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# Research on the synergy of the water–energy–food composite system in the Beijing–Tianjin–Hebei region

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## ABSTRACT

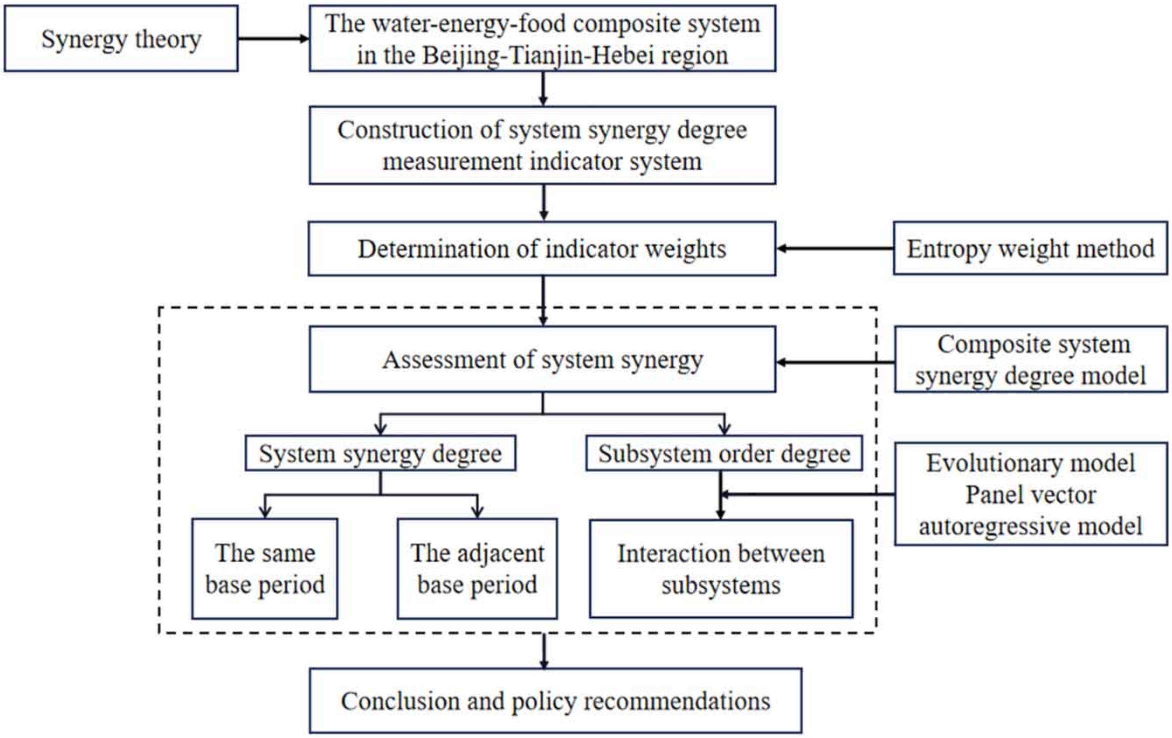
Water, energy, and food are interdependent and mutually restrictive, and changes in any one resource may have an impact on the others. In order to promote the sustainable utilization of resources, it is important to study the synergy of the water–energy–food composite system (WEFCS). Taking the Beijing–Tianjin–Hebei region as an example, this study adopts the composite system synergy degree model to quantitatively measure the synergy degree of WEFCS from 2011 to 2021, then constructs an evolutionary model to identify the interactions between the subsystems, and finally analyzes the interactions dynamically by using the panel vector autoregression model. The results show that the WEFCS synergy level in the Beijing–Tianjin–Hebei region is generally basic and shows low stability during the study period. Regional subsystems are more dependent than collaborative or competitive. Moreover, the regional water subsystem has a short-term positive impact on the energy subsystem, the energy subsystem has a short-term negative impact on the food subsystem, and the food subsystem has a delayed and complex influence on the water and energy subsystems, with the water subsystem being particularly affected. This study provides a decision-making basis for policymakers to optimize resource allocation.

**Key words:** Composite system synergy degree model, Evolutionary model, Sustainable development, Water–energy–food composite system

## HIGHLIGHTS

- Measure system synergies in terms of the same and adjacent base periods.
- The evolutionary model is used to determine the type of collaborative interaction between subsystems.
- The dynamic interactions between subsystems are further analyzed.
- The establishment of the index system considers the connection between subsystems.
- The level of synergy in the regional WEFCS is basic and exhibits low stability.

## GRAPHICAL ABSTRACT



## 1. INTRODUCTION

Water, energy, and food are fundamental and strategic resources essential for human survival and social development (Chang *et al.*, 2016). Each of these resources relies on the other two, creating a complex interconnection. As the population grows and social development accelerates, the demand for water, energy, and food is expected to rise. It is projected that by 2030, the demand for these resources will increase to 40, 35, and 50%, respectively (Rzepczynski, 2014). Currently, issues such as climate change, ecological degradation, and other related challenges are escalating. Given the interconnected nature of these resources, studying them in isolation hinders the promotion of their coordinated development. Therefore, it is necessary to study the collaborative evolution of water, energy, and food as a composite system.

Since the water–energy–food (WEF) nexus was proposed, domestic and foreign scholars have conducted numerous studies on it from various perspectives, yielding abundant results. These include coupling coordination (Qi *et al.*, 2022), risk (Ding & Chen, 2023), symbiosis (Fu *et al.*, 2023), efficiency (Li & Huang, 2023), security (Nkiaka *et al.*, 2021), and sustainability (Qian & Liang, 2021). Additionally, some scholars have explored the synergistic state of the system. It has been observed that the WEF system has been in a state of low cooperative evolution for an extended period, with a lack of synergy among some subsystems (Sun & Hao, 2022; Zhi *et al.*, 2022). Studying the synergistic relationship of the WEF system is crucial as it can offer insights into the sustainable use of resources. Currently, scholars have conducted relevant studies on the synergy within the WEF system. Qualitatively, Gu *et al.* (2016) examined the synergy between energy consumption and water use from various angles. Zhang *et al.* (2013) proposed a synergistic strategy for water resources and food security based on the current development status of food and water resources in China. Srigiri & Dombrowsky (2022) conceptualized the WEF nexus as a multi-center system, comprehended the system's components and their logical interrelationships, and suggested achieving coordination through the collaborative integration of governance models. Quantitatively, on the one hand, some scholars have employed different methods to investigate the synergistic relationship of the system. Peng *et al.* (2017) introduced the synergetic theory, developed a WEF collaborative optimization model, and conducted an empirical analysis focusing on the Yellow River Basin to achieve an integrated and optimal layout of food production, energy development, and water resource deployment in the basin. Li *et al.* (2019) constructed a synergy network to explore the synergy effect within the urban WEF nexus in Shenzhen. Liu & Zhao (2022) utilized the improved Lotka-Volterra symbiosis model to evaluate the synergistic evolution status of the WEF nexus system in the Yellow River Basin. Ren *et al.* (2021) developed a regional WEF system collaborative development model based on complex adaptive system theory, co-evolution algorithm, and grey correlation analysis method, using Heilongjiang Province as a case study to empirically analyze the system's collaborative development. Conversely, some scholars primarily concentrate on the synergy of the WEF system in agricultural regions. Alam *et al.* (2019) employed remote sensing and hydrologic models to quantify the water and energy footprints of crops and analyzed their spatio-temporal changes in order to comprehensively evaluate the interaction of the WEF system in the Central Valley of California, aiding in better management of agricultural system development. Do *et al.* (2020) investigated the synergistic effects of the water–food–energy nexus in the Lancang-Mekong River Basin by employing an integrated hydro-economic optimization model, discovering that tradeoffs could be transformed into synergy, and dam operation could enhance irrigation water use and increase income from irrigated crops without significantly compromising hydropower production. Li *et al.* (2021) introduced a relative index of the water–energy–food system ($\mathrm{WEF}_{\mathrm{RI}}$) to analyze the synergies among water use, energy consumption, and food supply of different planting structures at the field scale. Additionally, synergies between resources have been explored to facilitate sustainable resource utilization. Radmehr *et al.* (2021) proposed a multi-criteria decision nonlinear programming method that not only optimizes resource allocation during food production but also assesses management policies for regional resource planning, offering decision-makers effective strategies for integrated planning for groundwater, energy, and food. Sargentis *et al.* (2021) examined the relationship between the development of photovoltaic power plants and food production in the Thessaly Plain, the largest agricultural area in Greece, aiming to uncover conflicts and synergies between the two, thereby mitigating negative impacts on the other three resources caused by the utilization of water, energy, food, and land. Caixeta *et al.* (2022) introduced a sustainability-focused excellence model that integrates WEF principles and the business excellence model to assist agro-industrial companies in managing tradeoffs and synergies between resources and transitioning toward enhancing sustainability. Kitessa *et al.* (2022) explored various feasible scenarios to enhance access and sustainability of resources in Addis Ababa city based on the WEF nexus modeling approach.

