A Comprehensive Evaluation Framework of Water-Energy-Food System Coupling Coordination in the Yellow River Basin, China

YIN Dengyu[1, 2], YU Haochen[1, 2], LU Yanqi[2, 3], ZHANG Jian[2], LI Gensheng[2], LI Xiaoshun[2]

(1. *College of Economics and Management, Qingdao University of Science and Technology, Qingdao* 266061, *China*; 2. *School of Public Policy & Management, China University of Mining & Technology, Xuzhou* 221116, *China*; 3. *School of Landscape & Ecological Engineering, Hebei University of Engineering, Handan* 056038, *China*)

Abstract: For mankind's survival and development, water, energy, and food (WEF) are essential material guarantees. In China, however, the spatial distribution of WEF is seriously unbalanced and mismatched. Here, a collaborative governance mechanism that aims at nexus security needs to be urgently established. In this paper, the Yellow River Basin in China with a representative WEF system, was selected as a case. Firstly, a comprehensive framework for WEF coupling coordination was constructed, and the relationship and mechanism between them were analyzed theoretically. Then, we investigated the spatiotemporal characteristics and driving mechanisms of the coupling coordination degree (CCD) with a composite evaluation method, coupling coordination degree model, spatial statistical analysis, and multiscale geographic weighted regression. Finally, policy implications were discussed to promote the coordinated development of the WEF system. The results showed that: 1) WEF subsystems showed a significant imbalance of spatial pattern and diversity in temporal changes; 2) the CCD for the WEF system varied little and remained at moderate coordination. Areas with moderate coordination have increased, while areas with superior coordination and mild disorder have decreased. In addition, the spatial clustering phenomenon of the CCD was significant and showed obvious characteristics of polarization; and 3) the action of each factor is self-differentiated and regionally variable. For different factors, GDP per capita was of particular importance, which contributed most to the regional development's coupling coordination. For different regions, GDP per capita, average yearly precipitation, population density, and urbanization rate exhibited differences in geographical gradients in an east-west direction. The conclusion can provide references for regional resource allocation and sustainable development by enhancing WEF system utilization efficiency.

Keywords: water-energy-food (WEF); comprehensive framework; coupling coordination relationship; driving mechanism; Yellow River Basin, China

1 Introduction

The conflicts among water, energy, and food (WEF) are disrupting the world's economic pattern and environ-mental quality (Han et al., 2020; Wen et al., 2022). Recently, under the influence of major threats such as the COVID-19 and localized wars, the supply of WEF around the world have been confronted with huge chal-

lenges, and the problems of resource security have become prominent. With climate change, economic growth and dietary structure changes, the demands for WEF have been rising, especially in developing countries (Conway et al., 2015; D'Odorico et al., 2018). It is estimated that the demand for WEF would increase by 55%, 80%, and 60%, respectively in 2050 (Wen et al., 2022). The above-mentioned issues can also be concluded as follows: firstly, despite the dramatic increase in global food production over the past 50 yr, more than 820 million people are afflicted by hunger, and 2 billion people are in a hidden hunger; secondly, global energy prices continue to rise, and the commodities prices fluctuate, with coal, natural gas, and crude oil soaring by 27%–400% (Sun et al., 2021; Xiao et al., 2021); thirdly, water scarcity is becoming increasingly severe (Howells and Rogner, 2014). Renewable water resources per capita have decreased by 20% in the last 20 yr, and the global water-stressed population will reach 5 billion by 2050 (D'Odorico et al., 2018). Therefore, the supply and demand contradictions within each of the above three resources have been extremely salient. Additionally, these contradictions are not limited to a single resource but create a coupling relationship, such as water shortage affecting food production and energy processing. The internal relationships among the above three resources urgently need to be re-examined (Hellegers et al., 2008; Endo et al., 2017; Taniguchi et al., 2017).

China is the largest global consumer of WEF (Sun et al., 2021), and the resource endowments of these three resources vary significantly in time and space (Bai and Zhang, 2018). Its uneven and mismatched spatiotemporal distribution negatively affects the resource-flow efficiency and supply-demand balance (Yuan et al., 2021). Especially in China's arid and semi-arid regions, the fragile ecological environment and the extreme mismatches between water resources reserves, energy development, and food production have become important factors limiting the region to achieving economic and social development of high quality. For example, the Yellow River Basin (YRB), the sixth largest basin in the world, has been incorporated into the National Strategic Planning for High-Quality Development in China. However, the endowments and supply-demand of WEF resources show apparent spatial differences in the YRB (Xu et al., 2021). Herein, the upper reaches are the sources of the Yellow River with rich water resources;

the middle reaches produce nearly 69.7% of coal in China; the lower reaches are an essential food production base. Moreover, driven by energy and food security strategies, water demand in the YRB will increase significantly, and the contradictions of supply-demand among the three resources will be further revealed (Yin et al., 2021; 2023; Zhao et al., 2021).

Currently, exploring ways to meet the basic needs of WEF has become a global strategic priority (Conway et al., 2015). The WEF system is essential to achieving-sustainable socio-economic development, which has been highlighted by governments and academics worldwide since its proposal in 2011 (Chen et al., 2019; Fouladi et al., 2021). The relationship among water, energy, and food was first concluded as a 'nexus' at Bonn Conference (Hoff, 2011). Thereafter, the contents and extent of research on nexus have gradually diversified (Albrecht et al., 2017). Previous studies could be classified into three categories. Firstly, the analysis framework of the WEF nexus was addressed (Salmoral and Yan, 2018; Olawuyi, 2020), and the internal relationship among these three subsystems was quantified, which could improve the resource utilization efficiency (Martinez-Hernandez et al., 2017; Han et al., 2020). For example, Bazilian et al. (2011) studied the association framework of WEF based on the Climate, Land, Energy, and Water (CLEW) model and proposed a modelling tool to support integrated decision-making. Li et al. (2016) constructed a basic framework for WEF relationships using a 'resource integration concept' to optimize the proper allocation of WEF. Secondly, the dynamic changes and regulation strategies of WEF associations were explored through social and environmental factors (Clay et al., 2014; Mercure et al., 2019; Abdel-Aal et al., 2020). These external environmental changes would affect the production and utilization of WEF through interconnected processes, thus complicating the performance of the three subsystems (Zhang et al., 2018). Weather conditions and extreme disasters could upset the supply-demand balance of WEF, thus affecting regional sustainable livelihoods (Biggs et al., 2015; Hussien et al., 2018). Furthermore, economic development, diet structure, and technology can affect the synergy of the nexus system (Bai and Zhang, 2018; Li and Zhang, 2020). Thirdly, evaluating the performance of the whole coupling system is another mainstream research direction (Hellegers et al., 2008; Han et al., 2020). For in-

stance, Wang et al. (2021a) analyzed the spatiotemporal characteristics of the water-energy-food-ecology nexus in northwest China using a coupling coordination degree model. Sun et al. (2021) measured the WEF nexus coupling efficiency of provinces in China by employing the super-efficient network data envelopment analysis model.

Existing studies could provide valuable references to reveal the relationships among WEF. However, most studies mainly focused on coupling coordination evaluation, coupling efficiency measurement, and prediction simulation. The driving mechanism of coupling coordination development lacks sufficient explanation, especially ignoring the spatial scale with different factors. In similar research fields, it could be effectively addressed by multiscale geographic weighted regression (MGWR), which has been successfully applied in identifying the effects of different influences on the explanatory variables in different scales (Shen et al., 2020). Additionally, the existing research lacks a comprehensive evaluation index system of WEF coupling coordination, which may difficult to reveal the internal relationships among them. Moreover, most studies have been focused on the national, regional, basin, provincial or single municipality scale, and have explored the WEF coupling and spatial connection within cities from a microscopic perspective is inadequate.

Objectively, WEF has a linkage function among them, and the three have various permutations and combinations, and different resource locations can be exchanged to form different expressions, such as WEF, FEW, and EWF. This study is intended to be carried out by WEF for two reasons: 1) for the YRB, WEF can indicate the dominant functions of the Yellow River's upper, middle, and lower reaches; 2) water resources are the greatest constraint in the YRB, limiting energy and food production in the middle and lower reaches. As such, we considered the WEF nexus as a coupling system to detect interactions between the three subsystems.

In this case, we attempt to construct a comprehensive framework for the WEF system to further reveal the internal mechanisms from the perspective of economic and social systems and natural ecosystem linkages. Specifically, a multi-dimensional index system of WEF had been constructed from the production and utilization (consumption) perspectives, then an improved coupling coordination degree model (CCDM) was applied to

measure the coupling and coordinated development characteristics of WEF, and finally, the MGWR model was used to identify key driving factors.

The purposes of this paper include: 1) a WEF theoretical framework and a multi-dimensional evaluation index system are constructed to provide theoretical support for existing studies; 2) the coupling coordination degree (CCD) characteristics and mechanisms of WEF are revealed from the mesoscopic scale municipality, which expands the existing evaluation ideas and scales; 3) it verifies the spatial heterogeneity of the drivers of CCD, which can inform policy recommendations. This study could provide scientific evidence for optimizing the resource allocation of water, energy, and food in the YRB, as well as practical application solutions for other countries or regions to achieve sustainable development.

2　A Comprehensive Framework for WEF Coupling Coordination

2.1　Theoretical framework

Theoretically, WEF is an open system with complexity, uncertainty, and hierarchy (Scott et al., 2011), which belongs to a field where natural and social systems are highly intertwined. The interaction mechanism of the WEF system is a multi-dimensional and systematic process, and changes in one subsystem will cause a 'chain reaction' in the others (Bazilian et al., 2011). And three resources are closely linked while being subject to the pressures of a changing external environment. Relevant studies indicated that the WEF system was strongly linked to the economic society and environment (Hoff, 2011; Fuso Nerini et al., 2018), but this crossfeed relationship would change due to different resource endowments and development stages in regions. From a resource-linkage perspective, the WEF subsystems are interconnected at the biophysical and socioeconomic levels. Therefore, an integrated conceptual framework for the WEF system was constructed (Fig. 1).

