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# Synergies evaluation and influencing factors analysis of the water–energy–food nexus from symbiosis perspective: A case study in the Beijing–Tianjin–Hebei region

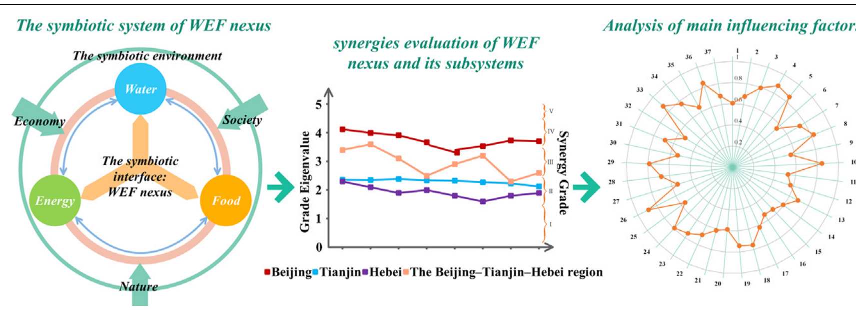
Yong Wang [a], Yanjing Xie [a,*], Lin Qi [a], Yuan He [b,*], He Bo [c]

[a] School of Statistics, Dongbei University of Finance and Economics, Dalian 116025, China
[b] School of Finance, Dongbei University of Financial and Economics, Dalian 116025, China
[c] School of Economics, Dongbei University of Finance and Economics, Dalian 116025, China

## HIGHLIGHTS

- Evaluating water–energy–food (WEF) nexus synergies in Beijing–Tianjin–Hebei region.
- The synergy evaluation index system is constructed based on symbiosis theory.
- Set pair analysis-variable fuzzy sets model is used into the study of WEF nexus.
- The main factors affecting WEF nexus synergies are analyzed.

## GRAPHICAL ABSTRACT

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## ABSTRACT

In the context of global population growth and environmental degradation, research on the synergies of the water–energy–food (WEF) nexus is important for sustainable regional development. Using symbiosis and synergy theories, the authors constructed a synergy evaluation index for the WEF nexus and used the set pair analysis-variable fuzzy sets model to analyze the WEF nexus synergies in the Beijing–Tianjin–Hebei region (BTH) of China, from 2005 to 2017. The main factors affecting WEF nexus synergies were also analyzed, with results indicating that: 1) the WEF nexus synergies were the best in Beijing, followed by the BTH as a whole, Tianjin, and then Hebei. We also found that WEF nexus synergy grades have been gradually improving over time, with Beijing improving the most, and Tianjin the least. 2) The WEF nexus synergy grades in each region, for symbiotic units, symbiotic relationships, and symbiotic environments, have also gradually improved. And symbiotic relationship synergies were better than symbiotic environment synergies than symbiotic unit synergies. 3) The WEF nexus symbiotic unit synergies were strongest in Tianjin, followed by Beijing, the BTH as a whole, and then Hebei. The symbiotic relationship synergies were strongest in Beijing, followed by Hebei, the BTH as a whole, and then Tianjin. The symbiotic environment synergies were also strongest in Beijing, followed this time by the BTH as a whole, Tianjin, and then Hebei. 4) Economic factors and symbiotic unit synergies were found to be the aspects most influential on WEF nexus synergies in each region. In addition, symbiotic relationship synergies were found to have important impacts on the WEF nexus synergies in Hebei and the BTH as a whole. Overall, we were able to conclude that the methodology developed in this study provided a scientific basis for synergy optimization in the context of a regional WEF nexus.



*Abbreviations:* The BTH, The Beijing–Tianjin–Hebei region; WEF, Water–energy–food.

* Corresponding authors at: No.217 Jianshan Street, Shahekou District, Dalian 116025, Liaoning, China.
*E-mail addresses:* ywang@dufe.edu.cn (Y. Wang), 15732186709@163.com (Y. Xie), sherryqilin@163.com (L. Qi), poisonliuli@gmail.com (Y. He), bohesandra@yahoo.com.cn (H. Bo).

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## 1. Introduction

### 1.1. Background

As essential basic resources, water, energy, and food allow humanity to flourish, and are important foundations for sustainable regional development (Martinez-Hernandez et al., 2017). At the same time, rapid economic development, rapid population growth, accelerated urbanization, and climate change have put significant pressure on the supply of these resources (Helmstedt et al., 2018). There are strong interrelationships between water, energy, and food resources. Coordination water, energy and food supply is a key to promote regional development, while adjusting and optimizing just one of these, and not the others, is not conducive to overall regional resource structure optimization (Zhang et al., 2021; Putra et al., 2020). Studying the water–energy–food (WEF) nexus as a whole is necessary to promote regional resource supply efficiency, and to achieve a supply–demand balance; this approach is also needed if individual resource developments are to be optimally coordinated. WEF nexus synergies refer to the overall effect of mutual influence and cooperation among individual WEF systems, with appropriate. Coordination among the resource exploitation mechanisms needed if simultaneous development, in terms of time, space, and functional structure, is to be achieved. A WEF nexus is affected by external factors such as the economy, society, and environment—to the point where, the WEF nexus can affect the stability of these external factors. Therefore, this means that when evaluating WEF nexus synergies, it is necessary to associate the related external systems, as this will help develop targeted guidance for optimizing regional resource allocation.