Most of the existing literature uses various models to study the synergy of the WEF system but rarely analyzes the degree of system synergy and the interaction between subsystems. As one of China's economic growth poles, the Beijing–Tianjin–Hebei region faces significant pressure in terms of water, energy, and food demand. These three regions have different levels of development, as well as varying natural resource endowments and usage structures (Liu *et al.*, 2023). Therefore, this paper focuses on the Beijing–Tianjin–Hebei region as a case study and employs the composite system synergy degree model, the improved logistic model, and the panel vector autoregressive model (PVAR) to comprehensively analyze the synergy of the water–energy–food composite system (WEFCS). The aim is to provide insights for sustainable resource utilization and regional collaborative development.

## 2. STUDY AREA AND METHODS

This section consists of four parts: (1) status of regional resources; (2) data sources; (3) theoretical analysis, in which the collaborative framework of the WEFCS is constructed and the evaluation index system of synergy degree is established; and (4) research methods, including the entropy weight method used to determine the weight of indicators, the model to study the system's synergy degree, and the evolutionary model and panel vector autoregressive models to study subsystems.

### 2.1. Study area

Located in the heart of the Bohai Sea in Northeast China, the Beijing–Tianjin–Hebei region, which includes Beijing, Tianjin, and Hebei province, is an important economic and population agglomeration area in China. In 2021, the GDP of the Beijing–Tianjin–Hebei region reached 9.6 trillion yuan, accounting for 8.93% of the country's total. The total population reached 11.1 million, accounting for 7.8% of the total population. The Beijing–Tianjin–Hebei region is inherently deficient in water resources, with per capita water resources in 2021 only 357.83 m$^3$, far lower than the national average of 2,098.5 m$^3$. The total energy consumption was 478.938 million tons of standard coal, accounting for 9.14% of the total energy consumption of the country; China's total food production was 41.128 million tons, accounting for 6.02% of the country's total food production. Economic development and population agglomeration bring pressure on the WEF system, and the interrelated and restrictive characteristics of the three resources are gradually emerging. Considering only one resource will slow down the development of other resources. Therefore, it is of great significance to take the Beijing–Tianjin–Hebei region as an example to study the synergy of the WEFCS.

### 2.2. Data sources

The research object of this paper is the Beijing–Tianjin–Hebei region. The data for each indicator are primarily sourced from the China Statistical Yearbook, China Energy Statistical Yearbook, Statistical Yearbook, and Water Resources Bulletin of Beijing, Tianjin, and Hebei from 2011 to 2021. Missing data have been substituted with linear trends. Additionally, to comprehensively evaluate the Beijing–Tianjin–Hebei region, the regional data has been obtained based on the average value of the three cities. The original data are provided in the Supplementary material.

### 2.3. Theoretical analysis

#### 2.3.1. System synergy relationship framework

Synergy theory was proposed by Haken in 1977 to study how composite systems are affected by the cooperation of subsystems. The WEFCS itself contains many elements and variables. According to the principle of the order parameter, the order parameter is generated by the competition and cooperation among the subsystems of water, energy, and food; otherwise, the order parameter cannot be generated spontaneously. Moreover, according to the principle of domination, if a certain element in a composite system has a greater influence on its ordered evolution, the element is an order parameter and plays a dominant role in the development of the regulatory system. In general, the order parameter can be any element or multiple elements in the three subsystems of water, energy, and food. Additionally, when subjected to external disturbances such as nature and society, the composite system will evolve into a new structure. Under the synergistic action of water, energy, and food subsystems, new order parameters will be further generated and control the synergistic development of the

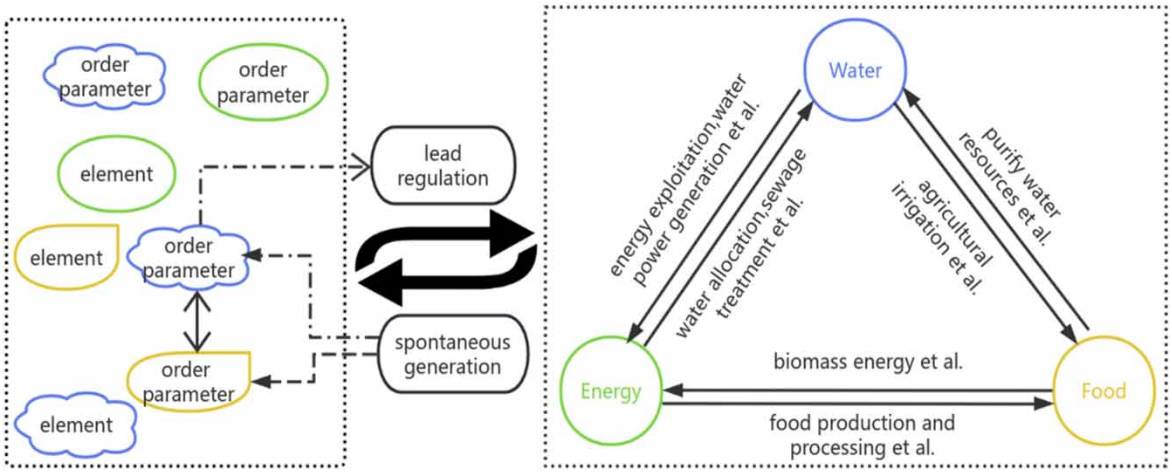


**Fig. 1** | The collaborative framework of the WEFCS.

composite system. In this repeated cycle, the system will gradually evolve to a more advanced state of stable synergistic development. The collaborative framework of the WEFCS is illustrated in Figure 1.

As illustrated in Figure 1, the interdependence of resources is evident in various aspects: Hydropower generation and fossil energy extraction rely on water resources, essential for irrigation and crop growth. The management of water resources, sewage treatment, and recycling processes necessitate significant energy consumption. Additionally, energy is crucial for food production and processing. Food, a fundamental human necessity, serves as a cornerstone for water and energy security. Rice cultivation can contribute to water purification, while crops like corn, wheat, and cassava offer bioenergy resources. Nonetheless, there are adverse interactions among these resources. Water scarcity directly impacts food irrigation and growth, resulting in reduced food production. In areas where water is scarce, hydropower generation can be greatly affected, and some energy production methods, such as thermal power generation and shale gas extraction, can be limited. Wastewater and emissions from fossil energy extraction and processing can pollute water resources and soil, affecting the cultivation of food crops. Fertilizers, pesticides, and other chemicals used in food production can likewise pollute water resources. In summary, water, energy, and food promote and constrain each other, and the synergistic effect between their corresponding sequential parameters dominates the synergistic evolution of the composite system, which will gradually form a more advanced and stable structure.

### 2.3.2. Indicator system construction

With reference to the existing research results (Zhang *et al.*, 2019; Zhi *et al.*, 2020), and in accordance with the systematic, typical, scientific, and operational principles of index selection as well as the availability of data, the WEFCS synergy degree measurement indicator system is constructed. For the water and energy subsystems, indicators are selected from the aspects of supply, consumption, and pollution; for the food subsystem, indicators are selected from the two aspects of production and consumption. In addition, this paper adds the water resources consumed by energy and food production into the level of water consumption, the rural electricity consumption into the level of energy consumption, the irrigated area of cultivated land, and the total power of agricultural

**Table 1** | WEFCS synergy degree measurement indicator.

| Subsystem | Dimension | Indicator | Unit | Attribute | Weights |
|---|---|---|---|---|---|
| Water | Supply | W1: Water resources per capita | $m^3$/person | + | 0.09955 |
| | | W2: Average precipitation | mm | + | 0.10796 |
| | Consumption | W3: Water consumption per capita | $m^3$/person | − | 0.12667 |
| | | W4: Water consumption per 10,000 yuan GDP | $m^3$/10,000 yuan | − | 0.17084 |
| | | W5: Water consumption for energy production | Billion $m^3$ | − | 0.12777 |
| | | W6: Total water use for agriculture | Billion $m^3$ | − | 0.28473 |
| | Pollution | W7: Total sewage discharge | Billion $m^3$ | − | 0.08248 |
| Energy | Supply | E1: Primary energy production | 10,000 tons of standard coal | + | 0.12547 |
| | | E2: Energy production per capita | Tons of standard coal | + | 0.18196 |
| | Consumption | E3: Energy consumption per capita | Tons of standard coal | − | 0.12598 |
| | | E4: Energy consumption of 10,000 yuan GDP | Tons of standard coal | − | 0.09369 |
| | | E5: Rural electricity consumption | 10,000 kW/h | − | 0.18605 |
| | Pollution | E6: Industrial sulfur dioxide emissions | tons | − | 0.28684 |
| Food | Production | F1: Food production per capita | kg | + | 0.10421 |
| | | F2: Food production per unit area | kg/$hm^2$ | + | 0.0469 |
| | | F3: Area sown in food crops | 10,000 $hm^2$ | + | 0.1849 |
| | | F4:Gross power of agricultural machinery | 10,000 kW | + | 0.19483 |
| | | F5: Cropland irrigated area | 1,000 $hm^2$ | + | 0.18625 |
| | Consumption | F6: Food consumption per capita | kg | − | 0.03385 |
| | | F7: Deposits of fertilizer applications | 10,000 tons | − | 0.18342 |
| | | F8: Consumer food price index for the population | − | − | 0.06565 |

machinery into the dimension of food production. This reflects the cooperative correlation between subsystems. The specific synergy degree measurement indicator and weight are shown in Table 1.