In terms of internal relationships, the essence of the WEF nexus is to integrate all three within one framework, and there are certain bonds among the different resources (Li et al., 2016). It can be described as follows: 1) energy production and food cultivation require the support of water resources; 2) the extraction and purification of water resources need energy and food systems to provide power; and 3) energy provides the
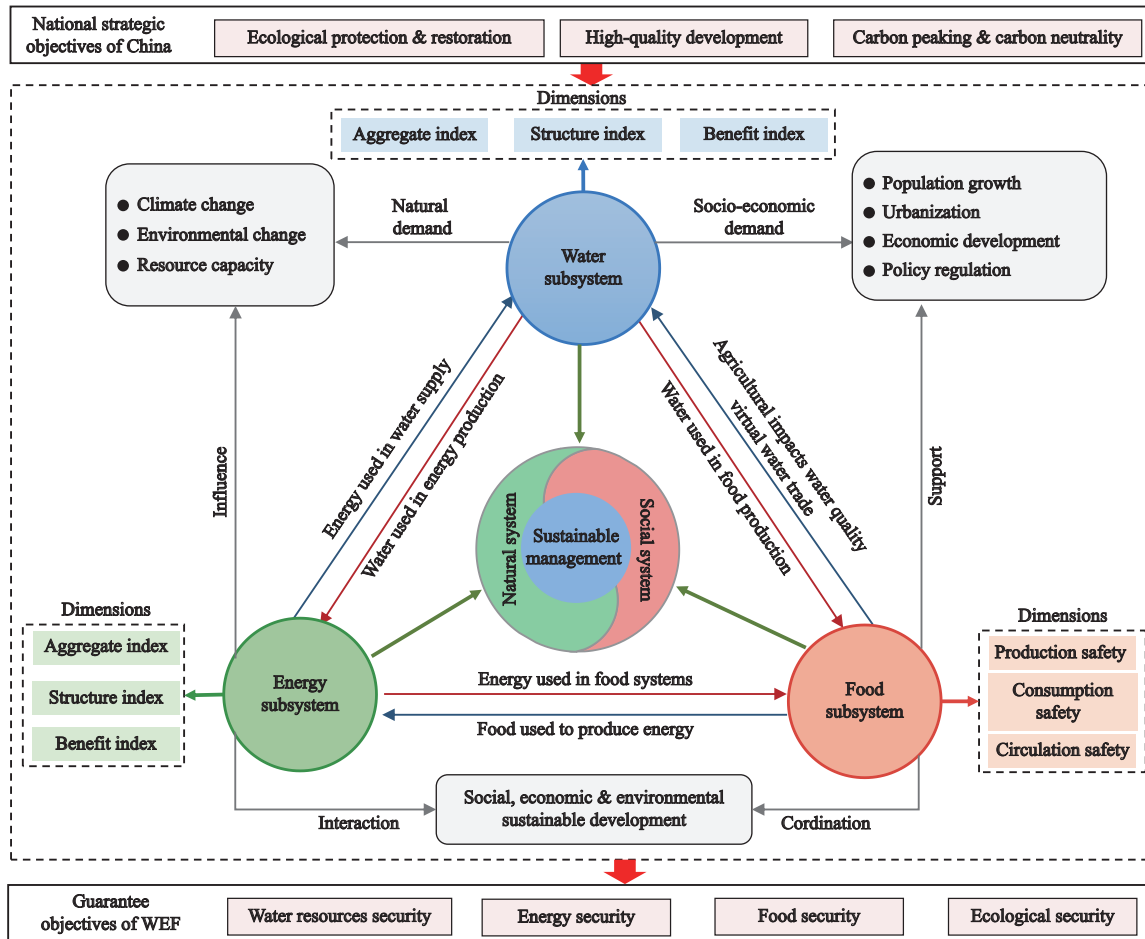
Fig. 1   Theoretical framework of the water, energy, and food (WEF) coupling coordination

majority of mechanical power for food production, and food is converted into energy through biomass. Given the current level of development, at least, WEF is almost being ignored. In terms of attributes, the three resources of water (W), energy (E), and food (F) are independent of each other. However, in the process of resource development and utilization, they also establish different cross-supply and other connections among them. The linkages among the three subsystems are established both from the differences in the division of labor among the uses of the different resources and from their accessibility at the current level of technology (Li and Zhang, 2020). Therefore, for the internal association of WEF, the degree of interdependence and constraint among the three subsystems needs to be reflected by the coupling coordination degree (CCD).

In addition to WEF's internal associations, it will also be linked to the external natural environment and socioeconomy, ultimately forming a driving force for sustainable social, economic, and environmental development

(Frankowska et al., 2019). These external influences are very broad and can lead to both natural environmental influences and socioeconomic feedback. The natural environment can form both a constraint on the innate resource endowment of the WEF and the impacts on natural variability. For example, resource endowment varies widely across regions. Meanwhile, climatic anomalies could exert a major influence on food production and also pose a significant threat to water resources (Conway et al., 2015). In addition, there are reciprocal feedback between the socioeconomic system and the WEF. For one thing, in the early stage of economic growth, resource inputs can determine the gross output value and efficiency to some extent. For another, economic growth can provide capital accumulation, talent, and technology for regional WEF production, and rapid urbanization can increase per unit of WEF consumption (Bai and Zhang, 2018). These externalities do not only stay in the natural environment and socioeconomics but also the policy direction. For example, the strategies that

China is currently implementing, such as ecological protection, high-quality development, and carbon neutrality, are all closely related to these three resources. Therefore, as indispensable resources for economic development, WEF needs to match the natural environmental system with the economic and social system and reveal the impact of these externalities.

Thus, the relationships of WEF should not only emphasize the crossfeed relationship and the coordinated sustainable development among them, but also consider the interaction mechanisms among association relationships as whole and external influences. The study involves many aspects of natural and socio-economic systems with different driving factors in different periods. A thorough investigation of the WEF relationship and its external influences could improve the YRB's security of water, energy, food, and even the ecology.

2.2 WEF index system

The WEF subsystems are closely interrelated and influenced by multiple factors, and a single indicator cannot provide a scientific evaluation of the system as a whole, so evaluating the level of WEF subsystems is complicated (Wang et al., 2021a). The role of the index system is not only to express the connotations and characteristics of each subsystem, but also to accurately reveal the complex connections among the elements of the three subsystems. In order to make an objective and reasonable evaluation of the WEF coupling coordination in the YRB, it is necessary to construct a multi-dimensional comprehensive evaluation index system. Therefore, based on the coupling mechanism of the WEF system described in Section 2.1, and drawing on relevant studies (Li and Zhang, 2020; Xu et al., 2021), while following the principles of scientificity, dynamicity, data availability, and hierarchy, this study constructed a multi-dimensional evaluation index system for WEF (Fig. 2).

Each of the WEF subsystems is multidimensional, complex, and differentiated. Among them, the water and energy subsystems have the mobility and regional nature of resources, so the characteristics of these two subsystems are portrayed from three aspects: aggregate, structure, and benefit. The aggregate index reflects the stock and consumption of resources, demonstrating the sustainable development capacity and security level of the system; the structure index mainly reflects the structure of resource consumption, including production con-

sumption, living consumption, and ecological consumption; and the benefit index reflects the production and utilization efficiency of resources and energy. For the food subsystem, food production, processing, and transportation are not supported by water and energy, and the development level of the food system depends on the degree to which food productivity meets human health security. Hence, the food subsystem is decomposed into three aspects: production safety, consumption safety, and circulation safety. This series of indicators can show the comprehensive development level of WEF more completely.

3 Materials and Methods

3.1 Study area

The YRB, China is divided into the upper reaches (flowing through Qinghai, Gansu, Ningxia, and Inner Mongolia), the middle reaches (flowing through Shanxi and Shaanxi), and the lower reaches (flowing through Henan and Shandong), with total length of 5464 km and a total basin area of 7.95×10^5 km² (95°53′E–119°05′E, 32°10′N–41°50′N), accounting for 8.28% of China's land area. Referring to Yin et al. (2022), 74 cities in 8 provinces/autonomous region where the YRB flows were selected as the objects (Fig. 3). By 2018, the GDP of 74 cities was 1.433×10^{13} yuan (RMB), accounting for 15.92% of China's GDP, with a total population of 2.57×10^8, accounting for 18.41% of China (https://nianjian.cnki.net).

