors on the WEF nexus, that is, these studies ignore WEF nexus efficiency. In addition, due to the lack of attention regarding WEF coupling efficiency, there is limited research on the spatial distribution characteristics and evolution trend of WEF coupling efficiency. The construction of the WEF coupling efficiency model in the YRB in this study is conducive to studying the effect and influence of economic and social resources invested by cities in the basin on the holistic WEF nexus The current WEF nexus provides a reference for other countries and regions in the world to improve the spatial adjustment and optimisation of social and economic resources.

Based on the above analysis and discussion, according to the different resource endowments and development levels of the YRB, the following suggestions are proposed for different clustering groups in the basin to improve the WEF coupling efficiency and realise the optimal allocation of resources.

The weaker industries and economies of cities in the high-clustering group restrict technology and scale development, thus creating pressure on regional security of water and food resources [69–72]. However, due to its important food and energy production status and good ecological cycle, it has clear advantages in the use of resources such as labour, food, green development and ecological water [46,73–75]. At the same time, the polarisation of urban WEF coupling efficiency in the high-clustering group is serious, so it is especially important to improve the specialisation of cities. Therefore, first, cities in the high-clustering group should alleviate the pressure of resource security, take resource conservation as the main constraint and reduce the amount of water used in agriculture and industry through the innovation of production technology. Second, cities in the high-clustering group, while making full use of their rich resource advantages, could improve infrastructure, build large hydropower stations and return farmland to forest and grazing, etc. They could also promote the extension of the city's resource advantages to the periphery and smooth the platform of resource sharing and cooperation with other cities to improve the WEF coupling efficiency of neighbouring cities.

The low-clustering group of cities is mostly concentrated in developed regions, where urban WEF coupling efficiency has improved. With the rapid rise of emerging high-tech industries and geographical advantages, this group of cities has made some achievements in economic development [76] and technological innovation [75,77]. However, studies have equally confirmed the shortcomings of these cities in sectors such as ecological and environmental management [60,78]. It can be seen that the blind pursuit of rapid economic development may result in the sustainable development of cities not keeping pace with the economic growth rate [79]. Therefore, first, cities in the low-clustering group should consider inter-sectoral cooperation approaches to increase the output of resources such as labour and capital to improve efficiency. Second, reducing pollutant emissions and improving the quality of ecological and environmental management will also be the focus of sustainable development in the low-clustering group. In addition, cities in the low-clustering group can develop an open cooperation model in multiple resource areas by carrying out a joint interaction with the high-clustering group. The ultimate goal of these measures is to accelerate the improvement of urban WEF coupling efficiency in the low-clustering group.

More than one-third of the cities in the YRB are in the median contiguous group, so it is equally worthwhile to pay attention to how to improve the efficiency of WEF coupling in this region. These cities in the median contiguous group are mostly concentrated in Shanxi, Shaanxi and Sichuan. These provinces are famous for their concentration on coal and chemical industries in China. According to the statistics, in 2022, Shanxi and Shaanxi rank first and third, respectively, in coal production. High energy consumption and highly polluting industries are the main obstacles to the green development of the region. Therefore, promoting the green development of urban industries in the median contiguous group is an indispensable element of achieving regional sustainable development [80]. In addition, research shows that Shanxi is similarly in the median transition region of two-level differentiation in terms of ecological efficiency [81], a high-quality urban development level [82] and efficient use of agricultural water [83]. Compared with the low-clustering group, the median contiguous group has more obvious advantages in receiving high-efficiency diffusion and, thus, can quickly absorb high-efficiency spillover effects from the periphery. For the median contiguous group, taking advantage of this acceptance and absorption to promote the green development of the industry is also one of the measures to achieve a rapid increase in the efficiency of its WEF coupling. In addition, in recent years, localised high-efficiency clustering has emerged in the median contiguous group. The emergence of sub-cluster centres with high efficiency in the median contiguous group helps to nurture new central cities and form new high-clustering centres. Based on this, the diffusion advantage of the central cities can be further expanded by nurturing new central cities and exerting demonstration effects.

5. Conclusion

Water, energy and food interact to form a complex nexus system. At the current level of system function, the effectiveness of investment in economic and social resources needs to be reflected in the policy-making process that guides these resource management departments. Defining the input–output efficiency of resources is the key to realising the optimal allocation of resources and sustainable development. In this study, a model framework for quantifying WEF coupling efficiency is constructed. It provides the efficient use of resources under the current WEF nexus level and can be used as the basis for the combined WEF departments to guide the management strategy. The model needs to be further improved to measure the efficiency between subsystems. Then, according to the needs of other countries and regions in the world, the model is modified and applied, which provides a reference for the combined WEF departments to realise the optimal allocation and adjustment of resources in the region.