## 2.4. Research methodology

### 2.4.1. Entropy weight method

The composite system $S = (\mathrm{S1}, \mathrm{S2}, \text{and } \mathrm{S3})$ is defined, where S1 is the water subsystem, S2 is the energy subsystem, and S3 is the food subsystem. To eliminate the impact of dimension, the positive and negative indicators in the original data are standardized, as shown in the following formula:

For the positive indicators:

$$X'_{ij} = \frac{x_{ij} - \min x_j}{\max x_j - \min x_j} \tag{1}$$

For the negative indicators:

$$X'_{ij} = \frac{\max x_j - x_{ij}}{\max x_j - \min x_j} \tag{2}$$

In the formula, $X'_{ij}$ represents the value of indicator $j$ of the standardized sample $i$, $x_{ij}$ represents the initial value, and $\max x_j$ and $\min x_j$ represent the maximum and minimum values of indicator $j$.

The entropy weight method is an objective measurement method used to determine weights based on the extent of data dispersion. This method helps to minimize the impact of human factors on index weights, leading to more objective evaluation results (Chen *et al.*, 2018). In this paper, the entropy weight method is used to determine the weight of each evaluation indicator. The specific calculation formulas are as follows:

$$p_{ij} = \frac{X'_{ij}}{\sum_{i=1}^{n} X'_{ij}} \tag{3}$$

$$E_j = -\frac{1}{\ln n}\sum_{i=1}^{n} p_{ij}\ln p_{ij}\ (i = 1, 2, \ldots, n;\ 0 \le E_j \le 1) \tag{4}$$

where $X'_{ij}$ represents the value of indicator $j$ of the standardized sample $i$.

Finally, the entropy weight of each indicator is obtained as follows:

$$W_{j1} = \frac{1 - E_j}{\sum_{i=1}^{n} (1 - E_j)} \tag{5}$$

The results of indicator weights are shown in Table 1.

### 2.4.2. Composite system synergy degree model

After the weights are obtained, the order degree is calculated using the following formula:

$$u_i(h_{ij}) = \sum_{i=1}^{3} \lambda_{ij} X'_{ij}, \quad i \in [1, 3] \tag{6}$$

where $u_i(h_{ij})$ is the order degree of the subsystem $i$.

When set at the initial time $t_0$, the value of the order degree of each subsystem is $u_i^0(h_i)$, and at the time $t_1$, the value of the order degree is $u_i^1(h_i)$, then the synergy degree of the composite system is:

$$\mathrm{SE} = \emptyset \sqrt[n]{\prod_{i=1}^{n} [u_i^1(h_i) - u_i^0(h_i)]} \tag{7}$$

Synergy $\mathrm{SE} \in [-1, 1]$, and the larger the value, the development of the system has reached high-quality synergy and long-term stability (Meng & Han, 1999), where $\emptyset = \min[u_i^1(h_i) - u_i^0(h_i)]/|\min[u_i^1(h_i) - u_i^0(h_i)]|$. Formula (7) has two calculation criteria. One is based on the same time, and the synergy degree obtained is called the same base period synergy, which is used to describe the long-term evolution trend of the composite system. The other is based on the adjacent time, and the obtained synergy degree is the adjacent base period synergy degree, which is used to describe the development stability of the composite system. The judgment criteria of two different synergy degrees (Xia & He, 2018) are shown in Table 2, in which the grade of the same base period synergy degree is more detailed to comprehensively assess the synergy of the composite system.

### 2.4.3. Evolutionary model

In WEFCS, the synergy among order parameters regulates the stable development of subsystems, and there are also flows of resources, energy, information, and other forms among subsystems. The self-development and

**Table 2** | Synergy evaluation criteria.

| Same base period synergy degree | Synergy degree level | Adjacent base period synergy degree | Synergy degree stability |
|---|---|---|---|
| $-1 \leq cor \leq -0.66$ | Highly unsynergistic | $-1 \leq cor \leq 0$ | Destabilizing synergy |
| $-0.66 < cor \leq -0.33$ | Moderately unsynergistic | $0 < cor \leq 0.2$ | Low stability synergy |
| $-0.33 < cor \leq 0$ | Mildly unsynergistic | $0.2 < cor \leq 0.6$ | Medium stability synergy |
| $0 < cor \leq 0.33$ | Basic synergy | $0.6 < cor \leq 1$ | High stability synergy |
| $0.33 < cor \leq 0.66$ | Good synergy | | |
| $0.66 < cor \leq 1$ | Quality synergy | | |

synergistic interaction of subsystems make the composite system form a self-organized structure and realize the evolution from disorder to order and from low order to high order. The evolution process of WEFCS is dynamic. Similar to other systems, WEFCS also experience a series of processes, such as birth, growth, maturity, decline, and death, and finally reach a certain orderly state (Fan *et al.*, 2013; Zhang *et al.*, 2020). The logistic model can describe the evolutionary process of multiple subsystems with symbiotic relationships from disorder to order. This model can be expressed by the following formula:

$$\frac{dX}{dt} = \alpha X(1 - X) \tag{8}$$

Based on this, this paper builds the WEFCS evolutionary model:

$$\begin{cases} \dfrac{dW}{dt} = f_1(W, E, F) = \alpha_W W(1 - W - \beta_{WE}WE - \beta_{WF}WF) \\ \dfrac{dE}{dt} = f_2(W, E, F) = \alpha_E E(1 - E - \beta_{EW}EW - \beta_{EF}EF) \\ \dfrac{dF}{dt} = f_3(W, E, F) = \alpha_F F(1 - F - \beta_{FW}FW - \beta_{FE}FE) \end{cases} \tag{9}$$

where $W$, $E$, and $F$ are the order degree of the water resources, energy, and food subsystem, respectively, and $\alpha_W$, $\alpha_E$, and $\alpha_F$ are the development coefficients of the water, energy, and food subsystem itself. When $\alpha_i > 0$ ($i = W, E, F$), the subsystem is growing positively, and vice versa. $\beta_{ij}$ ($i,j = W, E, F, i \neq j$) is the coefficient of interaction between the water, energy, and food subsystems. When $\beta_{ij} > 0$, it indicates that the development of subsystem $j$ inhibits the evolution of subsystem $i$. When $\beta_{ij} < 0$, it indicates that subsystem $j$ promotes the development of subsystem $i$.

Let $f_1(W, E, F) = 0$, $f_2(W, E, F) = 0$, and $f_3(W, E, F) = 0$, resulting in five equilibrium points: $Q_1(0, 0, 0)$, $Q_2(0, 0, 1)$, $Q_3(0, 1, 0)$, $Q_4(1, 0, 0)$, and $Q_5(X_1^0, X_2^0, X_3^0)$. $Q_5$ is the only stabilization point of the composite system. It can be obtained from the following equation:

$$A_1 = \begin{vmatrix} 1 & \beta_{12} & \beta_{13} \\ 1 & 1 & \beta_{23} \\ 1 & \beta_{32} & 1 \end{vmatrix}, \; A_2 = \begin{vmatrix} 1 & 1 & \beta_{13} \\ \beta_{21} & 1 & \beta_{23} \\ \beta_{31} & 1 & 1 \end{vmatrix}, \; A_3 = \begin{vmatrix} 1 & \beta_{12} & 1 \\ \beta_{21} & 1 & 1 \\ \beta_{31} & \beta_{32} & 1 \end{vmatrix}, \; A = \begin{vmatrix} 1 & \beta_{12} & \beta_{13} \\ \beta_{21} & 1 & \beta_{23} \\ \beta_{31} & \beta_{32} & 1 \end{vmatrix} \tag{10}$$

$$Q_5(X_1^0, X_2^0, X_3^0) = Q_5\left(\frac{A_1}{A}, \frac{A_2}{A}, \frac{A_3}{A}\right) \tag{11}$$

To determine the steady-state criterion, the singularity steady-state equation is transformed into a Taylor expansion equation, as shown below:

$$\begin{cases} f_1 = A_{11}(X - X_1^0) + A_{12}(X - X_2^0) + A_{13}(X - X_3^0) \\ f_2 = A_{21}(X - X_1^0) + A_{22}(X - X_2^0) + A_{23}(X - X_3^0) \\ f_3 = A_{31}(X - X_1^0) + A_{32}(X - X_3^0) + A_{33}(X - X_3^0) \end{cases} \tag{12}$$

$$A = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \tag{13}$$

Setting the solutions of the matrix to $\lambda$ ($\lambda_1$, $\lambda_2$, $\lambda_3$), the solutions can be obtained through matrix $A$ as follows:

$$|\lambda E - A| = \lambda^3 - p\lambda^2 + r\lambda - q = 0 \tag{14}$$

According to the Hurwitz criterion, the singular point is asymptotically stable when $\lambda < 0$. Therefore, when $p < 0$, $q < 0$, and $r > 0$, the point $Q_5$ is stable.