As well as being an important energy and food-producing region in China, the YRB suffers from a lack of water resources. 1) Water resources are the most important factor affecting food security. Presently, most of the upper and middle reaches of the basin are west of the 400 mm isohyte, with an annual average water resource of 6.47×10^{10} m³ (http://www.yrcc.gov.cn/other/hhgb/). It is estimated that 80% of water resources are exploited, which exceeds the ecological warning line (40%) by a wide margin (Zhao et al., 2021). 2) The middle reaches of the YRB are rich in energy. The energy consumption of eight provinces reached 1.388×10^9 t in 2018, accounting for 29.92% of China's consumption (https://nianjian.cnki.net). 3) The lower reaches are one of the important food production areas in China with a cultivated land of 26.24×10^6 hm² and an effective irrigated area of 12.07×10^6 hm². Food pro-
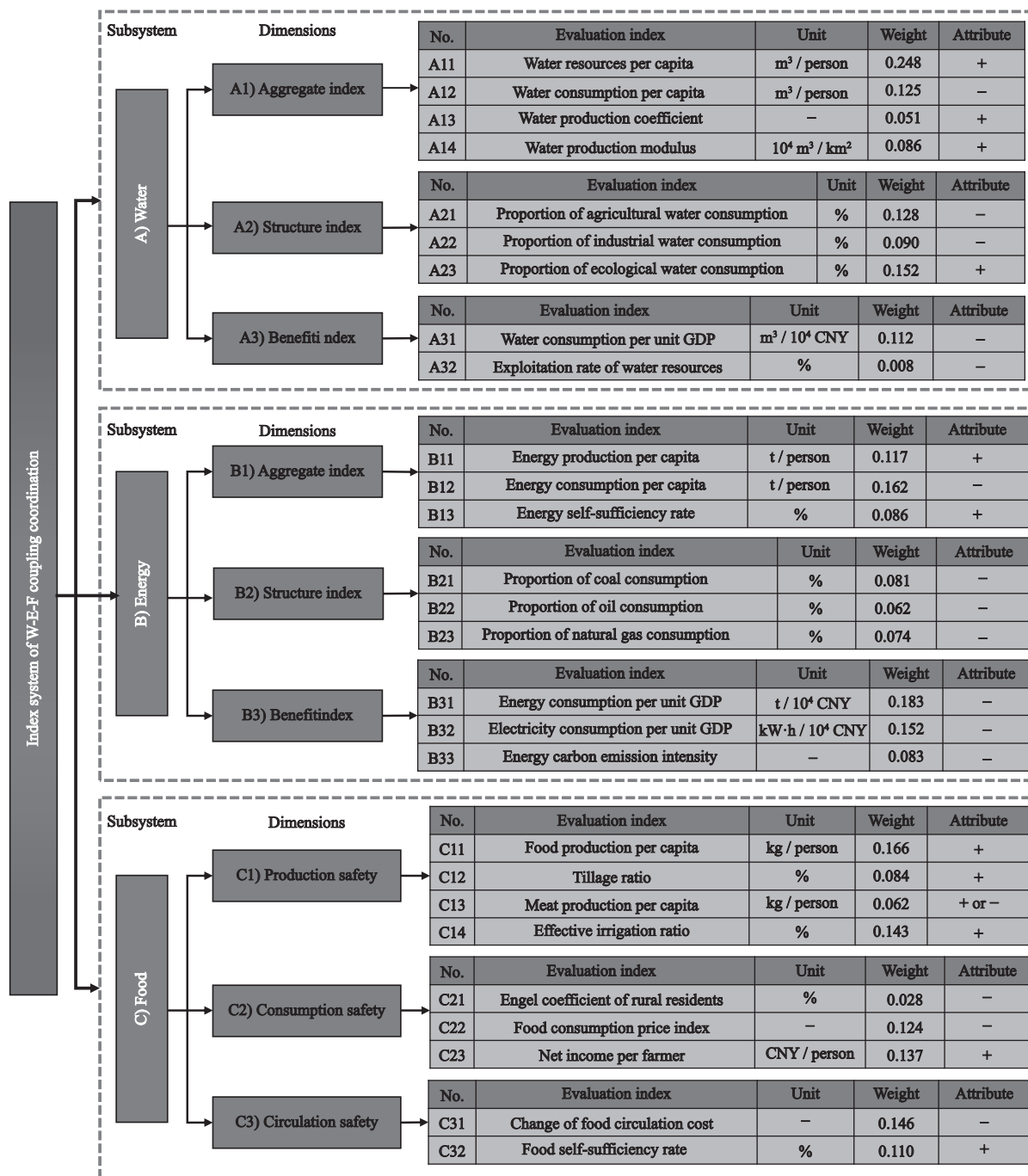
Fig. 2   Evaluation index system of WEF (water, energy, food) coupling coordination. CNY is yuan (RMB). + means a positive index, − means a negative index

duction has increased continuously in the past 30 yr, which has reached 12.45×10^6 t in 2018 (https://nianji-an.cnki.net).

3.2   Data sources

The data mainly includes regional spatial data and socio-economic data. The climate data (including temperature data and precipitation data) and elevation data were ob-

tained from the Data Centre for Resource and Environmental Sciences, Chinese Academy of Sciences (www.resdc.cn). Defense Meteorological Satellite Program (DMSP)/Operational Linescan System (OLS) night-time light data were derived from the official National Geographic Data Center (NGDC, http://www.ngdc.noaa.gov/dmsp/download.html), which was mainly used to retrieve the energy consumption of various cities. So-
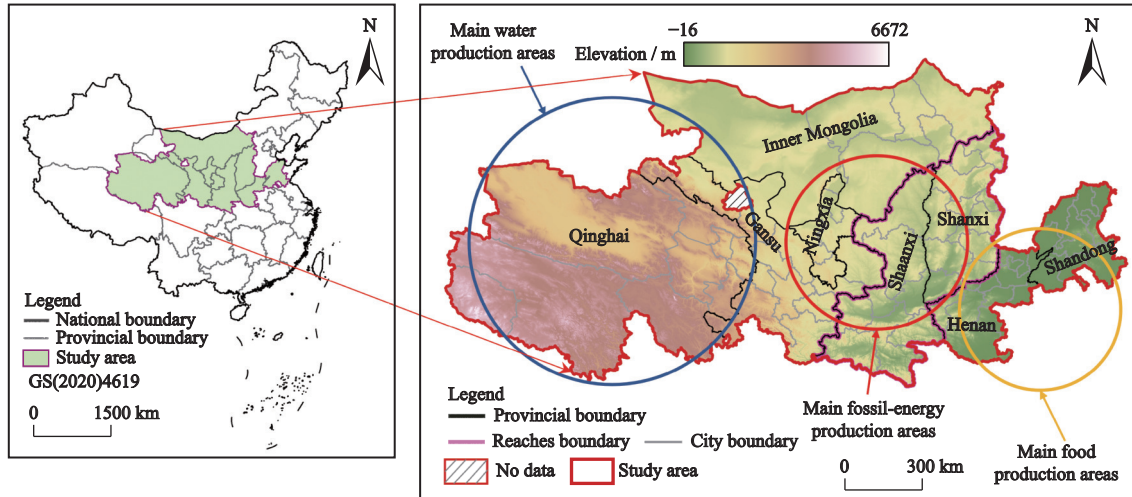
Fig. 3   Location of the Yellow River Basin (YRB) in China

cioeconomic data were obtained from the statistical yearbooks (https://nianjian.cnki.net/) and the website of the National Bureau of Statistics (https://www.stats.gov.cn/).

3.3   Methods

3.3.1   *Composite evaluation method applying barrel theory*

In the past, although the evaluation of the WEF system emphasized the relationships among the elements and the system, it usually used multiple indicators weighted composite way of a comprehensive evaluation, ignoring the possible existence of the threshold effect or short board effect. The YRB varies greatly in economic development level and resource endowment with a short board effect of WEF resources. Therefore, evaluating the development level of the WEF subsystem through the logarithmic function can improve the system's stability and credibility (Li et al., 2018). Firstly, the entropy method is used to determine the weights, which is widely used in various studies in the socio-economic field as an objective assignment method with high credibility and accuracy (Yin et al., 2022). Then, the weights of each index are compared to the width of the board, the scores of each function or index are compared to the height of the board, and the following formulas are used to reflect the short board effect on the final evaluation results.

$$W_w = w_1\log_5 X_1 + w_2\log_5 X_2 + w_3\log_5 X_3 + \cdots w_i\log_5 X_i \quad (1)$$

$$E_e = e_1\log_5 Y_1 + e_2\log_5 Y_2 + e_3\log_5 Y_3 + \cdots e_i\log_5 Y_i \quad (2)$$

$$F_f = f_1\log_5 Z_1 + f_2\log_5 Z_2 + f_3\log_5 Z_3 + \cdots f_i\log_5 Z_i \quad (3)$$

where W_w, E_e, and F_f are the composite evaluation indices of water subsystem, energy subsystem, and food subsystem, respectively. w_i, e_i, and f_i denote the weight evaluation indicators of water subsystem, energy subsystem, and food subsystem, respectively. X_i, Y_i, and Z_i represent the standardized values of the corresponding indicators.

3.3.2   *Coupling coordination degree model (CCDM)*

Currently, the coupling coordination degree model (CCDM) has been widely used in geography to study the mechanism of coupling, coordination and feedback within and among the systems. With relatively low validity and reliability, the traditional CCDM could significantly affect the results of academic research. Based on Wang et al. (2021b), we used a modified CCDM to quantify the interaction degree among the composite index of WEF subsystems in the YRB.

$$C = \left[1 - \left(\left((U_3 - U_1)^{1/2} + (U_2 - U_1)^{1/2} + (U_3 - U_2)^{1/2}\right)\Big/3\right) \right.$$
$$\left. (U_1 U_2/U_3{}^2)^{1/2}\right]^{1/2} \quad (4)$$

$$T = \alpha U_1 + \beta U_2 + \gamma U_3, \alpha + \beta + \gamma = 1 \quad (5)$$

$$D = \sqrt{C \times T} \quad (6)$$

where U_1, U_2, and U_3 are the standardized subsystem indices of WEF, respectively, and C is the coupling degree. T is the comprehensive index of the WEF system. α, β, and γ denote the coefficients to be determined. D is the CCD of U_1, U_2, and U_3, reflecting the coordinated state of system development. The value of D is between

0 and 1 and the higher the value, the higher the level. Referring to (Yin and Xu, 2022), we divided the coupling coordination degree into four stages from lowness to highness: severe disorder, mild disorder, moderate coordination, and superior coordination.