The study on the WEF coupling efficiency of 94 cities in the YRB shows that the energy subsystem restricts the development of the WEF nexus. Simultaneously, the food subsystem has become an important factor in regulating the WEF nexus. The phenomenon of the resource curse appears in some years. Thus, adjusting the spatial allocation of resources has become the key to solving this problem. The spatial correlation analysis and kernel density estimation analysis can effectively reveal the uneven spatial distribution and dynamic evolution characteristics of urban WEF coupling efficiency in the YRB. The results show that there are differences in the WEF coupling efficiency of cities in the YRB. The HH cluster is mainly concentrated in less developed regions and the LL cluster is mainly concentrated in developed regions. For clusters with different coupling efficiencies, such as high-clustering, low-clustering and median contiguous groups, the policies for improving urban WEF coupling efficiency and realising the sustainable development of resources are also different. For the high-clustering group, we should mainly save resources and ease the pressure on resources. In addition, the government should actively promote cross-city cooperation to expand the city's resources and location advantages. Regarding the low-clustering group, the government can also develop a joint interaction with the high-clustering group to form an open cooperation model with multiple resource departments while paying attention to improving the level of ecological management. For the median contiguous group, the government should focus on the cultivation of new central cities and promote the green development of industries (e.g. the coal industry).

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Data availability statement

All data are fully available without restriction. The datasets are taken from several public repository, the China Urban Construction Statistical Yearbook (https://cnki.ctbu.edu.cn/CSYDMirror/yearbook/Single/N2023010064), the China Urban Statistical Yearbook (https://cnki.ctbu.edu.cn/CSYDMirror/Yearbook/Single/%20N2022040095), the Qinghai Statistical Yearbook (http://tjj.qinghai.gov.cn/tjData/qhtjnj/), the Gansu Statistical Yearbook (https://tjj.gansu.gov.cn/tjj/c109464/info_disp.shtml), the Sichuan Statistical Yearbook (https://tjj.sc.gov.cn/scstjj/c105855/nj.shtml), the Ningxia Statistical Yearbook (https://nxdata.com.cn/publish.htm?cn=G01), the Inner Mongolia Statistical Yearbook (https://tj.nmg.gov.cn/tjyw/), the Shaanxi Statistical Yearbook (http://tjj.shaanxi.gov.cn/tjsj/ndsj/tjnj/), the Shanxi Statistical Yearbook (https://tjj.shanxi.gov.cn/tjsj/tjnj/), the Henan Statistical Yearbook (https://tjj.henan.gov.cn/tjfw/tjcbw/tjnj/) and the Shandong Statistical Yearbook (http://tjj.shandong.gov.cn/col/col6279/index.html).

CRediT authorship contribution statement

Yun Zhang: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yuping Wu:** Visualization, Validation, Supervision, Resources, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Zhaohan Lu:** Software, Investigation, Data curation. **Ling Li:** Software, Investigation, Data curation. **Peng Wang:** Validation, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

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

Appendix A

Table A
Urban WEF coupling degree in YRB from 2011 to 2020.