Since Formula (9) is a nonlinear equation, in order to obtain the parameters of interaction between subsystems, this paper adopts an accelerated genetic algorithm (AGA), which has the characteristics of strong universality and stable global optimization ability. The general optimization problem is set as follows: $\begin{cases} \min f(c_1, c_2, \ldots, c_i) \\ a_i \le c_i \le b_i \end{cases}$, where ($a_i$, $b_i$) is the initial change interval of $c_i$, and $f$ is the objective function. The new initial space of the algorithm is generated primarily based on the excellent individuals produced during the two iterations of the standard genetic algorithm. Subsequently, the variables are discretized and coded, and other steps are carried out sequentially to expedite the cycle (Jin *et al.*, 2001) until the function value of the optimal individual is less than a certain specified value or the algorithm reaches a predetermined number of acceleration cycles. At this point, the best individual in the current group represents the outcome of AGA.

Based on the AGA, with the minimization of the error sum of squares of the evolutionary model as the objective function and the steady-state criterion as the constraint, the following evolutionary model can be obtained:

$$f = \min \frac{1}{3}\left[\sum_{t=1}^{10}(F_1^t - f_1^t)^2 + \sum_{t=1}^{10}(F_2^t - f_2^t)^2 + \sum_{t=1}^{10}(F_3^t - f_3^t)^2\right] \tag{15}$$

$$\text{s.t.} \quad \begin{cases} p < 0 \\ q < 0 \\ r < 0 \\ 0 < X < 1 \end{cases} \tag{16}$$

where $F_1^t$, $F_2^t$, and $F_3^t$ are the order degrees of the water, energy, and food subsystems, respectively. The model is solved to obtain $\alpha$ and $\beta$, as well as the order degrees of the subsystems at the synergistic steady-state point.

### 2.4.4. Panel vector autoregressive model

The PVAR combines the advantages of the autoregressive model and panel data to better describe the complex relationship between variables. Therefore, this paper utilizes PVAR to explore the interaction response relationship of resource subsystems in the Beijing–Tianjin–Hebei region with the following formula:

$$Y_{it} = \mu_0 + \sum_{p=1}^{n} \delta_j Y_{it-j} + \varphi_i + \gamma_t + \varepsilon_{it} \tag{17}$$

where $i$ represents the region, $t$ is the time, $Y_{it}$ is the endogenous variable consisting of the order degree of the water resources, energy, and food subsystems, $\mu_0$ is the intercept term, $p$ is the lag order, $\delta_j$ is the parameter matrix of the lag order, $\varphi_i$ is the individual fixed effect, $\gamma_t$ represents the time-fixed effect, and $\varepsilon_{it}$ represents the random perturbation term.

## 3. RESULTS AND DISCUSSION

### 3.1. Assessment of synergy degree

Based on the weights of each indicator in Table 1 and the model constructed in Section 2.4.2, the synergy degree of WEFCS in the Beijing–Tianjin–Hebei region as well as in different regions is obtained, as shown in Figure 2.

From the perspective of the same base period synergy degree, during 2012–2014, the same base period synergy degree of Beijing, Tianjin, and the Beijing–Tianjin–Hebei region showed a downward trend as a whole. During 2014–2021, the three regions all showed a 'V' shaped development stage, indicating that the WEFCS coordination was unstable during this period, especially in Tianjin. In Hebei province, the same base period synergy degree increased year by year after 2013, indicating that the synergistic interaction among subsystems in this

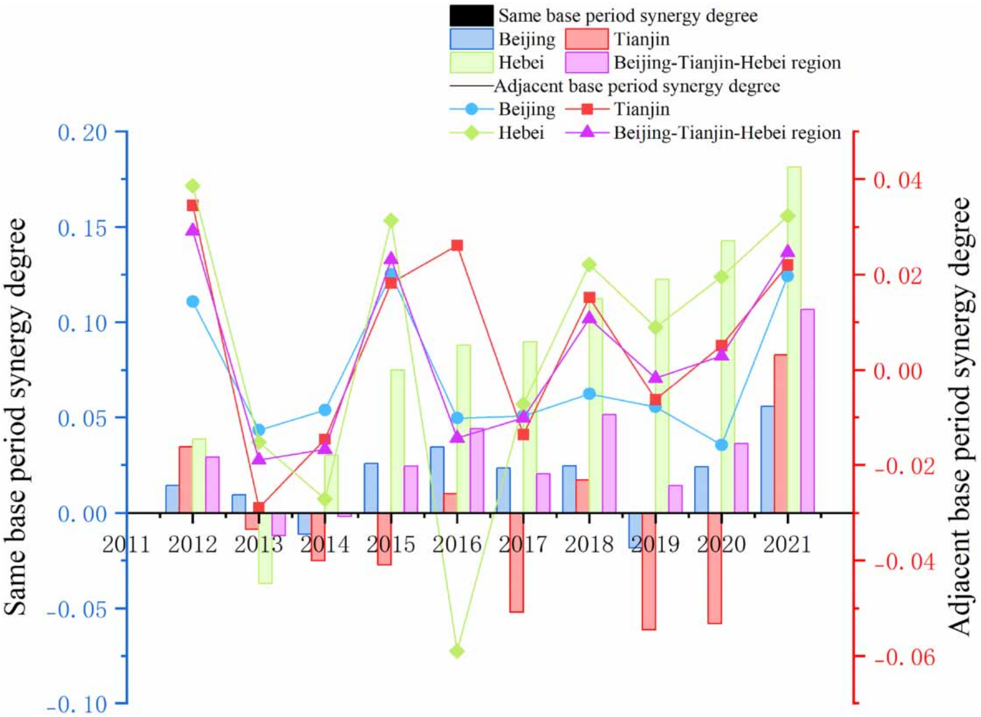


**Fig. 2** | The synergy degree of the WEFCS.

region is improving and evolving toward a better state of synergy. From the perspective of the adjacent base period synergy degree, all of the four changes were between [−0.1, 0.1]. The adjacent base period synergy degree of WEFCS in 2013, 2014, and 2016 showed negative values, with Hebei province experiencing significant fluctuations in 2016, oscillating between positive and negative values. It is evident that the composite system oscillates between low stable and unstable co-evolution states for an extended period, possibly due to substantial changes in the order degree of subsystems over the years.

### 3.2. Analysis of order degree

After analyzing the synergy degree, the order degree of regional subsystems is further examined, as illustrated in Figure 3.

According to Figure 3, it can be seen that in terms of the order degree of the water resources subsystem, Beijing > Tianjin > the Beijing–Tianjin–Hebei region > Hebei province (see Figure 3(a)), with similar trends in the order degree of the water resources subsystems in Beijing, Tianjin, and the Beijing–Tianjin–Hebei region. The water resources subsystem of Hebei province exhibits the fastest development rate, and despite its outward expansion,