3.3.3 Spatial statistical analysis

Hotspot analysis and spatial autocorrelations could reveal the spatial patterns and agglomeration characteristics of CCD in the YRB. A measure of global spatial autocorrelation is Moran's I index, which indicates whether certain spatial phenomena are relevant and different from each other (Sun et al., 2021). The Getis-Ord G_i^* index could describe WEF coupling coordination from a local perspective as a result of spatial dependence and heterogeneity (Chen et al., 2022). These operations are performed in the Spatial Statistics Tools of ArcGIS.

$$I = \left[n \sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij}(x_i - \overline{x})(x_j - \overline{x}) \right] \bigg/ \left[\sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij} \sum_{i=1}^{n} (x_i - \overline{x})^2 \right] \tag{7}$$

$$G_i^*(d) = \sum_{j=1}^{n} W_{ij} x_j \bigg/ \sum_{i=1}^{n} x_i \tag{8}$$

where n is the number of cities, x_i and x_j show the CCD for cities i and j, respectively. $\overline{x}$ indicates the average value for a spatial unit. W_{ij} represents the spatial weight matrix, which is mainly obtained using Euclidean distance. I is the degree of global autocorrelation in CCD, which ranges from –1 to 1. $G_i^*(d)$ is the local Moran's I for the city i. If $G_i^*(d) > 0$ indicates the study area is a hot spot, if $G_i^*(d) = 0$, it is a random distribution, and if $G_i^*(d) < 0$, it is a cold spot.

3.3.4 Multiscale geographic weighted regression (MGWR)

As the distributions of WEF are all closely related to natural geographical conditions, the spatial pattern of WEF coupling coordination is influenced by geospatial factors. According to (Shen et al., 2020), MGWR enhances classical GWR by allowing variables to have different bandwidths, resulting in more credible estimation results. Therefore, the MGWR model was used to analyze the factors affecting WEF changes. The formula is shown below:

$$y_i = \sum_{j=1}^{n} \beta_{bwj}(u_i, v_i) x_{ij} + \varepsilon_i \tag{9}$$

where y_i represents the dependent variable for element i; x_{ij} represents the attribute value of independent variable j at position i; β_{bwj} denotes the bandwidth applied in the regression coefficient of the jth variable; (u_i, v_i) is the spatial coordinate of the element i; and ε_i is the residual.

In this paper, the classical Residual Sum of Squares (RSS) variation ratio was used as the convergence criterion. The smaller the RSS value, the better the fit.

$$RSS = \left| \frac{RSS_{new} - RSS_{old}}{RSS_{new}} \right| \tag{10}$$

where RSS_{old} represents the RSS of the previous step and RSS_{new} represents the sum of squared residuals of this step.

Drawing on the relevant research (Qin and Tong, 2021; Yin et al., 2022), we intend to select the driving factors that affect the development of CCD from the aspects of natural and socio-economic systems. The natural system verified the influence of natural environmental factors from three aspects: air, water, and health. The yearly average temperature (AYT), average yearly precipitation (AYP), and environmental carrying capacity (ECC) were selected for characterization. The socio-economic system was characterized by population growth, industrial structure, economic development, science and technology, and government regulation. Specifically, population density (PD), urbanization rate (UR), the proportion of tertiary sector (PTS), GDP per capita (GPC), the proportion of science expenditure (PSE), and the proportion of fiscal expenditure (PFE) were selected for characterization.

4 Results

4.1 Spatio-temporal characteristics of WEF subsystems

Through constructing the evaluation indicator system, the composite degrees of the WEF subsystems were measured. The specific characteristics of spatiotemporal differentiation were shown in Fig. 4.

During 2003–2018, the mean value of water subsystem index of 74 cities in the YRB showed an upward trend and a slight fluctuation, with an annual increase rate of 1.61%. Among them, the index of most cities in Qinghai, Gansu, and Inner Mongolia increased significantly, while the index of some cities in Shaanxi, Henan, and Shandong declined. Spatially, the index of water
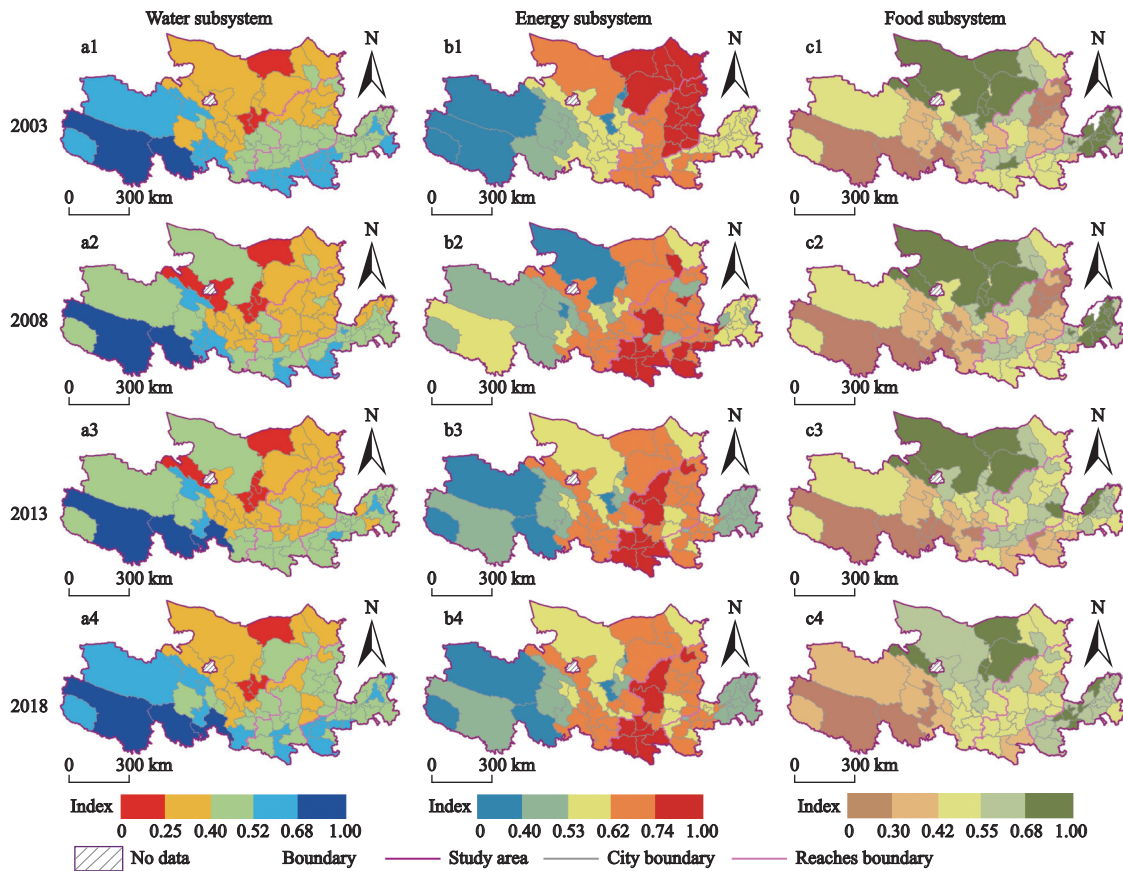
Fig. 4 Spatial distributions of indices of water subsystem (a1–a4), energy subsystem (b1–b4), and food subsystem (c1–c4) in the YRB, China from 2003 to 2018

subsystem showed a pattern of high in the southwest and low in the northeast areas, with significant differences in regional gradients. The high-value areas were concentrated in most cities of Qinghai, Shandong, and Henan, especially the index of Guoluozhou and Yushuzhou was above 0.85, which was related to their rich water resources. The low-value areas were concentrated towards the northwest, represented by Ningxia, Bayannur, Wuwei, and Zhangye, with large regional per capita water consumption and unreasonable water use structure, resulting in their low water resource index.

The mean value of energy subsystem index of 74 cities in the YRB declined to fluctuate, with a decrease of 8.85%. The index fluctuated downward significantly in various cities from Inner Mongolia and Shanxi, especially in Ulanqab League and Yangquan City (directly from 0.8 to 0.3), while it rose slightly across some cities in Shaanxi and Gansu. Spatially, the energy subsystem showed a distribution pattern of high in the center and low in the east or west areas. Specifically, the high-value areas were located in various cities of Shanxi,

Shaanxi, and Inner Mongolia, while the low-value areas were mainly concentrated in Qinghai and Ningxia. Notably, after 2013, the index of the majority of cities in Shandong has dropped to lower levels, such as Binzhou city from 0.57 to 0.26, mainly due to the gradual increase in energy consumption and low energy self-sufficiency in these cities. Overall, the energy subsystem showed the highest level of the three subsystems, indicating that significant progress has been made in the energy transition in the YRB.

The mean value of food subsystem index of 74 cities increased in a fluctuating manner, rising from 0.51 to 0.54, with an increase of 6.28%. Thereinto, the mountainous cities of Shanxi, Gansu, and Henan rose significantly, while cities in Shaanxi and Shandong showed a downward trend, and the high-value areas gradually decreased. Spatially, the index showed a spatial pattern of high in the northeast and low in the southwest areas, in contrast to the pattern of the water subsystem. This indicates that there is a serious mismatch between the distribution of water resources and food production in the

YRB. Concretely, the high-value areas were located in most cities of Inner Mongolia, Ningxia, and Shandong, while the low-value areas were concentrated in Qinghai, Gansu, and Shanxi. Notably, as large agricultural provinces, Henan and Shandong are regions with frequent agricultural natural disasters, and the development of the food subsystem also showed great fluctuations.

4.2   Analysis of the CCD for WEF

4.2.1   Spatio-temporal differentiation characteristics of CCD

The previous analysis showed that the spatio-temporal distribution of WEF subsystems in the YRB was uneven and mismatched. In order to clarify the matching degree of them, the spatiotemporal evolution of the CCD was further explored.