City	Code	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Ankang	1	0.5703	0.5860	0.6318	0.6072	0.5860	0.5917	0.5587	0.5977	0.5772	0.6225
Anyang	2	0.7753	0.7824	0.7827	0.7735	0.7827	0.7809	0.7686	0.7864	0.7864	0.7736
Bayanzhor	3	0.6860	0.6865	0.6945	0.7124	0.7172	0.7118	0.7426	0.7441	0.7513	0.7421
Bazhong	4	0.6148	0.6168	0.6163	0.6130	0.6353	0.6305	0.6088	0.6461	0.6405	0.6535
Baiyin	5	0.7167	0.7169	0.7077	0.7128	0.7185	0.7055	0.7133	0.7438	0.7071	0.7285
Baotou	6	0.7433	0.7491	0.7506	0.7885	0.8056	0.8068	0.8030	0.8421	0.8692	0.8477
Baoji	7	0.6387	0.6150	0.6476	0.6536	0.6134	0.6487	0.6557	0.6597	0.6666	0.6898
Binzhou	8	0.7598	0.7572	0.7501	0.7661	0.7887	0.7812	0.8390	0.8671	0.8544	0.8584
Changzhi	9	0.7050	0.6949	0.6903	0.6881	0.6819	0.6747	0.6425	0.6644	0.6151	0.6507
Chengdu	10	0.7625	0.7560	0.7614	0.7637	0.7649	0.7464	0.7376	0.7354	0.7555	0.6973
Dazhou	11	0.6252	0.6674	0.6564	0.6652	0.6553	0.6733	0.6815	0.6835	0.6873	0.6939
Datong	12	0.6424	0.6507	0.6556	0.6669	0.6792	0.6703	0.6747	0.6922	0.6924	0.6940
Deyang	13	0.6763	0.6814	0.6897	0.6905	0.6908	0.6789	0.6778	0.7053	0.6820	0.7020
Dezhou	14	0.7459	0.7706	0.7701	0.7821	0.7892	0.7836	0.7707	0.8003	0.8025	0.7927
Dingxi	15	0.6717	0.6723	0.6825	0.6729	0.6724	0.6372	0.6207	0.6544	0.6647	0.6834
Dongying	16	0.7827	0.7816	0.7815	0.7959	0.8003	0.8077	0.8231	0.8645	0.8284	0.8219
Ordos	17	0.7639	0.7531	0.7534	0.7404	0.7375	0.7393	0.8041	0.7936	0.8049	0.7957
Guyuan	18	0.6627	0.6948	0.6752	0.6956	0.7201	0.7052	0.6905	0.6823	0.6641	0.6922
Guang'an	19	0.6404	0.6242	0.6240	0.6238	0.6290	0.6383	0.6155	0.6405	0.8138	0.8489
Guangyuan	20	0.6440	0.6475	0.6594	0.6608	0.6619	0.6635	0.6404	0.6377	0.6626	0.6924
Hanzhong	21	0.5798	0.5800	0.5779	0.5769	0.5913	0.5888	0.5547	0.6047	0.5755	0.6202
Heze	22	0.6912	0.6920	0.6983	0.7131	0.7107	0.7008	0.6976	0.7064	0.7397	0.7689
Hebi	23	0.7458	0.7489	0.7435	0.7314	0.7281	0.7202	0.7026	0.7147	0.7354	0.7444
Hohhot	24	0.7329	0.7354	0.7435	0.7416	0.7420	0.7348	0.7662	0.7958	0.7955	0.7760
Jinan	25	0.8317	0.8314	0.8255	0.8286	0.8282	0.8251	0.8207	0.8472	0.8224	0.8138
Jining	26	0.7578	0.7560	0.7759	0.7775	0.7797	0.7686	0.7614	0.7558	0.7940	0.7816
Jiaozuo	27	0.7677	0.7708	0.7703	0.7673	0.7659	0.7431	0.7260	0.7567	0.7916	0.8010
Jinchang	28	0.7851	0.7842	0.7668	0.7625	0.7547	0.7443	0.7249	0.7443	0.7707	0.7779
Jincheng	29	0.6803	0.6891	0.6681	0.6502	0.6663	0.6374	0.6109	0.6328	0.5827	0.6034
Jinzhong	30	0.6672	0.6740	0.6859	0.6972	0.6947	0.6799	0.6460	0.6767	0.6560	0.6636
Jiuquan	31	0.6913	0.7009	0.6901	0.6968	0.6969	0.6912	0.6724	0.7073	0.7204	0.7189
Kaifeng	32	0.7617	0.7668	0.7528	0.7573	0.7588	0.7414	0.7304	0.7454	0.7467	0.7605
Lanzhou	33	0.6807	0.6950	0.6683	0.6891	0.7146	0.6818	0.6609	0.6874	0.6936	0.6593
Leshan	34	0.6471	0.6521	0.6459	0.6405	0.6393	0.6492	0.6582	0.6999	0.6981	0.7168
Liaocheng	35	0.7281	0.7282	0.7297	0.7299	0.7305	0.7304	0.7326	0.7433	0.7868	0.7805
Linfen	36	0.6677	0.6761	0.6772	0.6875	0.6748	0.6599	0.6453	0.6668	0.6415	0.6560
Linyi	37	0.7321	0.7416	0.7349	0.7389	0.7431	0.7256	0.7637	0.7826	0.7654	0.7655
Longnan	38	0.6858	0.6589	0.6525	0.6673	0.6675	0.5903	0.5532	0.5827	0.5876	0.5999
Luzhou	39	0.7236	0.7227	0.7281	0.7310	0.7353	0.7405	0.7436	0.7544	0.7589	0.7440
Lvliang	40	0.8043	0.8021	0.7543	0.7449	0.7512	0.7392	0.7259	0.7413	0.7510	0.7740
Luoyang	41	0.7024	0.7017	0.7207	0.7214	0.7330	0.7390	0.7086	0.7301	0.7346	0.7426
Luohe	42	0.5942	0.5966	0.6056	0.6091	0.5521	0.5569	0.5380	0.5860	0.5587	0.5901
Meishan	43	0.6257	0.6385	0.6394	0.6425	0.6428	0.6452	0.6235	0.6649	0.6663	0.6781
Mianyang	44	0.6658	0.6674	0.6860	0.6866	0.6887	0.6950	0.6981	0.7046	0.7114	0.7320
Neijiang	45	0.6409	0.6338	0.6464	0.6372	0.6271	0.6220	0.6129	0.6542	0.6449	0.6667
Nanchong	46	0.6222	0.6325	0.6369	0.6404	0.6441	0.6469	0.6285	0.6518	0.6725	0.7046
Nanyang	47	0.7487	0.7760	0.7964	0.7835	0.7977	0.7913	0.7773	0.7711	0.7674	0.7842
Pingdingshan	48	0.7523	0.7225	0.7204	0.6848	0.7206	0.7130	0.6883	0.7137	0.7292	0.7246
Pingliang	49	0.6368	0.6465	0.6482	0.6417	0.6375	0.6225	0.5853	0.6331	0.6314	0.6586

(continued on next page)

Table A (*continued*)