The Beijing-Tianjin-Hebei region (the BTH) (Fig. 1) is China's core economic zone and is representative of China's densely populated and industrialized areas. It faces problems, such as degradation of the natural environment and resource waste, while resource development and utilization have been intense and resource demand pressure high. The contradiction between resource supply and social development is deepening in the BTH. In 2018, the total BTH population reached 113 million, accounting for 8.1% of China's total population, while its arable land area accounted for only 5.3% of the national total. The total BTH energy consumption in 2018 required 474.31 million tons of standard coal, accounting for 10% of China's total energy consumption, while the energy self-sufficiency rate was only 26%. In 2018, its per capita water resources were 192.72 $m^3$/person, which were much lower than the national average, of 1971.85 $m^3$/person, indicating that regional water resources have been under significant pressure. Basic resource shortages have become an important factor restricting sustainable BTH development. Due to better coordinated BTH development, and a series of environmental protection policies, the utilization efficiency of resources has improved to a certain extent recently. Constructing projects such as the South-to-North Water Transfer has also relieved pressure on resources supply in the BTH, however, WEF resource management remains uncoordinated, causing a major obstacle to BTH synergetic development, and affecting its forward development potential. It has therefore become clear that improving the BTH WEF nexus synergies is essential if the resource supply–demand imbalance is to be resolved and sustainable social development is to be promoted.

### 1.2. Research review

While most studies on basic resources focused on the relationship between a single resource and population growth, economic development and ecological conservation (Shabani et al., 2021; Yasmeen et al., 2021; Song et al., 2020a; Chen et al., 2020), the WEF nexus provides a new idea for regional resource management and allocation. Research on the WEF nexus issue focused initially on correlations between the two systems of water, energy, and food (Karp, 2011; Mukherji, 2007; Scott et al., 2011). Some investigators placed the three resources in the same framework for discussion—such as the water–energy relationship to food production (Khan and Hanjra, 2009; Khan et al., 2009), and land and water requirements for bioenergy production (Yang et al., 2009)—but the research still focused on correlations between two systems. In 2011, the concept of "water-energy-food" nexus was formally proposed (Hoff, 2011) and important correlations among water, energy, and food resources were defined. The research focus gradually shifts from correlations between two systems to correlations among the