In terms of the development trends, the values of CCD varied considerably (ranging from 0.3 to 0.8) among different cities, and also showed individual char-

acteristics such as fluctuating changes (Fig. 5). Overall, the mean value of CCD in the YRB was at moderate coordination, showed a 'V' shaped upward trend (Fig. 6a), with a small increase of only 0.08%. This indicates that the CCD values of various cities in the YRB have fluctuated (reaching the lowest in 2013), but are relatively stable overall. The CCD values of cities in the upper reaches were low, while that of cities in the middle and lower reaches were slightly higher, thus reflecting that the development level of CCD is closely related to the stage and level of economic development for different cities. Furthermore, the CCD of most cities in the upper and middle reaches increased, while that in the lower reaches decreased. This is mainly because the lower reaches' economic development and agricultural production put enormous pressure on regional water and energy resources, negatively affecting the regional WEF coupling coordination.

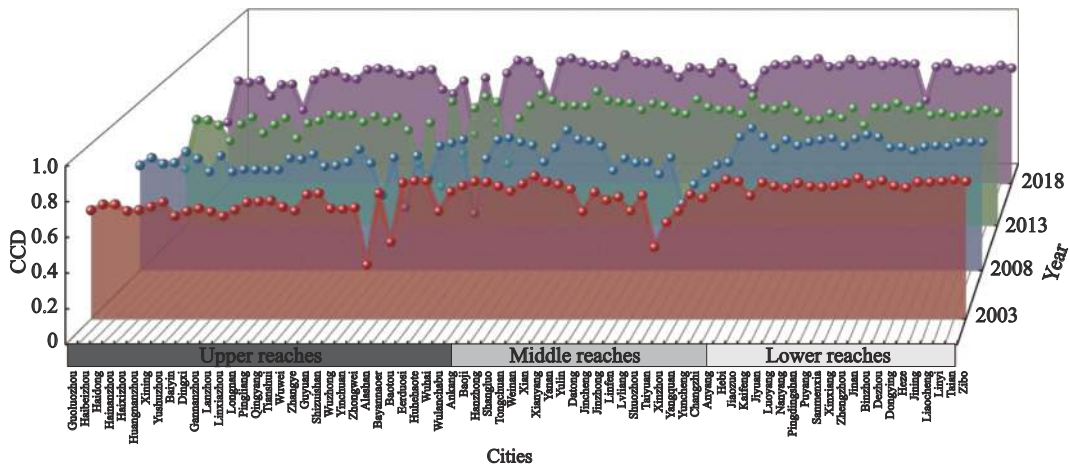In terms of spatial distribution, there were significant

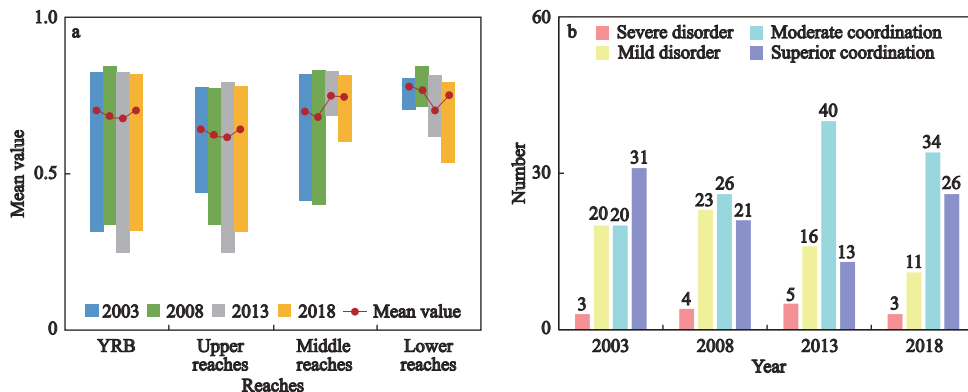Fig. 5   Coupling coordination degree (CCD) of various cities in the YRB, China from 2003 to 2018

Fig. 6   Changes (a) and number of cities with different types of CCD (b) in the YRB, China from 2003 to 2018
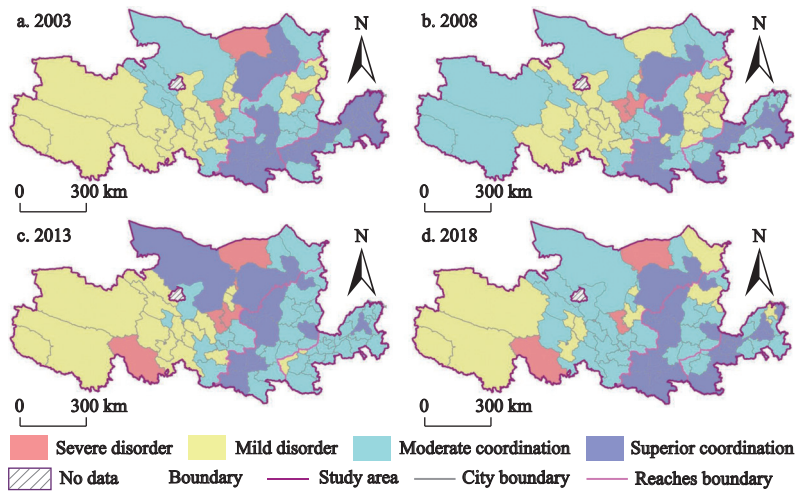
Fig. 7 Spatial distributions of CCD for WEF in the YRB, China from 2003 to 2018

east-west and north-south differences in CCD (Figs. 7a–7d), and this imbalance first narrowed and then increased as time evolved. It embodied a concentrated expression in the clustering development with urban agglomeration as the development carriers, such as the Shandong Peninsula urban agglomeration and the Guanzhong Plain urban agglomeration, which had maintained at superior coordination. This was mainly because the single subsystems of these cities were at a high level. From 2003 to 2018, the number of cities in superior coordination and mild disorder decreased, while the number of cities in moderate coordination increased. The number of cities experiencing severe disorder was the least, maintaining a relatively stable state (Fig. 6b). Notably, 2013 saw the lowest value in CCD, with the number of cities in superior coordination decreasing to a minimum (13). Nearly 62% of the cities experienced varying degrees of CCD decline during this year, concentrated in the middle and lower reaches of the YRB. For instance, most of the cities in Henan and Shandong had reduced from superior coordination to moderate coordination, mainly because the energy subsystem and the food subsystem of these regions were low in 2013. In 2018, the majority of cities have rebounded in CCD values (compared to 2013), but still some cities have not reached the base period level (2003). Spatially, there was a divergence between high and low-level areas, with areas of superior and moderate coordination increasing and gradually concentrating in the middle and lower reaches. As the severe and mild disorder areas shrank and spread to the middle and upper reaches, the CCD imbalance in the YRB was exacerbated.

4.2.2 Spatial agglomeration characteristics of CCD

Clearly, the CCD showed centralized distribution, suggesting a spatial correlation. Thus, global Moran's I values in different years were calculated to explore the heterogeneity of CCD. The results suggested an obvious spatial dependence on the CCD of cities, i.e. the areas or cities with high level of CCD adjoined to other areas or cities with relatively higher level, and cities with lower level of CCD tended to be close to each other. It was worth noting that the spatial aggregation of the CDD has weakened with the changes over time, indicating that the radiation effect of the core cities was reduced.

To gain further insight into the spatial patterns of coupling coordination in the YRB, the Getis-Ord G_i^* index was applied to analyze the CCD in 2003, 2008, 2013, and 2018, which divided the YRB into cold and hot spot areas (Fig. 8). 1) The spatial variation of CCD in the YRB was apparent, with hotspot areas concentrated in the lower reaches and coldspot areas in the middle and upper reaches. The polarization was more obvious and characterized by excellent spatial stability. 2) The spatial scope of the hotspot areas gradually decreased, and the highly significant areas progressively decreased, while the middle and low significant areas gradually increased, clustering in the cities in Shandong, Henan, and southern Shaanxi to Henan and southern Shaanxi by degrees. 3) The spatial agglomeration pattern of the coldspot areas experienced an obvious transition. In 2003, cold spot areas centered on Taiyuan and Lanzhou were formed respectively; in 2008, the banded agglomeration area of 'Northern Shanxi-Northern Shaanxi-Ningxia-Southern Gansu-Eastern Qinghai' was for-
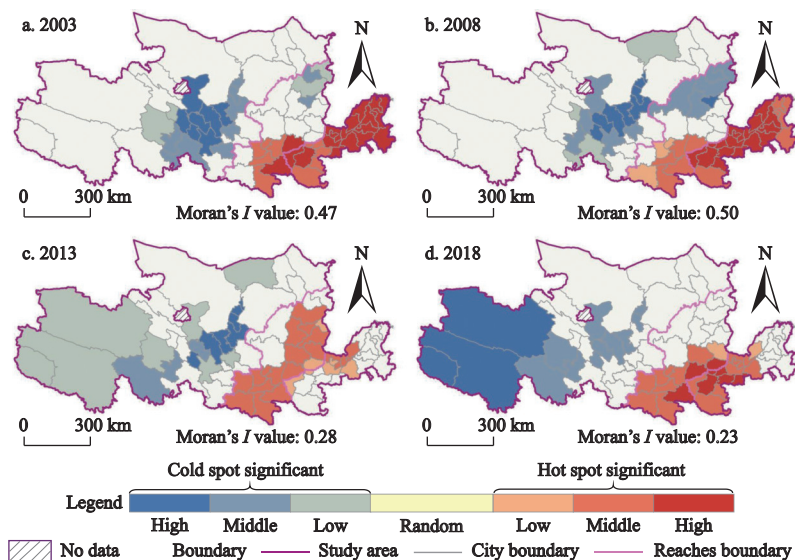
Fig. 8   Spatial pattern of cold and hot spots of CCD in the YRB, China from 2003 to 2018

med; in 2013, it evolved into two coldspot areas and concentrated in the upper reaches; in 2018, the spatial agglomeration of cold spot areas in Qinghai strengthened, while that of Ningxia weakened.