City	Code	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Puyang	50	0.7281	0.7302	0.7311	0.7334	0.7239	0.7343	0.7109	0.7358	0.7357	0.7549
Qingdao	51	0.8103	0.7625	0.8238	0.8261	0.8336	0.8168	0.8308	0.8045	0.8457	0.8251
Qingyang	52	0.6270	0.6433	0.6478	0.6506	0.6482	0.6317	0.6126	0.6373	0.6367	0.6493
Rizhao	53	0.7119	0.7076	0.7022	0.7012	0.6969	0.7009	0.7121	0.7644	0.7234	0.7373
Sanmenxia	54	0.6370	0.6402	0.6269	0.6265	0.6516	0.6191	0.6097	0.6322	0.6307	0.6401
Shangluo	55	0.5692	0.5172	0.5549	0.5882	0.5452	0.6044	0.5711	0.5249	0.5340	0.5559
Shangqiu	56	0.7672	0.7648	0.7638	0.7540	0.7610	0.7411	0.7299	0.7399	0.7400	0.7554
Shizuishan	57	0.7331	0.7836	0.7938	0.8054	0.8022	0.7884	0.8334	0.8486	0.8330	0.8513
Shuozhou	58	0.6923	0.6993	0.7075	0.7120	0.7096	0.6992	0.6826	0.7042	0.6938	0.7101
Suining	59	0.6413	0.6528	0.6550	0.6554	0.6569	0.6392	0.6051	0.6482	0.6486	0.6677
Taiyuan	60	0.6560	0.6786	0.6817	0.6916	0.6755	0.6499	0.6466	0.6350	0.5733	0.5780
Tai'an	61	0.7006	0.7033	0.7015	0.7010	0.7021	0.6902	0.6987	0.7173	0.7127	0.7126
Tianshui	62	0.6042	0.6119	0.6045	0.6199	0.6303	0.6044	0.6033	0.6043	0.6164	0.6455
Tongchuan	63	0.6250	0.6068	0.6536	0.6285	0.5936	0.6119	0.6217	0.6369	0.6414	0.6688
Weihai	64	0.7411	0.7404	0.7350	0.7565	0.7544	0.7387	0.7349	0.7123	0.7347	0.7406
Weifang	65	0.7802	0.7859	0.7870	0.7817	0.7793	0.7598	0.7733	0.7794	0.7921	0.7975
Weinan	66	0.6483	0.6139	0.6548	0.6558	0.6044	0.6607	0.6450	0.6980	0.7152	0.7177
Wuhai	67	0.8431	0.8407	0.8431	0.8188	0.7748	0.8124	0.7896	0.8024	0.7424	0.7156
Ulanqab	68	0.6504	0.6583	0.6276	0.6267	0.6261	0.6227	0.6338	0.6783	0.6949	0.7517
Wuzhong	69	0.6850	0.6855	0.6909	0.6816	0.6619	0.6626	0.6725	0.6981	0.6873	0.6969
Wuwei	70	0.7080	0.7429	0.7402	0.7582	0.7399	0.7184	0.6946	0.7000	0.6978	0.7185
Xi'an	71	0.7208	0.6966	0.7271	0.7306	0.6995	0.7347	0.7299	0.7034	0.7298	0.7092
Xining	72	0.6236	0.6498	0.6294	0.6577	0.6469	0.6433	0.6783	0.6969	0.7092	0.6715
Xianyang	73	0.6653	0.6446	0.6804	0.6712	0.6453	0.6878	0.6656	0.7079	0.7094	0.7363
Xinzhou	74	0.6336	0.6420	0.6521	0.6506	0.6421	0.6568	0.6394	0.6841	0.6805	0.6871
Xinxiang	75	0.7566	0.7581	0.7618	0.7615	0.7607	0.7503	0.7441	0.7504	0.7596	0.7387
Xinyang	76	0.7216	0.7012	0.7037	0.6830	0.7100	0.7035	0.6894	0.7023	0.7082	0.7503
Xuchang	77	0.7377	0.7279	0.7277	0.7136	0.7278	0.7187	0.6841	0.6928	0.7140	0.7291
Ya'an	78	0.6390	0.6282	0.6133	0.6189	0.6262	0.6326	0.6145	0.6533	0.6449	0.6608
Yantai	79	0.7723	0.7852	0.7860	0.7853	0.7954	0.7708	0.7848	0.8167	0.7987	0.8018
Yan'an	80	0.5960	0.5575	0.6095	0.6117	0.5478	0.5990	0.5976	0.6287	0.6342	0.6509
Yangquan	81	0.6833	0.6998	0.7016	0.7371	0.6778	0.6861	0.6592	0.6988	0.6479	0.6203
Yibin	82	0.6140	0.6253	0.6518	0.6349	0.6695	0.6769	0.6687	0.6815	0.6981	0.7433
Yinchuan	83	0.7533	0.7933	0.7797	0.7621	0.7874	0.8226	0.7944	0.8116	0.8145	0.8019
Yulin	84	0.6218	0.5797	0.6367	0.6765	0.5776	0.6637	0.6786	0.7147	0.7076	0.7306
Yuncheng	85	0.6785	0.6858	0.6874	0.6894	0.6802	0.6580	0.6264	0.6761	0.6576	0.6689
Zaozhuang	86	0.7509	0.7450	0.7417	0.7278	0.7232	0.7111	0.7008	0.6927	0.7064	0.7226
Zhangye	87	0.6885	0.6822	0.6823	0.6870	0.7014	0.6998	0.6587	0.6869	0.7035	0.7054
Zhengzhou	88	0.7194	0.7111	0.7295	0.7453	0.7801	0.7533	0.7582	0.7604	0.7493	0.7260
Zhongwei	89	0.7330	0.7316	0.7522	0.7167	0.7100	0.6881	0.7417	0.7223	0.7075	0.7307
Zhoukou	90	0.7024	0.7046	0.7034	0.6871	0.6943	0.6954	0.6466	0.6911	0.6993	0.7204
Zhumadian	91	0.7603	0.7610	0.7618	0.7447	0.7432	0.7136	0.6816	0.7145	0.7164	0.7302
Ziyang	92	0.6529	0.6510	0.6548	0.6473	0.6471	0.6594	0.6492	0.6497	0.6242	0.6546
Zibo	93	0.8360	0.8316	0.8166	0.8249	0.8243	0.8054	0.8010	0.8060	0.7992	0.8122
Zigong	94	0.6777	0.6775	0.6649	0.6558	0.6622	0.6710	0.6601	0.6638	0.6637	0.6952