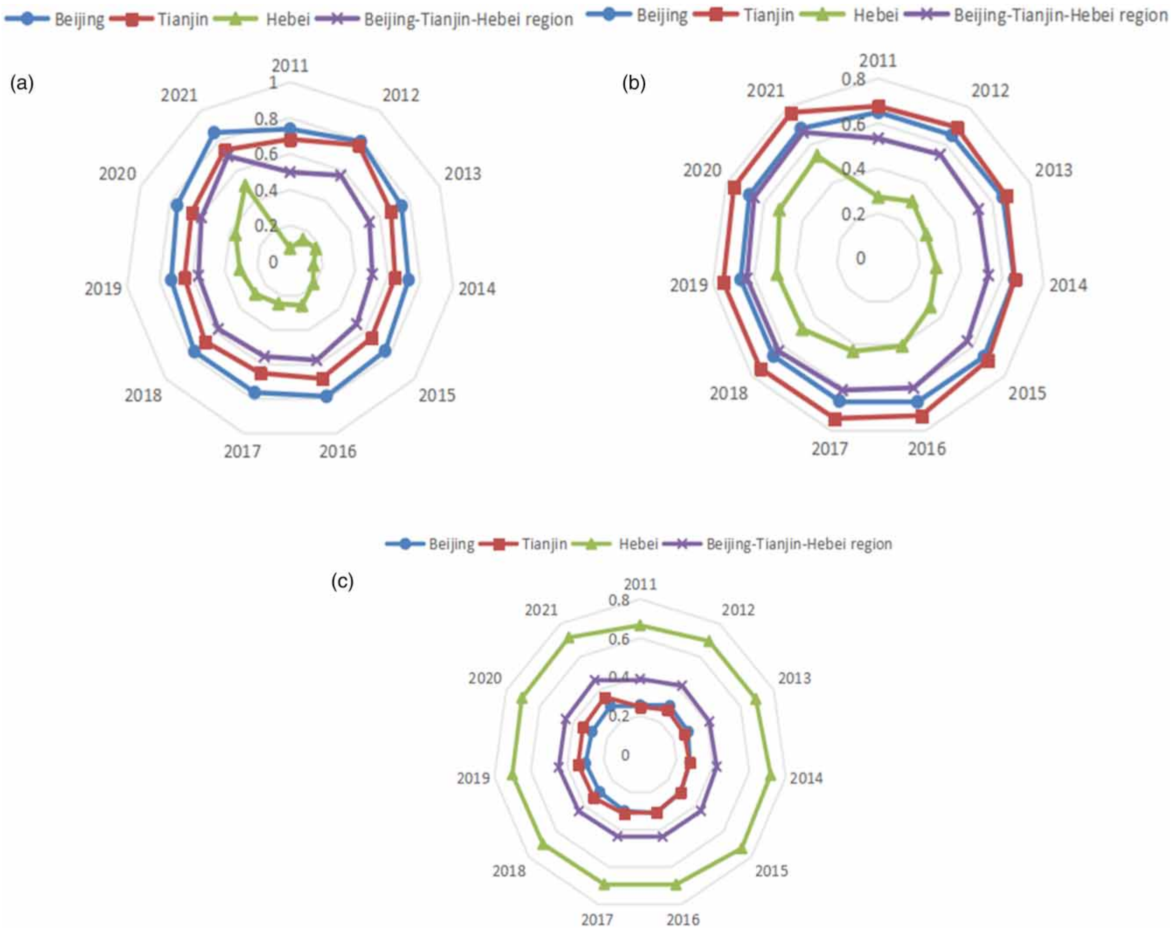


**Fig. 3** | Order degree of subsystems. (a) Water resources subsystem, (b) energy subsystem, (c) food subsystem.

it still lags behind the order degree of the water resources subsystem in the Beijing–Tianjin–Hebei region. This is attributed to the fact that Hebei is a major agricultural province, with an industrial structure dominated by the secondary industry, and that both agriculture and industry consume a large amount of water resources. It is evident that Hebei province should enhance the management of water resources. In terms of the order degree of the energy subsystem, Tianjin > Beijing > the Beijing–Tianjin–Hebei region > Hebei province (see Figure 3(b)). Despite the relatively low order degree of the energy subsystem in Hebei province, its development is quite rapid, while Beijing and the Beijing–Tianjin–Hebei region exhibit a relatively slower development of the energy subsystem. In terms of the order degree of the food subsystem (see Figure 3(c)), the region shows a slow but steady growth trend. Particularly, the order degree of the food subsystem is higher in Hebei province than in the other two cities.

### 3.3. Discrimination of subsystem interaction types

Given that the collaborative state of regional WEFCS has not yet achieved a highly stable state, the water resources and energy subsystems are better developed in Beijing and Tianjin than in Hebei Province, while the food subsystem is better developed in Hebei Province than in Beijing and Tianjin. In order to realize the coordination between resources, the evolutionary model is further used to identify the correlation between the three subsystems. Combined with the order degree values of the subsystems above, the WEFCS evolutionary model is solved by an AGA, and the subsystems themselves and interaction parameters are obtained. The interaction types of subsystems in the Beijing–Tianjin–Hebei region are shown in Table 3.

Table 3 shows that $\alpha_E > 0$, $\alpha_W < 0$, and $\alpha_F < 0$, which indicates that the energy subsystem is evolved in the steady state, while the water and food subsystems are degraded. For the water–energy system, where $\beta_{WE} < 0$ and $\beta_{EW} > 0$, this indicates that the water resources and energy subsystems are interdependent. The clean energy production and utilization process has a relatively low demand for water resources, but in energy production processes such as fossil fuel extraction and thermal power generation, water scarcity may severely constrain energy production, leading to a decrease in the order degree of the energy subsystem. For the water–food system, where $\beta_{WF} > 0$ and $\beta_{FW} < 0$, this means that the water resource and food subsystems are interdependent. Expansion of food cultivation area can increase the order degree of the food subsystem, but this also correspondingly increases the demand for water resources and reduces the order degree of the water subsystem. In turn, an increase in agricultural water use ensures the security of food supply and increases the order degree of the food subsystem. For the energy–food system, $\beta_{EF} < 0$, $\beta_{FE} > 0$, which shows that the energy and food subsystems are interdependent. The Beijing–Tianjin–Hebei region, with its geographical advantages in the North China Plain, has rich food resources and can provide biomass energy for the region, which is conducive to the orderly development of the energy subsystem. However, due to insufficient energy endowment, the region has certain limitations in energy supply, which affects the development of the food subsystem to some extent. Table 3 also indicates that the order degree of the water, energy, and food subsystems in a stable state reaches 1.2441, 1.0174, and 1.5556, respectively. This suggests that the water, energy, and food subsystems still require further

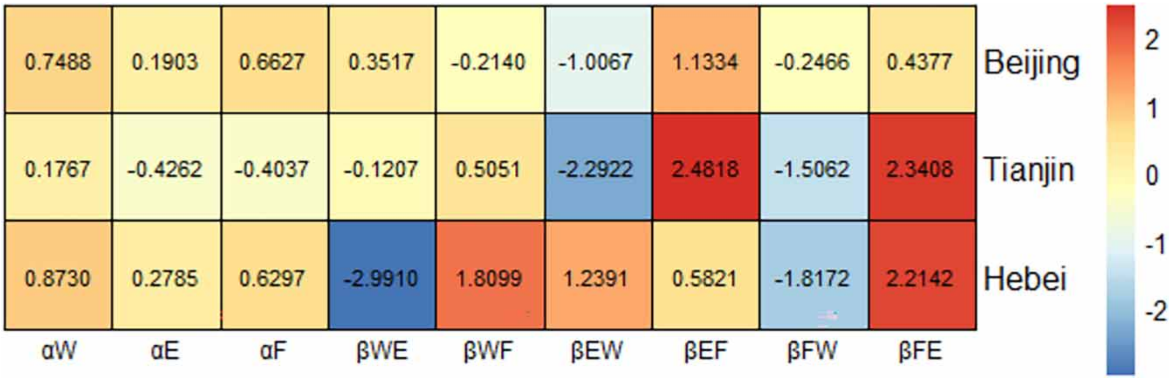
**Table 3** | Synergistic evolution results in a steady state.

| **Subsystems** | $\alpha_i$ | $\beta_{\text{one}}$ | $\beta_{\text{two}}$ | **Order degree** |
|---|---|---|---|---|
| Water | − 0.8848 | − 1.3735 | 0.7414 | 1.2441 |
| Energy | 0.1592 | 0.6017 | − 0.4924 | 1.0174 |
| Food | − 0.0532 | − 2.1642 | 2.1003 | 1.5556 |

improvement. Despite synergizing and competing with each other, the composite system ultimately evolves toward a stable structure.

The types of subsystem interactions in each region are further analyzed, as shown in Figure 4. In terms of the water–energy system, there is an energy dependence on water resources in Beijing ($\beta_{WE} > 0$, $\beta_{EW} < 0$). With the rapid development of Beijing's economy, the demand for water generated by high-energy-consuming industries reduces the order degree of the water resources subsystem. The supply of water resources can alleviate regional water scarcity and support energy production, further increasing energy dependence on water resources. For Tianjin, there is a mutually beneficial relationship ($\beta_{WE} < 0$, $\beta_{EW} < 0$). Tianjin is faced with a water shortage problem, and industrial water accounts for a large proportion. In recent years, the government has adopted policies to strengthen water-saving technological transformation and optimize the water resources allocation system. In addition, key energy-saving and emission-reduction projects have been implemented. This has effectively curbed the blind development of high-energy-consuming, high-emission, and low-level projects. Furthermore, energy-saving and emission-reduction policies and mechanisms have been enhanced. These measures have resulted in a synergistic relationship between water and energy. For Hebei province, it is dependent on water resources on energy ($\beta_{WE} < 0$, $\beta_{EW} > 0$). Regional water resources are scarce, energy and mineral reserves are abundant, and the economy is mainly developed by steel, coal, and mining heavy industries, which further increases water consumption. Conversely, the development and utilization of clean energy reduces the dependence on water resources, thus increasing the order degree of the water resources subsystem.

In terms of the water–food system, Beijing has a mutually beneficial relationship ($\beta_{WF} < 0$ , $\beta_{FW} < 0$). Despite having a small cultivated land area, low grain output, and relatively scarce water resources, measures such as the South-to-North Water Diversion Project have enhanced water security for food production and alleviated the current water shortage situation. In addition, scientific and technological measures have further promoted the adjustment of agricultural industrial structure and promoted the development of green agriculture, which are conducive to the coordinated development of the water–food system. For both Tianjin and Hebei provinces, food is dependent on water resources ($\beta_{WF} > 0$, $\beta_{FW} < 0$). Although the development of the food subsystem in Tianjin is relatively slow, the development of water resources in this region is restricted by agriculture as a major water consumer. Hebei province is one of the important grain production bases in our country. Food planting in this region not only consumes a large amount of water resources but also causes certain pollution to water resources and destroys the orderly development of the water resources subsystem. Through the construction of water



| | αW | αE | αF | βWE | βWF | βEW | βEF | βFW | βFE |
|---|---|---|---|---|---|---|---|---|---|
| Beijing | 0.7488 | 0.1903 | 0.6627 | 0.3517 | -0.2140 | -1.0067 | 1.1334 | -0.2466 | 0.4377 |
| Tianjin | 0.1767 | -0.4262 | -0.4037 | -0.1207 | 0.5051 | -2.2922 | 2.4818 | -1.5062 | 2.3408 |
| Hebei | 0.8730 | 0.2785 | 0.6297 | -2.9910 | 1.8099 | 1.2391 | 0.5821 | -1.8172 | 2.2142 |

**Fig. 4** | Subsystem itself and interaction parameters.

conservancy projects such as reservoirs and embankments, the agricultural production water of the two places has been effectively guaranteed, and the development of the food subsystem has been promoted.