4.3   Driving factors for the WEF coupling coordination

4.3.1   Overall analysis

The CCD of WEF in the YRB was characterized by spatial clustering (Fig. 8), and its spatial effects should be verified. To ensure the validity of the model, the selected indicators were first tested for multi-collinearity. The SPSS software was used to calculate the variance inflation factors (VIF) for each factor, and the results showed that the VIF value of each factor was less than five and there was no multi-collinearity. When the F-test was performed on the model, it was found that the model passed the F-test ($F = 11.387$, $P < 0.05$), which means that the model construction is meaningful. Therefore, we selected all factors to be included in the MG-WR 2.2 software. As shown in Table 1, the MGWR's

goodness-of-fit value ($R^2 = 0.752$) was significantly higher than that of the GWR ($R^2 = 0.670$) and OLS ($R^2 = 0.564$), and the *AICc* value was lower than the other two models, providing greater credibility. Moreover, the MGWR model has less RSS and larger effective parameters. Therefore, we used the MGWR model to explore the spatial heterogeneity of the factors affecting CCD.

The MGWR results revealed significant differences in the effecting scales of the different variables (Table 2). Among the nine influencing factors, the intercept (INT), average yearly precipitation (AYP), population density (PD), urbanization rate (UR), GDP per capita (GPC), and proportion of science expenditure (PSE) significantly affected the CCD. However, the regression coefficients of yearly average temperature (AYT), environmental carrying capacity (ECC), the proportion of tertiary sector (PTS), and the proportion of fiscal expenditure (PFE) were not significant. The INT indicated the effect of different positions on the CCD when other independent variables were fixed. The absolute values of the factors' contribution from large to small were: GPC >

Table 1   Model index of Multiscale Geographic Weighted Regression (MGWR), Geographic Weighted Regression (GWR), and Ordinary Least Squares (OLS)

Model indices	MGWR	GWR	OLS
R^2	0.752	0.670	0.564
AICc	166.154	166.628	174.836
Residual Sum of Squares (RSS)	18.337	24.426	32.265
Number of effective parameters	19.905	14.115	–

Table 2 Statistical description of MGWR coefficients

Variable	Mean	Standarddeviation	Minimum	Median	Maximum
Intercept (INT)	0.215	0.012	0.198	0.212	0.240
Yearly average temperature (AYT)	−0.063	0.040	−0.114	−0.079	0.005
Average yearly precipitation (AYP)	0.540	0.204	0.200	0.619	0.864
Environmental carrying capacity (ECC)	−0.025	0.078	−0.127	−0.049	0.173
Population density (PD)	0.272	0.012	0.249	0.268	0.307
Urbanization rate (UR)	−0.317	0.011	−0.331	−0.320	−0.292
GDP per capita (GPC)	0.541	0.160	0.289	0.575	0.750
Proportion of tertiary sector (PTS)	0.008	0.070	−0.112	0.020	0.132
Proportion of science expenditure (PSE)	−0.262	0.304	−0.889	−0.126	0.022
Proportion of financial expenditure (PFE)	−0.190	0.037	−0.249	−0.180	−0.142

AYP > UR > PD > PSE > INT.

The spatial distribution of each significant variable's regression coefficient on the level of CCD was shown in Fig. 9. Among these variables, the GPC, AYP and PSE's variable bandwidth had smaller effecting scale than that of other variables, and were more sensitive to changes in regional scale with greater spatial heterogeneity. The INT, PD and UR were global variables whose effects did not vary significantly across space.

4.3.2 Analysis of specific factors

GPC was the dominant factor affecting regional coupling coordination, positively affecting the CCD: the higher the GPC, the better the CCD. This is mainly due to the fact that economic development promotes the efficient use and optimal allocation of resources, which in turn facilitates the improvement of the CCD. Its spatial pattern showed a clear tendency towards a reversed geographical gradient (Fig. 9a), in other words, GPC promoted the CCD of the upper reaches better than that of the middle and lower reaches. Specifically, the most affected areas were concentrated in the various cities of Gansu and Qinghai, while the least in the cities of Shandong and Henan. The reason is that economically developed regions (such as Henan and Shandong) have great capital accumulation, well-developed industrial structures, and talent gathering. According to the marginal utility principle, it is difficult to achieve a substantial increase in CCD even with continued additional economic investment. On the contrary, in Qinghai, Gansu, and Ningxia, with relatively weak economic bases, in-
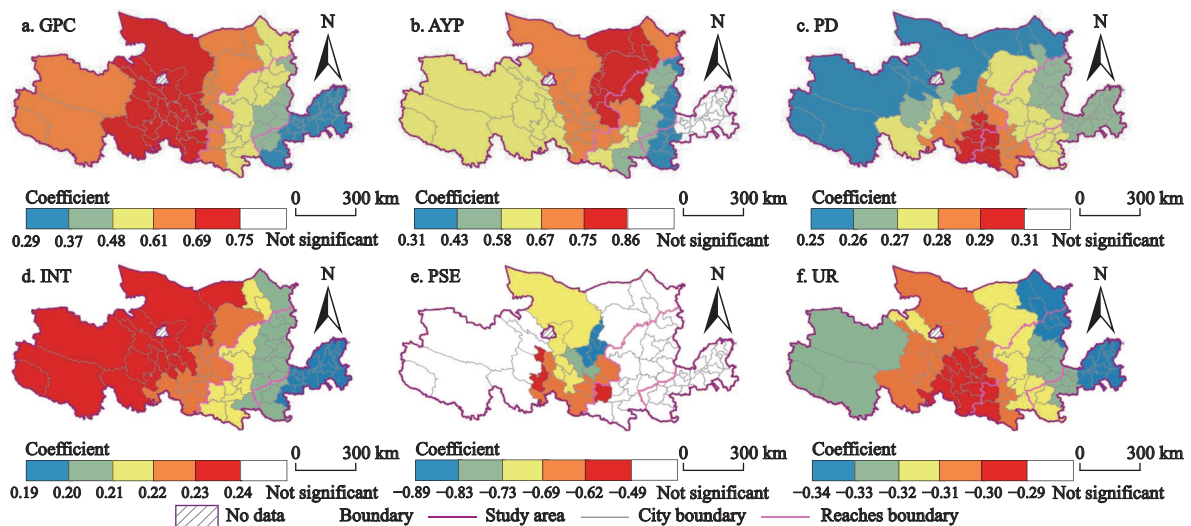

Fig. 9 Spatial pattern of MGWR (Multiscale Geographic Weighted Regression) coefficients in the YRB, China. GPC: GDP per capita; AYP: average yearly precipitation; PD: population density; INT: intercept; PSE: proportion of science expenditure; UR: Urbanization rate

sufficient talent and innovation mechanisms, and inadequate growth momentum, improvement in economic development will significantly lift the CCD of these regions.

The module value of the regression coefficient for the AYP was the largest (minimum value > 0), indicating that AYP positively influenced CCD. The increase in precipitation can effectively support the overall regional water resource situation, which in turn enhances the energy and food subsystems and promotes the coupling and coordination of the three. Spatially, the high-value areas of the regression coefficient for AYP were mainly concentrated in most cities of Inner Mongolia, Ningxia, and Shaanxi (Yulin and Qingyang), while areas with low values were concentrated in most cities of Shanxi and Henan (Fig. 9b). It was spatially characterized by 'high in the center and low in the surroundings', with a majority of higher-value areas. This is mainly attributed to the fact that the ecological environment in the middle reaches and some regions in the upper reaches are fragile, with large per capita water consumption and low water resources utilization efficiency. In particular, water resources are extremely scarce in Ningxia, and Bayannur City, Inner Mongolia. Thus, increasing precipitation can be conducive to vegetation growth to improve the eco-environment and the CCD.

The regression coefficient of the PD had a maximum value of 0.307 and a minimum value of 0.249, indicating that the PD had a positive impact on the CCD, with a narrow gap in the influence degree (Fig. 9c). The regression width of the PD was large and thus was a global variable, indicating that PD's positive effects on the CCD of different cities were consistent. The increase in PD can bring about the agglomeration effect, improve the utilization rate of resources and energy, and make the energy utilization gradually achieve intensification and become more efficient. The areas with high values were distributed in southern Shaanxi, Ningxia, and southern Gansu, while low-value areas were distributed in Qinghai and Inner Mongolia. The distribution pattern was 'high in the south and the east, and low in the north and the west'. This was mainly due to the regional differences in population carrying capacity, with the south carrying more people than the north and the east carrying more people than the west.

INT showed a clearly circular structure with a positive effect of location on CCD (Fig. 9d). This indicates that the resource endowments of the upper, middle, and lower reaches of the Yellow River Basin differ greatly. The high-value areas were mainly concentrated around the 'Qinghai-Northern Gansu-Western Inner Mongolia'. Of these variables, the INT had the weakest impact in terms of its coefficient. It should be noted that the INT indicates how different locations affect the CCD when other variables are kept constant. Aside from natural and social factors that could be controlled, INT could also reflect the impacts of regional factors such as resource endowment and economic development.

PSE had a negative correlation with CCD, with a maximum regression coefficient of –0.022, a minimum value of –0.889, and a mean value of –0.262. Regarding the absolute value of the coefficients, PSE's influence intensity was weak. This indicates that the YRB is facing a lack of motivation in science and technology innovation. Spatially, the impacted areas were relatively small and only played an important negative driving role in parts of the upper reaches (Fig. 9e), which reflects that parts of the upper reaches are facing brain drain and insufficient scientific and technological innovation capacity. It also illustrates that the improvement of the CCD still depends on the large-scale development of resource endowment, and the basin's sustainable development capacity needs to be urgently improved.