Appendix B

Table B
Urban WEF coupling efficiency in YRB from 2011 to 2020.

City	Code	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Ankang	1	0.6771	0.7079	0.7132	0.6743	0.6457	0.6108	0.6612	0.7430	0.8078	0.6755
Anyang	2	0.3647	0.4124	1.0280	0.4342	0.3698	0.3461	0.4143	0.3821	0.3832	0.3938
Bayanzhor	3	0.5771	0.5759	0.6206	0.5470	0.5611	0.5517	0.6917	0.6360	0.6259	0.6985
Bazhong	4	0.6216	0.5523	0.5972	0.5472	0.5379	0.5238	0.5558	0.5493	0.5692	0.5564
Baiyin	5	0.6559	0.6363	0.6609	0.6251	0.6023	0.6698	0.6846	0.7005	1.0424	1.0206
Baotou	6	0.4033	0.4135	0.4256	0.4552	0.4641	0.4423	0.5004	0.5105	0.4767	0.5038
Baoji	7	0.4471	0.4261	0.4955	0.4518	0.4327	0.4402	0.4750	0.4787	0.4622	0.5423
Binzhou	8	0.3878	0.4272	0.4876	0.4311	0.3923	0.3858	0.4267	0.4489	0.4591	0.4490
Changzhi	9	0.4636	0.4734	0.5228	0.4683	0.4636	0.4569	0.4890	0.5026	0.4901	0.4974
Chengdu	10	0.2180	0.2085	0.2085	0.2192	0.2333	0.2007	0.2548	0.2557	0.2583	0.2474
Dazhou	11	0.7747	0.5764	0.4794	0.5809	0.5111	0.3994	0.4170	0.4307	0.4779	0.4694
Datong	12	0.4888	0.4945	0.4939	0.4868	0.5597	0.4813	0.5099	0.5034	0.4826	0.5533
Deyang	13	0.4443	0.4709	0.4657	0.4609	0.4650	0.4412	0.4798	0.4605	0.4420	0.4978
Dezhou	14	0.3261	0.3210	0.3358	0.3903	0.2769	0.2821	0.4065	0.3704	0.4359	0.4246

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Table B (*continued*)