In terms of the energy–food system, there is competition between energy and food in the three regions of Beijing, Tianjin, and Hebei province ($\beta_{EF} > 0$, $\beta_{FE} > 0$). The Beijing–Tianjin–Hebei region is located in the main food-producing area and has great potential for renewable energy development, especially in Hebei province, which contains natural gas, biomass, and other energy sources (Yan *et al.*, 2021). The development and utilization of water resources are overloaded and their carrying capacity is insufficient, while food and energy rank first in the consumption of water resources at the same time. Due to the tight constraint of water resources, the conflict between the energy and food subsystems for water is relatively prominent, resulting in a restraining relationship between them.

### 3.4. Analysis of subsystem dynamic interactions

There are various types of interactions between regional resource subsystems. To further investigate the development of the composite system, studying the dynamic interaction between subsystems is essential. Therefore, the PVAR model is chosen for analysis. Moreover, the first-order difference sequences of the water resources (WATER), energy (ENERGY), and food subsystems (FOOD) are represented as DWATER, DENERGY, and DFOOD, respectively.

Firstly, a unit root test is performed on the panel data to ensure model reliability and validity. In this paper, the Levin–Lin–Chu (LLC) test, augmented Dickey–Fuller (ADF) test, and Phillips–Perron (PP) test are selected to conduct a unit root test for the three variables, as shown in Table 4.

The results in Table 4 indicate that none of the three original variables pass the stability test. However, after the first-order difference processing, all variables pass the stability test at the 5% significance level.

According to the unit root test, these three variables belong to the same-order single-integer sequence. Therefore, the cointegration test can be conducted to determine whether there is a long-term equilibrium relationship among the three variables. By using the homogeneous Kao test, a *p*-value of 0.02070 is obtained, indicating the presence of a cointegration relationship among the water, energy, and food subsystems. To ensure the validity of the subsequent analysis, the robustness of the model is tested, and the result is shown in Figure 5.

Figure 5 illustrates that the inverses of the unit root modes all lie within the unit circle, indicating the stability of the constructed PVAR model.

Considering that the latter is more concerned with the interaction between subsystems, the focus is not on the construction of the PVAR model, but the relationship is further investigated with the impulse response based on the PVAR model. The impulse response curve can describe the impact of a one-unit variance change of each

**Table 4** | Results of the unit root test.

| | **LLC** | | **ADF** | | **PP** | | |
|---|---|---|---|---|---|---|---|
| **Variable** | **Statistic** | **Significance** | **Statistic** | **Significance** | **Statistic** | **Significance** | **Conclusion** |
| WATER | 1.32075 | 0.9067 | 0.95439 | 0.9873 | 0.42325 | 0.9987 | Unstable data |
| ENERGY | 2.41991 | 0.9922 | 0.12750 | 1.0000 | 0.05937 | 1.0000 | Unstable data |
| FOOD | 2.21059 | 0.9865 | 0.67650 | 0.9950 | 0.31996 | 0.9994 | Unstable data |
| DWATER | − 4.13567 | 0.0000 | 23.6474 | 0.0006 | 23.1667 | 0.0007 | Stable data |
| DENERGY | − 3.57350 | 0.0002 | 17.6799 | 0.0071 | 16.6686 | 0.0106 | Stable data |
| DFOOD | − 5.68908 | 0.0000 | 34.3024 | 0.0000 | 43.0084 | 0.0000 | Stable data |

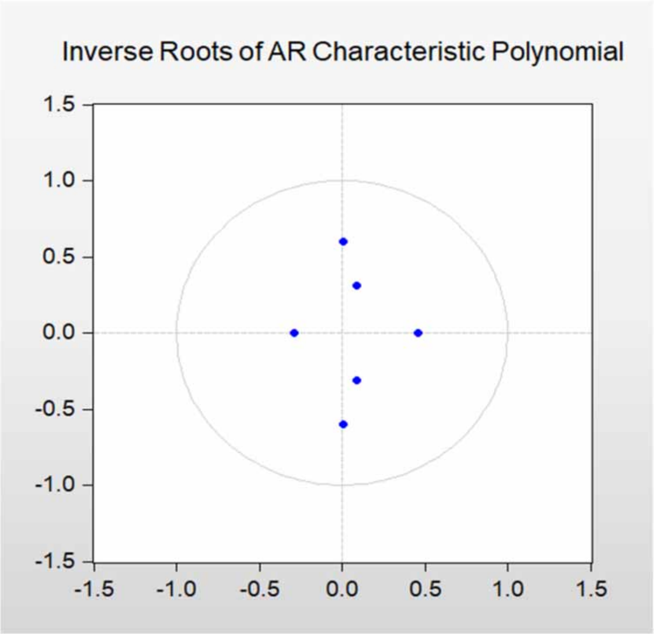


**Fig. 5** | Partial plot of the unit root.

variable on other variables and itself. The specific results are shown in Figure 6, where the horizontal axis represents the different stages after the impact, and the vertical axis represents the dynamic response of the variables to the impact.

Figure 6 illustrates that initially, the water, energy, and food subsystems all exhibit positive responses to respective impacts and reach their peaks. Over time, the responses of the three subsystems gradually diminish in different ways, indicating the future stable development of these subsystems. When the water subsystem experiences a standard deviation shock, the energy subsystem immediately shows a positive response, peaks, and then decreases to zero, suggesting a direct but limited influence from water to energy. The food subsystem initially shows no response, then responds positively and peaks in the second stage, followed by alternating between positive and negative responses before gradually approaching zero. This pattern indicates that the water resources subsystem has a delayed and complex effect on the food subsystem. When the energy subsystem is subjected to a standard deviation shock, the water resources subsystem initially does not respond. Subsequently, the second and third stages show significant positive and negative responses, respectively. After the sixth stage, the impact weakens to zero, indicating a lag and fluctuation in the impact of the energy subsystem on the water resources subsystem. The food subsystem initially responds negatively, then shifts to a positive response in the fourth stage, eventually converging to zero after fluctuations. This demonstrates the intricate interdependence between the energy subsystem and the food subsystem. When the food subsystem experiences a standard deviation shock, the water and energy subsystems are initially unresponsive. Subsequently, the water subsystem is negatively affected in the third stage, with a brief positive response in the fifth stage. However, this positive effect diminishes over time and turns negative again in the seventh stage. The energy subsystem exhibits a rapid increase in positive response in the second stage, followed by fluctuation until it reaches zero. This suggests that the food subsystem has a delayed and complex influence on the water and energy subsystems, with the water subsystem being more significantly affected.