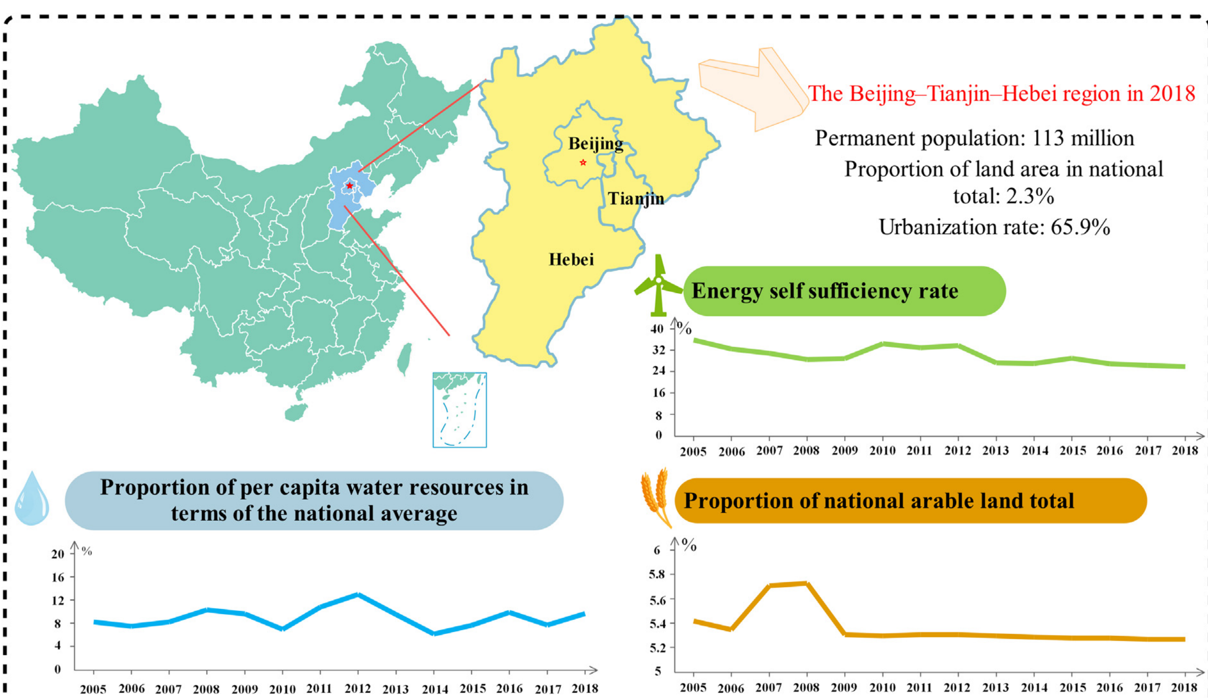


**Fig. 1.** Basic Beijing–Tianjin–Hebei region information.

three nexus resources (Smajgl et al., 2016; Bazilian et al., 2011; Terrapon-Pfaff et al., 2018). WEF resource coordination and sustainable development have also started to receive more attention in terms of external factors—such as economic development, climate change, population growth, and urbanization (Yue et al., 2020; Biggs et al., 2015; Zeng et al., 2019; Zhao and You, 2021; Ziv et al., 2018).

WEF nexus research currently employs qualitative and quantitative methods. In qualitative research, WEF correlations are reviewed and analyzed (de Amorim et al., 2018), and recommendations relevant to coordinated WEF nexus development are developed using case studies (Romero-Lankao et al., 2018; Zarei, 2020). Based on causal loop diagrams, Zhang et al. (2021) explored correlations between water, energy, and food; they concluded that policy measures focusing on the interaction between surface water and groundwater could alleviate the water shortage issue in the Bayannur WEF nexus; Yuan et al. (2021) used Amsterdam, Eindhoven, Taipei, and Tainan as their case studies, discussing urban priority development strategies and concluded that renewable energy had an essential role to play in the WEF nexus.

Quantitative research has mainly involved constructing models for use in evaluating and analyzing WEF interactions and on reviewing the sustainable development status between WEF nexus and the external environment. The main quantitative research methods include: system dynamics model (Bakhshianlamouki et al., 2020), life cycle assessment method (Sherwood et al., 2017) and data envelopment analysis model (Ibrahim et al., 2019). System dynamics model (Sušnik, 2018) can be used to quantify and simulate the WEF nexus correlations under different scenarios by establishing a causal feedback loop between internal WEF nexus variables. The life cycle assessment method (Li and Ma, 2020) can be used to analyze the total amount of direct or indirect resources consumption in the WEF nexus, and to review their potential environmental impact. The data envelopment analysis model (Sun et al., 2021; Song et al., 2021; Song et al., 2020b) can be applied in evaluating systems quantitatively, using several input–output indicators, thus providing a reference for resource allocation and sustainable development. More recently, more research has been conducted on WEF nexus synergies (Do et al., 2020; Fader et al., 2018; Wu et al., 2021). By exploring the synergies within the Shenzhen WEF nexus, Li et al. (2019) found that stabilizing water supplies, coordinating energy exports and reducing crop sowing areas played a positive role in improving Shenzhen WEF nexus synergies. Zhou et al. (2019) proposed to use the WEF nexus synergies for small-hydropower generation using artificial intelligence techniques. Li et al. (2021) proposed a relative index of WEF nexus to assess the synergies of WEF nexus under different cropping systems. Zhang et al. (2020) established a coupled assessment–optimization model, to study WEF nexus synergies in Bayannur, identifying WEF nexus steady states there. These research approaches have been summarized in Table 1.

As the WEF nexus is a semi-open system, many uncertainties become apparent when selecting indicators and evaluating results—which has made it necessary to introduce an uncertainty analysis method. The set pair analysis-variable fuzzy sets model—which has achieved good results when applied to flood risk assessment (Zou et al., 2013), and evaluating the environment impact of construction waste disposal (Kong and Ma, 2020)—can be used in the objective evaluation of uncertainty.

Overall, several shortcomings in existing WEF nexus research have become apparent.

Firstly, there have been few studies on WEF nexus synergies, and evaluation index system selection has not been sufficiently comprehensive. Ignoring the synergetic development of various resources in the WEF nexus hinders understanding interactions between resources correctly, and threatens the overall sustainable development of the system. At the same time, existing research has not taken factors such as technological investment or population quality into account. Ignoring such factors prevents fully understanding the development coordination requirements needed between the WEF nexus and its background economy and society, which in turn then degrades any analysis of the main WEF nexus synergy influencing factors.