City	Code	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Dingxi	15	1.0597	1.1900	1.2451	1.1555	1.2130	1.2302	1.2257	1.3327	1.3767	1.2136
Dongying	16	0.4971	0.4971	0.5110	0.5029	0.5089	0.4818	0.4954	0.4820	0.4730	0.4933
Ordos	17	0.5846	0.5917	0.5852	0.5790	0.5563	0.5549	0.6198	0.6829	1.2240	0.6046
Guyuan	18	1.1380	1.1661	1.2020	1.2338	1.2299	1.2405	1.2978	1.1387	1.0753	1.1088
Guang'an	19	0.6423	0.6334	0.5729	0.5497	0.5308	0.5310	0.5590	0.5751	0.6233	0.6052
Guangyuan	20	0.5601	0.5677	0.5769	0.5617	0.5360	0.5272	0.5759	0.5813	0.5912	0.5860
Hanzhong	21	0.6459	0.6235	0.6089	0.5721	0.5705	0.5880	0.6055	0.6026	0.5845	0.5717
Heze	22	0.3700	0.4533	0.4456	0.4006	0.2847	0.2786	0.4296	0.4253	0.4614	0.4344
Hebi	23	0.5905	0.6457	0.6263	0.6026	0.5967	0.5896	0.6251	0.6371	0.6520	0.6495
Hohhot	24	0.4020	0.4235	0.4167	0.4471	0.4538	0.4156	0.4541	0.4380	0.3970	0.4066
Jinan	25	0.2590	0.2600	0.2699	0.2820	0.2977	0.2749	0.3235	0.3351	0.2911	0.3009
Jining	26	0.2811	0.2981	0.3059	0.2915	0.3273	0.2852	0.3176	0.3094	0.3200	0.3162
Jiaozuo	27	0.4234	0.4321	0.4419	0.4246	0.4305	0.4395	0.4566	0.4745	0.4663	0.5129
Jinchang	28	1.2741	1.2476	1.1335	1.0678	1.0765	1.0643	1.0802	1.1622	1.1739	1.1270
Jincheng	29	0.6001	0.6044	0.6186	0.5883	0.5576	0.5526	0.6101	1.5000	0.6309	0.6600
Jinzhong	30	0.5861	0.5397	0.5473	0.5217	0.4852	0.4730	0.5314	0.5439	0.5810	0.5790
Jiuquan	31	1.1622	1.1388	1.1311	1.1592	1.1331	1.1530	1.2104	1.1010	1.1381	1.1205
Kaifeng	32	0.4346	0.4534	0.4214	0.4217	0.3899	0.3720	0.4277	0.4481	0.4614	0.4659
Lanzhou	33	0.4894	0.4943	0.4799	0.4541	0.4802	0.5247	0.5929	0.5965	0.5942	0.5872
Leshan	34	0.5524	0.5957	0.5899	0.5537	0.5452	0.5222	0.5346	0.5404	0.5162	0.5196
Liaocheng	35	0.4126	0.4237	0.3542	0.3299	0.3171	0.3081	0.4315	0.3663	0.4218	0.4289
Linfen	36	0.5830	0.4960	0.4952	0.4866	0.4907	0.4645	0.4967	0.5347	0.6056	0.5591
Linyi	37	0.2520	0.2564	0.2488	0.2470	0.2507	0.2459	0.2601	0.2770	0.2790	0.2756
Longnan	38	1.1141	1.0755	1.1490	1.1028	1.0965	1.0621	1.0868	1.0974	1.0934	1.3199
Luzhou	39	0.4270	0.4364	0.4305	0.4556	0.4482	0.4284	0.4739	0.4386	0.4089	0.4025
Lvliang	40	0.6404	0.6349	0.6474	0.6465	0.6917	0.6803	0.7164	0.6685	0.7564	0.6733
Luoyang	41	0.3490	0.3350	0.3589	0.3577	0.4665	0.3352	0.3579	0.3444	0.3329	0.3749
Luohe	42	0.5970	0.5240	0.6009	1.0938	0.5651	0.4691	0.4986	0.5416	0.5440	0.5496
Meishan	43	1.2509	0.5678	0.5579	0.5286	0.5099	0.5008	0.5863	0.6126	0.5992	0.5867
Mianyang	44	0.3751	0.3829	0.3924	0.3916	0.3866	0.3682	0.3852	0.3822	0.3714	0.3810
Neijiang	45	0.5306	0.5527	0.5543	0.5292	0.5004	0.4921	0.5247	0.5485	0.5370	0.5364
Nanchong	46	0.3712	0.3915	0.3714	0.3685	0.3526	0.3476	0.4151	0.4065	0.4148	0.4766
Nanyang	47	0.3239	0.3074	0.3669	0.3178	0.2749	0.2782	0.3530	0.3444	0.3745	0.3757
Pingdingshan	48	0.4728	0.3984	0.4700	0.4238	0.4533	0.4322	0.4167	0.4443	0.4381	0.4933
Pingliang	49	0.7003	1.0719	0.6664	0.6661	0.6562	0.6618	0.6839	0.6820	0.7613	0.7313
Puyang	50	0.4771	0.5127	0.5299	0.4997	0.4216	0.4287	0.5053	0.5239	0.5363	0.5440
Qingdao	51	0.2187	0.2084	0.2337	0.2464	0.2602	0.2443	0.2982	0.2816	0.2842	0.2935
Qingyang	52	0.6932	0.6997	0.7106	0.7323	1.1137	0.7668	0.7029	1.1105	0.6611	0.7044
Rizhao	53	0.5189	0.5502	0.5526	0.5217	0.5294	0.5449	0.5637	0.5856	0.5498	0.5611
Sanmenxia	54	0.6806	0.6849	0.6895	0.6623	0.6549	0.6289	0.6556	0.6574	0.6460	0.6622
Shangluo	55	0.8096	0.7410	0.7541	1.0208	1.0732	0.7093	0.7351	1.0054	1.0598	1.0922
Shangqiu	56	0.5703	0.4144	0.4928	0.4130	0.3603	0.3744	0.3620	0.3656	0.3828	0.3894
Shizuishan	57	0.6073	0.6424	1.0426	1.0545	1.0386	1.0342	1.0150	1.0625	1.0690	1.0640
Shuozhou	58	0.6251	0.6280	0.6206	0.6172	0.6254	0.6059	0.6429	0.6318	0.6736	0.6669
Suining	59	0.5359	0.5440	0.5545	0.5155	0.5024	0.4758	0.5485	0.5523	0.5116	0.4965
Taiyuan	60	0.4568	0.4590	0.4713	0.5080	0.5268	0.5100	0.5490	0.5526	0.5546	0.5639
Tai'an	61	0.3556	0.3835	0.3989	0.3919	0.3774	0.3743	0.4324	0.4304	0.4408	0.4337
Tianshui	62	0.6122	0.6125	0.5998	0.5882	0.5782	0.6098	0.6046	0.6029	0.6140	0.5993
Tongchuan	63	1.0495	1.0193	1.0734	1.0708	1.0560	1.0341	1.1056	1.0319	1.0225	0.8185
Weihai	64	0.5364	0.5682	0.5840	0.5195	0.5368	0.5403	0.6149	0.5968	0.6126	0.6289
Weifang	65	0.2603	0.2854	0.3219	0.2862	0.2860	0.2894	0.3127	0.3155	0.2732	0.2867
Weinan	66	0.4613	0.4753	0.4850	0.4598	0.4065	0.4354	0.4968	0.5421	0.5627	0.4982
Wuhai	67	1.4133	1.4194	1.4068	1.4043	1.4065	1.4070	1.3885	1.4014	1.4138	1.4095
Ulanqab	68	0.7325	0.6703	0.6339	0.6483	0.6268	0.6222	0.6787	0.6866	1.0608	1.0041
Wuzhong	69	0.6194	0.6589	0.6639	0.6234	0.6087	0.6006	0.6485	0.6768	0.6928	0.6892
Wuwei	70	0.6668	0.7261	1.1281	0.6793	0.6716	0.6546	0.7263	0.7121	0.7345	0.8014
Xi'an	71	0.3011	0.2880	0.3040	0.3141	0.3084	0.2998	0.3172	0.3796	0.3794	0.3810
Xining	72	0.5849	0.5750	0.5605	0.5864	0.5952	0.5867	0.6349	0.6360	0.6255	0.6250
Xianyang	73	0.3904	0.3870	0.4039	0.4036	0.3926	0.3825	0.4372	0.5207	0.5243	0.4622
Xinzhou	74	0.5801	0.5507	0.5470	0.5353	0.5752	0.5764	0.6144	0.5790	0.6075	0.6401
Xinxiang	75	0.5713	0.4133	0.4780	0.4481	0.4477	0.3151	0.3905	0.3839	0.4161	0.4068
Xinyang	76	0.5871	0.5206	0.4436	0.4051	0.4543	0.3748	0.4616	0.4087	0.4278	0.4385
Xuchang	77	0.6796	0.5289	0.5463	0.5746	0.4554	0.4186	0.4817	0.4883	0.5040	0.5008
Ya'an	78	0.8254	0.7234	0.7258	0.7017	0.6979	0.7048	1.0148	1.0156	0.7937	1.0040
Yantai	79	0.3195	0.3208	0.3487	0.3382	0.3601	0.3474	0.4226	0.4275	0.4107	0.4275
Yan'an	80	0.6453	0.6315	0.6510	0.6436	0.6225	0.6156	0.6396	0.6563	0.6370	0.6264
Yangquan	81	0.6677	0.6466	0.6487	0.6713	0.6722	0.6683	1.0307	1.1664	1.2944	1.0591
Yibin	82	0.4501	0.4866	0.5417	0.4285	0.4127	0.4378	0.4731	0.4572	0.4378	0.4358
Yinchuan	83	0.4652	0.4604	0.4603	0.4540	0.4859	0.4736	0.4835	0.4913	0.4886	0.4890
Yulin	84	0.5761	0.5418	0.5803	0.5747	0.5418	0.5415	0.5852	0.5027	0.5267	1.4961