UR also showed a significant negative correlation with CCD (Fig. 9f). In terms of absolute coefficient, UR showed a strong degree of influence. Urbanization development can increase the human demand for various resources and intensify the pressure on WEF, especially with the expansion of construction land occupying certain cultivated land, which seriously affects food security. The areas with high values of UR regression coefficients were concentrated in Shandong, eastern Mongolia, and northern Shanxi, while the areas with low values were concentrated in Gansu and southern Shaanxi. This was mainly due to the high labor-economic elasticity coefficient in high-value areas: each additional urban resident consumed more water, food, and energy, thus causing a larger variation in the combined WEF index per unit of UR, making its coupling less coordinated.

5 Discussion

5.1 Evaluation of WEF subsystems

The natural conditions and resource endowments of dif-

ferent areas in the YRB show great disparities. And there is also an insurmountable divide in the economic development of different regions in the YRB, reflecting the imbalance among the upper, middle, and lower reaches. According to the Food and Agriculture Organization of the United States (FAO), there is a symbiotic relationship among WEF, both as input and output products of economic trade and as natural ecological factors (D'Odorico et al., 2018). Considering the great variation within the basin, this study attempts to adopt a comprehensive evaluation method applying barrel theory to evaluate the development level of the three subsystems, which could provide a new idea for related research. This study showed that the index of the water and food subsystem had increased, while the energy subsystem showed the opposite. This has similarities and differences with the study by (Xu et al., 2021). The reason for this was that we had chosen the cities as the study scale, which can better reveal the variations of the WEF subsystems compared to the provincial scale. Additionally, we also found that the spatial distribution of the evaluation index of the WEF subsystem in the YRB was consistent with their resource endowment distribution pattern, which was similar to the previous literature's results (Han et al., 2020; Li and Zhang, 2020). Comparatively speaking, the level of energy subsystem for Shandong in this study was not very high, mainly because Shandong has a low energy self-sufficiency rate and high coal and oil consumption.

5.2   Explanation on the CCD of the WEF

The development level of the WEF subsystem is related to the coupling coordination level of the whole system (Mercure et al., 2019; Sun et al., 2021). Due to the different natural resource endowments of various cities, the subsystem will face varying degrees of pressure under the influence of social factors such as population and economic structure. Thus, the development and changes of each subsystem in cities could affect the CCD of the WEF system.

WEF are highly interconnected and interdependent, and exploring the linkages among them is a challenging process, especially at the scale of the cities within the basin. In this study, we analyzed the coupling coordination for the WEF by using a modified CCDM, improving the reliability of the results (Wang et al., 2021a). We found that the CCD level of WEF in the YRB showed

an upward trend, but the overall level was not high (remained at moderate coordination) and there were large differences within the region. This conclusion was similar to the existing research results (Xu et al., 2021; Zhao et al., 2021). Compared to provincial-scale resource studies, this study can exactly highlight the individual characteristics of the development level of WEF in different cities. Furthermore, we found that the spatial agglomeration phenomenon of the CCD was obvious, with a more serious polarization of the basin, and this imbalance gradually increased. Constrained by regional resource and environmental conditions, and as the economic development level of lower reaches improves, the differences in the CCD among the upper, middle, and lower reaches are challenging to fundamental transformations.

5.3   Interpretation of driving mechanisms for WEF coordination

The factors influencing the WEF coordination vary from region to region. In addition to natural endowments, economic levels, and the ability to exploit resources, natural disasters, and regional policies could have a certain impact on the coordination of WEF in various regions. Unlike previous studies (Bai and Zhang, 2018; Xu et al., 2021), we used MGWR to analyze spatial scale differences of CCD.

Overall, the CCD in the YRB was more strongly driven by economic factors. Benefiting from national major development strategies and geographic advantages, economic development has made a significant contribution to the improvement of the overall CCD, but there were differences in the size of its contribution to each region or city. This view was supported by Li and Zhang. (2020). They argued that regions with a high level of economic development, a rational industrial structure, and well-developed infrastructure, had more advantages in terms of population, talent, and materials. These advantages can provide a good development space for the utilization of WEF and promote their CCD. This study also concluded that AYP significantly influenced the CCD, with a maximum regression coefficient of 0.864. Studies have shown that climate has a significant impact on the development of the WEF nexus, especially for critical regions such as socio-economically vulnerable areas and agricultural areas (Clay et al., 2014; Conway et al., 2015). Contrary to the research of Qin and Tong (2021),

this study found that PSE played an important negative driving role for the YRB, particularly in the upper reaches. This reflects that the YRB is facing the problem of improving scientific and technological development levels, and the path to stimulate the driving effect of innovation is long and arduous (Lu et al., 2020).

5.4   Limitations and future prospects

Although this study provides theoretical guidance and practical exploration for better coordinating the WEF nexus, there are some limitations that need further improvement. Firstly, as the statistical caliber of the relevant data in different regions is not completely unified, this study can only use the current index system for analysis, and regard the WEF system of each city as an independent individual and explore its CCD level. In the future, the flow network of water, energy, and food resources can be described by defining the resources flow boundary. Secondly, considering the availability of data, this study only studies the coupling coordination evolution characteristics of four-time nodes, and future research should start from long time series and multi-scale. Furthermore, in terms of driving factors, although we have selected important indicators from the natural environment and socio-economic development, they may not fully reveal the coupling mechanism of WEF. In the future, the impact of difficult-to-quantify factors such as policy factors on the WEF nexus should be included.

6   Conclusions and Policy Implications

6.1   Conclusions

In the context of ecological civilization, accelerating the construction of the WEF nexus security system is a matter of sustainable human development. In the new stage of ecological protection and high-quality development of the YRB, China, how to improve the efficiency of WEF utilization is the difficulty and the key point. To this end, from the city scale, we measured the CCD of WEF in the YRB from 2003 to 2018 and explored the spatial clustering characteristics and driving mechanisms among them. It drew the following conclusions: 1) the indices of the water and food subsystems exhibited an upward trend, while the energy subsystem index was on the contrary, and their spatial distribution patterns were consistent with the distribution of WEF re-

source endowments. 2) The overall trend of CCD showed a 'V'-shaped fluctuation, but remained at moderate coordination; spatially, it displayed a gradient distribution of downstream > midstream > upstream, and the imbalance of CCD increased. 3) MGWR analysis found that the CCD was driven by a combination of natural and socioeconomic factors, with large differences in the scales of different variables. Notably, GPC contributed the most to the coupling coordination of regional development. The marginal contributions of this study include: firstly, a theoretical framework and a multi-dimensional evaluation index system of WEF were constructed; secondly, the coupling coordination characteristics and mechanisms were verified from the mesoscopic scale; and finally, relevant policy implications were drawn from the key findings.

6.2   Policy implications

(1) Integrate WEF resources and improve the supply-side structure of different resources. The essence of watershed creation and revitalization is born from water and flourished along the river. The most important problem of the suboptimal CCD of the WEF system is the uneven distribution of the three resources and the low efficiency of resource utilization in the YRB. The upper reaches of the YRB are relatively rich in water resource, but economic development is lagging behind. Considering the stronger water demand of YRB in the future, water resources constraints will become more obvious. Therefore, it's urgent to strengthen the economical and intensive use of water resources and to make it the greatest rigid constraint to guarantee the high-quality development of the YRB. As the middle reaches is an important energy center of gravity in China, long-term rough development has led to numerous ecological problems, so there is a need to explore a model that matches energy development with the ecological environment. For the lower reaches, it has a high level of economic development, but it is also an important food-producing area, and relevant measures should be introduced to prevent the squeezing of cultivated land space by economic development.

(2) Enhance the shortage factor of CCD for WEF nexus, and promote the optimization of scarce resource allocation with differentiated policies. Scarcity resource allocation is the core of economics and the key to solving WEF. The upper reaches can promote economic de-

velopment level by fostering the free flow of resources, technology, talents, and other factors. For the middle reaches, it is necessary to accelerate the green and low-carbon transformation of the coal power and coal chemical industries to achieve the whole process of water-saving operation and to increase the treatment and reuse efforts, so as to improve the reuse rate of the enterprises' own wastewater. However, the various influence factors have minimal impacts on the lower reaches, thus implying that the traditional path of factor-driven economic development has been not suitable for the lower reaches' demands. Therefore, it is urgent to transform the mode of economic development, strengthen the reform on the market-based collocation of production factors, and enhance the level of scientific and technological development. It should also vigorously foster the development of technology and data markets, and fundamentally promote the CCD of the WEF system.

(3) Reshape the WEF green industry form and promote WEF cross-regional resource flow and synergistic development. Since not a single region can have all the resources, it is wise to seek a union. Therefore, it is necessary to establish the concept of harmonious coexistence between humans and nature, improve the ecological carrying capacity of the WEF nexus system, realize the green development of the region, and enhance the overall benefits. Meanwhile, there is a clustering characteristic of the WEF system coordination degree, so we should actively embrace the spillover effect and radiation drive of the areas with a high level of CCD to the neighboring areas while paying attention to the areas with a low level of CCD, and find the optimal model of WEF system according to local conditions. Additionally, the cross-regional flow of resources should be fully mobilized to achieve the synergistic development of resource elements in the YRB. Guided by industrial integration, urban-rural integration, and factor integration, we will promote the optimization of industrial structure, integrated urban-rural development, and interoperability of resource elements in an integrated manner to achieve sustainable development of the whole region.