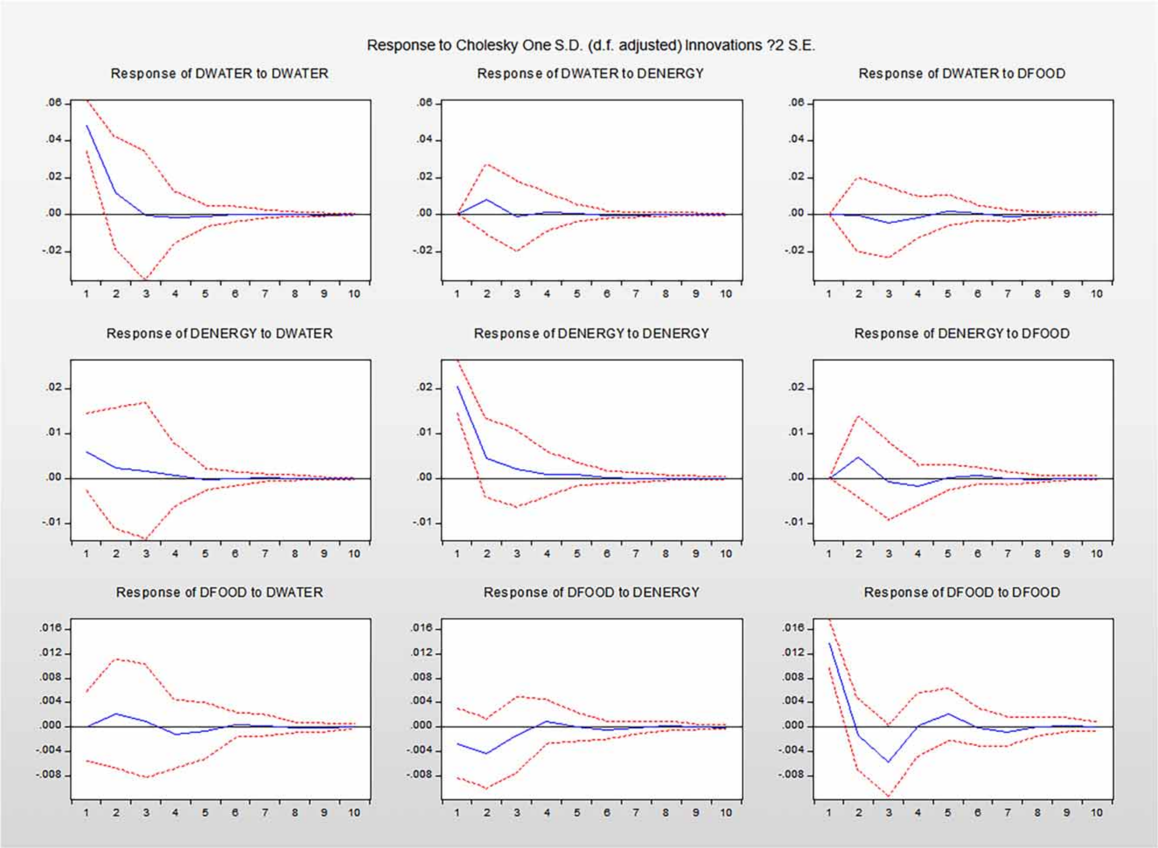


**Fig. 6** | Impulse response curves.

## 4. DISCUSSION

### 4.1. Further analysis

Compared with previous studies (Zhang *et al.*, 2019; Liu *et al.*, 2023), this paper aims to investigate the development trend of the WEFCS and the interaction of internal subsystems from the perspective of synergy. Based on the evaluation results of synergy degree and order degree, from 2011 to 2021, the synergy degree of the composite system in the Beijing–Tianjin–Hebei region remains at a basic level, while the order degree of the water, energy, and food subsystems all exhibit an increasing trend. This is consistent with the findings of Zhi *et al.* (2022). Furthermore, regarding the types of subsystem interactions, in comparison with Sun & Hao (2022), both studies conclude that there are synergistic, dependent, and competitive relationships within the internal subsystems. Additionally, this paper reveals that for a short period, the energy subsystem has a negative impact on the food subsystem, while the food subsystem has a positive effect on the energy subsystem. Zhang *et al.* (2022) demonstrated that energy consistently displayed a negative response to food shocks. Despite some discrepancies between our findings and those of other studies, these variations may highlight issues that have been overlooked or underemphasized in previous research, aiding in the identification of potential challenges.

The composite system is complex and needs to consider the impact of future policy or environmental changes. Firstly, if the government further strengthens the management of water resources, such as widely promoting water-saving irrigation technology and strengthening water pollution control, the Beijing–Tianjin–Hebei region is expected to improve the efficiency of water use. Wen *et al.* (2022) found that improving water use efficiency in agriculture and industry could effectively save water resources and thus alleviate the pressure of water shortages. Feng *et al.* (2023) pointed out the importance of strengthening water pollution management in the context of global warming. These measures will greatly facilitate the optimal use of regional water resources. Secondly, if the region vigorously develops clean energy, the security and stability of the energy subsystem will be improved. Sun *et al.* (2018) predicted that by 2030, the regional energy structure would tend to be low-carbon, cleaner, and electrified. This transition can significantly reduce air pollutant emissions from fossil fuel combustion (Bo *et al.*, 2023) and water utilization, playing a key role in the synergy of the WEFCS. Thirdly, if the government further optimizes the layout of food production and strengthens research in agricultural science and technology, food production will be further improved. Improving irrigation systems and planting drought-resistant crops have been shown to be effective in reducing agricultural water demand (Opoku *et al.*, 2022). Considering the severe water challenges faced by the Beijing–Tianjin–Hebei region as a major food-producing area (Wang *et al.*, 2022), realizing synergistic development of water resources and food production is key to alleviating the pressure.

This paper mainly uses the synergy model, evolutionary model, and panel vector autoregression model to study the synergy of the composite system, and these assessment models can be applied to complex systems involving multiple factors in other regions. The Beijing–Tianjin–Hebei region differs from other regions in terms of resource endowment, economic development, and demographics, so the policies proposed in this study are not directly applicable to other regions, but can provide valuable references for them. As a priority area for synergistic development, the Beijing–Tianjin–Hebei region is expected to receive more resources, which provides the possibility for policy implementation. However, resource management involves the interests of many parties, this may also affect the implementation of policies. Specifically for individuals or enterprises, there may still be opposition to the new policy.

### 4.2. Policy implications

Based on the above analysis, policy recommendations are put forward: as the synergy degree of the composite system has not yet reached a high level, the sector should formulate unified policy planning for water, energy, and food, and establish a sound early warning mechanism for the risks of the composite system. The region should strengthen cooperation, establish an information-sharing platform, and enhance cross-regional cooperation in major infrastructure construction and environmental protection. In regions where water and energy are interdependent, the government should increase efforts in researching, developing, and applying new energy technologies and promoting the use of clean energy in energy production. They should further promote water-saving technologies and take strict measures to control sewage discharge. In areas where water and food are interdependent, agricultural water-saving technologies, such as sprinklers and drip irrigation, should be vigorously promoted. The strategy of 'food crop production strategy based on farmland management and technological application' should be implemented to improve comprehensive agricultural production capacity. Regarding the dependence or competition between energy and food, under the constraints of water, land, and other resources, the government should rationally plan the layout of the food and energy industries and promote energy utilization technologies for agricultural waste.

### 4.3. Limitation and future research

This paper explores the synergy of the WEFCS, but there are still deficiencies. Firstly, missing data and data anomalies have some impact on the acquisition of indicators, thus affecting the assessment of synergy degree, which can be solved by considering new techniques in the future. Then, it mainly focuses on the empirical analysis of the synergy of the system and does not explore the advantages and disadvantages of different methods in the synergy analysis, which can be considered for comparative analysis with other models in the future. Finally, the long-term impacts of the synergistic relationship are complex, and further research will consider collecting data over a longer period of time, strengthening cooperation with related disciplines of geography, environmental science, and economics to jointly explore the long-term impacts, as well as examining the impact of external factors such as population growth, economic development, and urbanization.

## 5. CONCLUSION

Expanding from the system and subsystem perspectives, this paper analyzes the synergy of the WEFCS in the Beijing–Tianjin–Hebei region from 2011 to 2021. The results indicate that regional WEFCS synergy is low and unstable during the study period, and the synergy degree of the respective composite system in the three regions fluctuates and changes with instability by region. At the subsystem level, the development of the food subsystem lags behind in the region, while the water resource subsystem performs well in Beijing, the energy subsystem dominates in Tianjin, and the food subsystem develops more prominently in Hebei province. Additionally, there are obvious dependencies among different subsystems in the Beijing–Tianjin–Hebei region as a whole. For each region, some subsystem combinations such as the water–food system in Beijing and the water–energy system in Tianjin show mutually beneficial synergistic relationships, while other subsystem combinations show dependence or competition relationships. Moreover, the interactions among regional subsystems include not only direct effects, such as the positive promotion of the water resources subsystem on the energy subsystem and the negative restriction of the energy subsystem on the food subsystem but also numerous delayed and complex effects, in which the water resources subsystem is particularly affected by the food subsystem. These findings provide important references for future resource management and policy formulation in the Beijing–Tianjin–Hebei region and help to promote the sustainable development of the regional WEFCS.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

## REFERENCES

Alam, S., Gebremichael, M. & Li, R. (2019). Remote sensing-based assessment of the crop, energy and water nexus in the Central Valley, California. *Remote Sensing 11*(14), 1701. https://doi.org/10.3390/rs11141701.

Bo, X., You, Q., Sang, M., Wang, P., Chen, S., Xu, X., Shan, W., Wang, Y., Bessagnet, B., Li, H. & Xiao, Y. (2023). The impacts of clean energy policies on air pollutants and $CO_2$ emission reduction in Shaanxi, China. *Atmospheric Pollution Research 14*(12), 101937. https://doi.org/10.1016/j.apr.2023.101937.

Caixeta, F., Carvalho, A. M., Saraiva, P. & Freire, F. (2022). Sustainability-focused excellence: A novel model integrating the water-energy-food nexus for agro-industrial companies. *Sustainability 14*(15), 9678. https://doi.org/10.3390/su14159678.

Chang, Y., Xia, P. & Wang, J. (2016). Overview of the water-energy-food linkage and its implications for China. *Water Conservancy Development Research 16*(05), 67–70. https://doi.org/10.13928/j.cnki.wrdr.2016.05.019.

Chen, J., Yu, X., Qiu, L., Deng, M. & Dong, R. (2018). Study on vulnerability and coordination of water-energy-food system in Northwest China. *Sustainability 10*(10), 3712. https://doi.org/10.3390/su10103712.

Ding, T. & Chen, J. (2023). Spatio-temporal evaluation of the water–energy–food nexus system risk from a provincial perspective: A case study in China. *Water Supply 23*(6), 2404–2425. https://doi.org/10.2166/ws.2023.142.

Do, P., Tian, F., Zhu, T., Zohidov, B., Ni, G., Lu, H. & Liu, H. (2020). Exploring synergies in the water-food-energy nexus by using an integrated hydro-economic optimization model for the Lancang-Mekong River basin. *Science of the Total Environment 728*, 137996. https://doi.org/10.1016/j.scitotenv.2020.137996.