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Table B (*continued*)

City	Code	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Yuncheng	85	0.5523	0.5469	0.5345	0.4714	0.5428	0.4663	0.4750	0.5106	0.5218	0.5154
Zaozhuang	86	0.4377	0.4427	0.4677	0.4380	0.4415	0.4450	0.5096	0.4936	0.5140	0.5513
Zhangye	87	1.0366	1.3387	0.7608	0.6413	0.6510	0.6109	0.8116	0.7042	0.7583	0.7216
Zhengzhou	88	0.2996	0.2894	0.3002	0.3204	0.3276	0.3181	0.3873	0.3729	0.3760	0.3785
Zhongwei	89	1.1546	1.1252	1.0917	1.1347	1.0394	1.0412	1.0478	1.0962	1.0729	1.0755
Zhoukou	90	0.5671	0.5569	0.4773	0.3839	0.3392	0.3552	0.4637	0.3866	0.3891	0.4446
Zhumadian	91	0.3766	0.4828	0.4789	0.4547	0.3273	0.3115	0.3721	0.3719	0.4042	0.4415
Ziyang	92	0.5125	0.5242	0.5360	0.5251	0.5660	0.5618	0.6329	0.6118	0.6113	0.6469
Zibo	93	0.3141	0.3313	0.3372	0.3506	0.4034	0.3563	0.4178	0.4257	0.4189	0.4301
Zigong	94	0.5089	0.5245	0.5029	0.5095	0.5152	0.5173	0.5413	0.5428	0.5301	0.5542

Appendix C

Table C
Urban WEF coupling efficiency clustering types for YRB from 2011 to 2020, and group category.