References

Abdel-Aal M, Haltas I, Varga L, 2020. Modelling the diffusion and operation of anaerobic digestions in Great Britain under future scenarios within the scope of water-energy-food nexus. *Journal of Cleaner Production*, 253: 119897. doi: 10.1016/j.jclepro.2019.119897

Albrecht T R, Crootof A, Scott C A, 2017. The water-energy-food Nexus: a systematic review of methods for nexus assessment. *Environmental Research Letters*, 13(4): 043002. doi: 10.1088/1748-9326/aaa9c6

Bai Jingfeng, Zhang Haijun, 2018. Spatio-temporal variation and driving force of water-energy-food pressure in China. *Scientia Geographica Sinica*, 38(10): 1653–1660. (in Chinese)

Bazilian M, Rogner H, Howells M et al., 2011. Considering the energy, water and food nexus: towards an integrated modelling approach. *Energy Policy*, 39(12): 7896–7906. doi: 10.1016/j.enpol.2011.09.039

Biggs E M, Bruce E, Boruff B et al., 2015. Sustainable development and the water-energy-food nexus: a perspective on livelihoods. *Environmental Science and Policy*, 54: 389–397. doi: 10.1016/j.envsci.2015.08.002

Chen Junyu, Wang Huimin, Liu Gang et al., 2019. Evaluation of ecosystem services and its adaptive policies in the Hangjiahu region under water-energy-food nexus. *Resources and Environment in the Yangtze Basin*, 28(3): 542–553. (in Chinese)

Chen J B, Wen S B, Liu Y C, 2022. Research on the efficiency of the mining industry in China from the perspective of time and space. *Resources Policy*, 75: 102475. doi: 10.1016/j.resourpol.2021.102475

Clay D E, Clay S A, Reitsma K D et al., 2014. Does the conversion of grasslands to row crop production in semi-arid areas threaten global food supplies? *Global Food Security*, 3(1): 22–30. doi: 10.1016/j.gfs.2013.12.002

Conway D, van Garderen E A, Deryng D et al., 2015. Climate and southern Africa's water-energy-food nexus. *Nature Climate Change*, 5(9): 837–846. doi: 10.1038/nclimate2735

D'Odorico P, Davis K F, Rosa L et al., 2018. The global food-energy-water nexus. *Reviews of Geophysics*, 56(3): 456–531. doi: 10.1029/2017RG000591

Endo A, Tsurita I, Burnett K et al., 2017. A review of the current state of research on the water, energy, and food nexus. *Journal of Hydrology:Regional Studies*, 11: 20–30. doi: 10.1016/j.ejrh.2015.11.010

Fouladi J, AlNouss A, Al-Ansari T, 2021. Sustainable energy-water-food nexus integration and optimisation in eco-industrial parks. *Computers and Chemical Engineering*, 146: 107229. doi: 10.1016/j.compchemeng.2021.107229

Frankowska A, Jeswani H K, Azapagic A, 2019. Environmental sustainability issues in the food-energy-water nexus in the UK vegetables sector: energy and water consumption. *Energy Procedia*, 161: 150–156. doi: 10.1016/j.egypro.2019.02.074

Fuso Nerini F, Tomei J, To L S et al., 2018. Mapping synergies and trade-offs between energy and the sustainable development goals. *Nature Energy*, 3(1): 10–15. doi: 10.1038/s41560-017-0036-5

Han D N, Yu D Y, Cao Q, 2020. Assessment on the features of coupling interaction of the food-energy-water nexus in China. *Journal of Cleaner Production*, 249: 119379. doi: 10.1016/j.jclepro.2019.119379

Hellegers P, Zilberman D, Steduto P et al., 2008. Interactions

between water, energy, food and environment: evolving perspectives and policy issues. *Water Policy*, 10(S1): 1–10. doi: 10.2166/wp.2008.048

Hoff H, 2011. *Understanding the Nexus: Background paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus*. Stockholm, Sweden: Stockholm Environment Institute.

Howells M, Rogner H H, 2014. Assessing integrated systems. *Nature Climate Change*, 4(4): 246–247. doi: 10.1038/nclimate2180

Hussien W A, Memon F A, Savic D A, 2018. A risk-based assessment of the household water-energy-food nexus under the impact of seasonal variability. *Journal of Cleaner Production*, 171: 1275–1289. doi: 10.1016/j.jclepro.2017.10.094

Li Chengyu, Zhang Shiqiang, 2020. Chinese provincial water-energy-food coupling coordination degree and influencing factors research. *China Population, Resources and Environment*, 30(1): 120–128. (in Chinese)

Li Guijun, Huang Daohan, Li Yulong, 2016. Water-Energy-Food Nexus (WEF-Nexus): new perspective on regional sustainable development. *Journal of Central University of Finance and Economics*, (12): 76–90. (in Chinese)

Li T H, Ding Y, Xia W, 2018. An integrated method for waterway health assessment: a case in the Jingjiang Reach of the Yangtze River, China. *Physical Geography*, 39(1): 67–83. doi: 10.1080/02723646.2017.1345537

Lu X, Qu Y, Sun P L et al., 2020. Green transition of cultivated land use in the Yellow River Basin: a perspective of green utilization efficiency evaluation. *Land*, 9(12): 475. doi: 10.3390/land9120475

Martinez-Hernandez E, Leach M, Yang A D, 2017. Understanding water-energy-food and ecosystem interactions using the nexus simulation tool NexSym. *Applied Energy*, 206: 1009–1021. doi: 10.1016/j.apenergy.2017.09.022

Mercure J F, Paim M A, Bocquillon P, 2019. System complexity and policy integration challenges: the Brazilian energy-water-food nexus. *Renewable and Sustainable Energy Reviews*, 105: 230–243. doi: 10.1016/j.rser.2019.01.045

Olawuyi D, 2020. Sustainable development and the water-energy-food nexus: legal challenges and emerging solutions. *Environmental Science and Policy*, 103: 1–9. doi: 10.1016/j.envsci.2019.10.009

Qin Teng, Tong Jinping, 2021. Spatiotemporal change of water-energy-food coupling efficiency and influencing factors in the Yangtze River economic belt. *Resources Science*, 43(10): 2068–2080. (in Chinese)

Salmoral G, Yan X Y, 2018. Food-energy-water nexus: a life cycle analysis on virtual water and embodied energy in food consumption in the Tamar catchment, UK. *Resources, Conservation and Recycling*, 133: 320–330. doi: 10.1016/j.resconrec.2018.01.018

Scott C A, Pierce S A, Pasqualetti M J et al., 2011. Policy and institutional dimensions of the water-energy nexus. *Energy Policy*, 39(10): 6622–6630. doi: 10.1016/j.enpol.2011.08.013

Shen Tiyan, Yu Hanchen, Zhou Lin et al., 2020. On hedonic price of second-hand houses in Beijing based on multi-scale Geographically Weighted Regression: scale law of spatial heterogeneity. *Economic Geography*, 40(3): 75–83. (in Chinese)

Sun C Z, Yan X D, Zhao L S, 2021. Coupling efficiency measurement and spatial correlation characteristic of water-energy-food nexus in China. *Resources, Conservation and Recycling*, 164: 105151. doi: 10.1016/j.resconrec.2020.105151

Taniguchi M, Endo A, Gurdak J J et al., 2017. Water-energy-food nexus in the Asia-Pacific region. *Journal of Hydrology: Regional Studies*, 11: 1–8. doi: 10.1016/j.ejrh.2017.06.004

Wang M, Zhu Y F, Gong S W et al., 2021a. Spatiotemporal differences and spatial convergence of the water-energy-food-ecology nexus in Northwest China. *Frontiers in Energy Research*, 9: 665140. doi: 10.3389/fenrg.2021.665140

Wang Shujia, Kong Wei, Ren Liang et al., 2021b. Research on misuses and modification of coupling coordination degree model in China. *Journal of Natural Resources*, 36(3): 793–810. (in Chinese)

Wen C L, Dong W H, Zhang Q C et al., 2022. A system dynamics model to simulate the water-energy-food nexus of resource-based regions: a case study in Daqing City, China. *Science of the Total Environment*, 806: 150497. doi: 10.1016/j.scitotenv.2021.150497

Xiao W, Chen W Q, Deng X Y, 2021. Coupling and coordination of coal mining intensity and social-ecological resilience in China. *Ecological Indicators*, 131: 108167. doi: 10.1016/j.ecolind.2021.108167

Xu Hui, Wang Yiwen, Zhang Zongyan et al., 2021. Coupling mechanism of water-energy-food and spatiotemporal evolution of coordinated development in the Yellow River Basin. *Resources Science*, 43(12): 2526–2537. (in Chinese)

Yin D Y, Yu H C, Ma J et al., 2022. Interaction and coupling mechanism between recessive land use transition and food security: a case study of the Yellow River Basin in China. *Agriculture*, 12(1): 58. doi: 10.3390/agriculture12010058

Yin D Y, Yu H C, Shi Y Y et al., 2023. Matching supply and demand for ecosystem services in the Yellow River Basin, China: a perspective of the water-energy-food nexus. *Journal of Cleaner Production*, 384: 135469. doi: 10.1016/j.jclepro.2022.135469

Yin X L, Xu Z R, 2022. An empirical analysis of the coupling and coordinative development of China's green finance and economic growth. *Resources Policy*, 75: 102476. doi: 10.1016/j.resourpol.2021.102476

Yuan M H, Chiueh P T, Lo S L, 2021. Measuring urban food-energy-water nexus sustainability: finding solutions for cities. *Science of the Total Environment*, 752: 141954. doi: 10.1016/j.scitotenv.2020.141954

Zhang C, Chen X X, Li Y et al., 2018. Water-energy-food nexus: concepts, questions and methodologies. *Journal of Cleaner Production*, 195: 625–639. doi: 10.1016/j.jclepro.2018.05.194

Zhao Liangshi, Liu Sijia, Sun Caizhi, 2021. Study on coupling and coordinated development of water-energy-food security system in the Yellow River Basin. *Water Resources Protection*, 37(1): 69–78. (in Chinese)