Fan, F., Sun, C. & Wang, X. (2013). Construction and application of a co-evolutionary model for social, economic and resource-environmental composite systems – A case study of Dalian City. *Systems Engineering – Theory & Practice 33*(02), 413–419.

Feng, Z., Zhang, Z., Zuo, Y., Wan, X., Wang, L., Chen, H., Xiong, g., Liu, Y., Tang, Q. & Liang, T. (2023). Analysis of long term water quality variations driven by multiple factors in a typical basin of Beijing-Tianjin-Hebei region combined with neural networks. *Journal of Cleaner Production 382*, 135367. https://doi.org/10.1016/j.jclepro.2022.135367.

Fu, Y., Ren, Y. & Pei, W. (2023). Evaluation of the symbiosis level of the water-energy-food complex system based on the improved cloud model: A case study in Heilongjiang province. *Environmental Science and Pollution Research 30*(9), 22963–22984. https://doi.org/10.1007/s11356-022-23555-y.

Gu, A., Jiang, D. & Zhang, Y. (2016). Current status of energy-water relationship research and its implications for China. *Ecological Economy 32*(07), 20–23 + 28.

Jin, J., Yang, X. & Ding, J. (2001). An improvement scheme of the standard genetic algorithm-accelerated genetic algorithm. *Systems Engineering – Theory & Practice 21*(4), 8–13.

Kitessa, B. D., Ayalew, S. M., Gebrie, G. S. & Teferi, S. T. M. (2022). Optimization of urban resources efficiency in the domain of water–energy–food nexus through integrated modeling: A case study of Addis Ababa city. *Water Policy 24*(2), 397–431. https://doi.org/10.2166/wp.2022.213.

Li, J. & Huang, D. (2023). Multi-dimensional dynamic spatio-temporal evolution of the green development efficiency of water-energy-food in China. *Water Policy 25*(2), 122–145. https://doi.org/10.2166/wp.2023.145.

Li, G., Wang, Y. & Li, Y. (2019). Synergies within the water-energy-food nexus to support the integrated urban resources governance. *Water 11*(11), 2365. https://doi.org/10.3390/w11112365.

Li, J., Cui, J., Sui, P., Yue, S., Yang, J., Lv, Z., Wang, D., Chen, X., Sun, B., Ran, M. & Chen, Y. (2021). Valuing the synergy in the water-energy-food nexus for cropping systems: A case in the North China Plain. *Ecological Indicators 127*, 107741. https://doi.org/10.1016/j.ecolind.2021.107741.

Liu, S. & Zhao, L. (2022). Development and synergetic evolution of the water–energy–food nexus system in the Yellow River Basin. *Environmental Science and Pollution Research 29*(43), 65549–65564. https://doi.org/10.1007/s11356-022-20405-9.

Liu, M., Pan, P., Ren, J., Wen, J. & Zhang, B. (2023). Research on the coupling and coordination of food security and agricultural water security in Beijing–Tianjin–Hebei. *Chinese Journal of Agricultural Resources and Regional Planning 44*(2), 170–182.

Meng, Q. & Han, W. (1999). Research on the overall coordination degree model of composite system. *Journal of Hebei Normal University (Natural Science) 23*(2), 38–40 + 48.

Nkiaka, E., Okpara, U. T. & Okumah, M. (2021). Food-energy-water security in sub-Saharan Africa: Quantitative and spatial assessments using an indicator-based approach. *Environmental Development 40*, 100655. https://doi.org/10.1016/j.envdev.2021.100655.

Opoku, E. K., Adjei, K. A., Gyamfi, C., Vuu, C., Appiah-Adjei, E. K., Odai, S. N. & Siabi, E. K. (2022). Quantifying and analysing water trade-offs in the water-energy-food nexus: The case of Ghana. *Water-Energy Nexus 5*, 8–20. https://doi.org/10.1016/j.wen.2022.06.001.

Peng, S., Zheng, X., Wang, Y. & Jiang, G. (2017). Study on water-energy-food collaborative optimization for Yellow River basin. *Advances in Water Science 28*(05), 681–690. https://doi.org/10.14042/j.cnki.32.1309.2017.05.005.

Qi, Y., Farnoosh, A., Lin, L. & Liu, H. (2022). Coupling coordination analysis of China's provincial water-energy-food nexus. *Environmental Science and Pollution Research 29*, 23303–23313. https://doi.org/10.1007/s11356-021-17036-x.

Qian, X. & Liang, Q. (2021). Sustainability evaluation of the provincial water-energy-food nexus in China: Evolutions, obstacles, and response strategies. *Sustainable Cities and Society 75*, 103332. https://doi.org/10.1016/j.scs.2021.103332.

Radmehr, R., Ghorbani, M. & Ziaei, A. N. (2021). Quantifying and managing the water-energy-food nexus in dry regions food insecurity: New methods and evidence. *Agricultural Water Management 245*, 106588. https://doi.org/10.1016/j.agwat.2020.106588.

Ren, X., Ren, Y., Wu, F., Si, T. & Wang, Z. (2021). Collaborative development model of regional water-energy-food linkage system. *Bulletin of Soil and Water Conservation 41*(5), 218–225. https://doi.org/10.13961/j.cnki.stbctb.2021.05.029.

Rzepczynski, S. M. (2014). Global trends 2030: Alternative worlds. 2012. *Financial Analysts Journal 70*(3), 60–63.

Sargentis, G. F., Siamparina, P., Sakki, G. K., Efstratiadis, A., Chiotinis, M. & Koutsoyiannis, D. (2021). Agricultural land or photovoltaic parks? The water–energy–food nexus and land development perspectives in the Thessaly Plain, Greece. *Sustainability 13*(16), 8935. https://doi.org/10.3390/su13168935.

Srigiri, S. R. & Dombrowsky, I. (2022). Analysing the water-energy-food nexus from a polycentric governance perspective: Conceptual and methodological framework. *Frontiers in Environmental Science 10*, 725116. https://doi.org/10.3389/fenvs.2022.725116.

Sun, C. & Hao, S. (2022). Research on the competitive and synergistic evolution of the water-energy-food system in China. *Journal of Cleaner Production 365*, 132743. https://doi.org/10.1016/j.jclepro.2022.132743.

Sun, L., Pan, B., Gu, A., Lu, H. & Wang, W. (2018). Energy–water nexus analysis in the Beijing–Tianjin–Hebei region: Case of electricity sector. *Renewable and Sustainable Energy Reviews 93*, 27–34. https://doi.org/10.1016/j.rser.2018.04.111.

Wang, P., Li, Y., Huang, G. & Wang, S. (2022). A multivariate statistical input–output model for analyzing water-carbon nexus system from multiple perspectives – Jing-Jin-Ji region. *Applied Energy 310*, 118560. https://doi.org/10.1016/j.apenergy.2022.118560.

Wen, C., Dong, W., Zhang, Q., He, N. & Li, T. (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. https://doi.org/10.1016/j.scitotenv.2021.150497.

Xia, Y. & He, G. (2018). Comprehensive measurement of science and technology innovation-industry upgrading synergy in China. *Science and Technology Management Research 38*(8), 27–33.

Yan, X., Gao, D. & Li, Y. (2021). Thoughts and countermeasures to promote energy revolution in Beijing–Tianjin–Hebei region. *China Engineering Science 23*(1), 24–31.

Zhang, Z., Duan, Z., Xu, P. & Zhang, X. (2013). Synergistic strategies for food and water security in China. *Chinese Journal of Ecological Agriculture 21*(12), 1441–1448.

Zhang, H., Zeng, J., Qu, J., Li, H., Liu, L., Wu, J. & Xu, L. (2019). Research on the coupling coordinative degree among water-energy-food system in high-intensity flow areas: A case study of Beijing, Tianjin and Hebei Province. *China Rural Water Resources and Hydropower 5*, 17–21 + 28.

Zhang, T., Tan, Q., Yu, X. & Zhang, S. (2020). Synergy assessment and optimization for water-energy-food nexus: Modeling and application. *Renewable and Sustainable Energy Reviews 134*, 110059. https://doi.org/10.1016/j.rser.2020.110059.

Zhang, J., Wang, S., Pradhan, P., Zhao, W. & Fu, B. (2022). Mapping the complexity of the food-energy-water nexus from the lens of Sustainable Development Goals in China. *Resources, Conservation and Recycling 183*, 106357. https://doi.org/10.1016/j.resconrec.2022.106357.

Zhi, Y., Chen, J., Wang, H., Liu, G. & Zhu, W. (2020). Assessment of water–energy–food nexus fitness in China from the perspective of symbiosis. *China Population, Resources and Environment 30*(1), 129–139.

Zhi, Y., Wang, H., Zhang, F., Wang, Z. & Zhu, W. (2022). Assessment of synergistic relationship among water resources, energy and food systems in Northwest China-based on the perspective of co-evolution of complex systems. *Journal of Arid Land Resources and Environment 36*(10), 76–85. https://doi.org/10.13448/j.cnki.jalre.2022.254.

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