City	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	group category
Ankang											***
Anyang	LL	LL	HL	LL	LL	LL	LL	LL	LL	LL	**
Bayanzhor				LH		HH	HH		HH	HH	*
Bazhong											***
Baiyin	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	*
Baotou											***
Baoji	LH	LH	LH	LH	LH	LH	LH	LH	LH	LH	***
Binzhou	LL	LL	LL	LL	LL	LL	LL	LL	LL	LL	**
Changzhi		LL	LL		LL	LL	LL				***
Chengdu											***
Dazhou											***
Datong											***
Deyang											**
Dezhou	LL	LL	LL	LL	LL	LL	LL	LL	LL	LL	*
Dingxi	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	**
Dongying	LL	LL	LL	LL	LL	LL	LL	LL	LL	LL	***
Ordos			HH		HH	HH	HH	HH			*
Guyuan	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	***
Guang'an								LL	HL	HL	***
Guangyuan											*
Hanzhong	HH	HH		HH	HH	HH		HH		LH	**
Heze	LL	LL	LL	LL	LL	LL	LL	LL	LL	LL	***
Hebi	HL	HL	HL	HL	HL	HL	HL	HL	HL	HL	***
Hohhot									LH		**
Jinjian	LL		LL	LL	LL	LL	LL	LL	LL	LL	**
Jining	LL	LL	LL	LL	LL	LL	LL	LL	LL	LL	**
Jiaozuo	LL	LL			LL	LL	LL			LL	*
Jinchang	HH	HH	HH						HH	HH	***
Jincheng						HL					***
Jinzhong		LL	LL		LL	LL		LL			***
Jiuquan		HH									**
Kaifeng	LL	LL	LL	LL	LL	LL	LL	LL	LL	LL	***
Lanzhou	LH	LH	LH	LH	LH	LH	HH	LH	LH	LH	***
Leshan									LL		**
Liaocheng	LL	LL	LL	LL	LL	LL	LL	LL	LL	LL	***
Linfen											**
Linyi	LL	LL	LL	LL	LL	LL	LL	LL	LL	LL	***
Longnan											***
Luzhou											***
Lvliang						LL	LL			LL	**
Luoyang	HL	LL	HL	HL	HL	LL	LL	LL	LL	LL	***
Luohe											***
Meishan											***
Mianyang											***
Neijiang											**
Nanchong			LL				LL		LL	LL	***
Nanyang									LL		**
Pingdingshan		LL			LL	LL	LL	LL	LL	LL	*
Pingliang	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	**

(*continued on next page*)

Table C (*continued*)

City	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	group category
Puyang	LL		LL	LL	LL	LL	LL	LL	LL	LL	**
Qingdao	LL	LL	LL	LL	LL	LL	LL	LL	LL	LL	*
Qingyang	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	**
Rizhao	LL	LL	LL	LL	LL	HL	LL	LL	LL	LL	***
Sanmenxia						HL	HL			HL	***
Shangluo											**
Shangqiu	LL	LL	LL	LL	LL	LL	LL	LL	LL	LL	*
Shizuishan	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	***
Shuozhou											***
Suining											***
Taiyuan											**
Tai'an	LL	LL	LL	LL	LL	LL	LL	LL	LL	LL	*
Tianshui	HH	HH	HH	HH	HH	HH	HH	HH	HH	LH	***
Tongchuan								HH			**
Weihai	LL	LL	HL	LL	LL	HL	HL	LL	HL	HL	**
Weifang	LL	LL	LL	LL	LL	LL	LL	LL	LL	LL	***
Weinan											*
Wuhai			HH	HH		HH	HH		HH		***
Ulanqab											*
Wuzhong	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	*
Wuwei	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	***
Xi'an	LH	LH		LH	LH						*
Xining	HH	HH	LH	HH	HH	HH	HH	HH	HH	HH	***
Xianyang	LH	LH	LH	LH	LH	LH		LH	LH	LH	***
Xinzhou											**
Xinxiang	LL	LL	LL	LL	LL	LL	LL	LL	LL	LL	**
Xinyang		LL			LL	LL	LL	LL	LL	LL	**
Xuchang	HL	LL	LL	HL	LL	LL	LL	LL	LL	LL	***
Ya'an									HL	HL	**
Yantai	LL	LL	LL	LL	LL	LL	LL	LL	LL	LL	***
Yan'an		HH	HH		HH	HH		HH			***
Yangquan											***
Yibin											***
Yinchuan	LH	LH	LH	LH	LH	LH	LH	LH	LH	LH	***
Yulin				HH	LH	HH	HH	LH	LH	LH	***
Yuncheng											**
Zaozhuang	LL	LL	LL	LL	LL	LL	LL	LL	LL	LL	*
Zhangye	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	***
Zhengzhou	LL	LL	LL	LL	LL	LL	LL	LL	LL	LL	**
Zhongwei	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	*
Zhoukou	LL	LL	LL	LL	LL	LL	LL	LL	LL	LL	**
Zhumadian		LL			LL	LL	LL	LL	LL	LL	**
Ziyang									HL		***
Zibo	LL	LL	LL	LL	LL	LL	LL	LL	LL	LL	**
Zigong											***

"*" means urban WEF coupling efficiency high clustering group; "**" means urban WEF coupling efficiency low clustering group; "***" means urban WEF coupling efficiency median contiguous group.

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