Secondly, existing WEF nexus synergy studies have been based mainly on deterministic methods, and have not measured uncertainty. Because it is difficult to avoid uncertainties when selecting synergy evaluation indexes and synergy grades, using deterministic methods may affect the accuracy of the resulting evaluations. This, in turn, hinders the rational planning necessary for WEF nexus synergetic development.

### *1.3. Innovation in this study*

Based on the symbiosis theory, the authors constructed an evaluation index system applicable to WEF nexus synergies, including the three criteria: symbiotic units, symbiotic relationships, and symbiotic environments. A set pair analysis-variable fuzzy sets model was then used to evaluate synergies of WEF nexus and synergies of its symbiotic units, symbiotic relationships, and symbiotic environments, both in Beijing, Tianjin, and Hebei individually, and across the BTH as a whole, from 2005 to 2017. The grey correlation degree model was then applied to analyze the main influencing factors of WEF nexus synergies in each region.

Compared with the existing studies, several innovations have been developed and applied in the study described herein.

Firstly, using symbiosis theory, a more complete evaluation index system has been constructed to analyze and evaluate WEF nexus synergies. Evaluating these has benefited understanding the complex relationships between resources, has allowed the balance between resource supply and demand to be promoted and has allowed the

**Table 1**
Summary of major WEF nexus research methods.

| Methods | Key studies | Advantages | Shortcomings |
|---|---|---|---|
| Causal loop diagrams | Zhang et al., 2021<br>Purwanto et al., 2019 | Can describe system behavior qualitatively, by analyzing causal relationships between variables | System dynamic behavior is not assessed quantitatively |
| System dynamics model | Naderi et al., 2021<br>Keyhanpour et al., 2020 | 1. Accounts for feedbacks and delays between variables<br>2. Can quantitatively describe correlations between complex dynamic systems and is suited to researching long–term dynamic trends | Data demand is high, and the decision–making involved in the system simplification process can involve levels of subjectivity |
| Life cycle assessment method | Li and Ma, 2020<br>Al-Ansari et al., 2015 | Can quantify subsystem impacts on the environment, and avoid underestimating resource consumption | Due to it high time demand, it is not suited to dynamic analysis of complex systems |
| Data envelopment analysis model | Ibrahim et al., 2019<br>Sun et al., 2021 | WEF nexus coupling efficiencies can be measured simultaneously using multiple input and output indicators, without the need for dimensionless data processing | Very sensitive to outliers |
| Coupled assessment -optimization model | Zhang et al., 2020 | Can judge WEF nexus steady states based on evaluating WEF nexus synergies | Synergies grades cannot be evaluated or classified |

resources support needed for sustainable regional development to be identified. It should also be remembered that the WEF nexus is not only about interactions among the three systems of water, energy, and food, but also concerns interactions with economic, social, and natural factors. With this in mind, and applying symbiosis theory, an index system including factors such as technology investment, population quality, urbanization rate, and climate has been constructed, using the symbiotic units, symbiotic relationships, and symbiotic environments criteria. This approach has been more conducive to the comprehensive and accurate analysis of WEF nexus synergies.

Secondly, the set pair analysis theory has been introduced, and the set pair analysis-variable fuzzy sets model used, to evaluate synergy grades in the WEF nexus. The variable fuzzy sets model has been commonly used to resolve uncertainty problems, although determining the degrees of difference between sets has remained a relatively subjective exercise. The concept of the connection degree function in set pair analysis has been clear, however, and facilitates comprehensive consideration of multiple indicator characteristics. Combining set pair analysis with variable fuzzy sets theory has reduced the uncertainty involved in the process of selecting an evaluation index system and classifying synergy grades, while also providing a more objective, reliable, and efficient solution.

The remainder of this paper has been organized as follows: Section 2 covers model construction and data sources. Section 3 evaluates the synergy grades of WEF nexus and its symbiotic units, symbiotic relationships, and symbiotic environments in the BTH. Section 4 analyzes the factors influencing WEF nexus synergies. Section 5 provides the discussion and analysis. Section 6 provides the conclusions and policy implications. The research process used in this study has been illustrated in Fig. 2.

## 2. Model construction and data sources

### 2.1. Constructing a synergy evaluation index system from the symbiosis perspective

Symbiosis refers to a specific relationship formed between two or more different units according to a specific symbiosis mode, under a certain symbiosis environment, to improve the survival and development capacity of both units (Yang et al., 2018). This makes it an important basis for the synergetic and sustainable development of multiple subjects. Symbiosis theory first originated in the field of biology and was then widely used in economics, sociology, and other research fields (Bartolozzi et al., 2006; Shi et al., 2019; Huang et al., 2019; Wein et al., 2019). The study of symbiotic systems can connect the symbiotic subsystem to the external environment through the symbiotic environment, and can then analyze the interaction between both the internal resources of the system, and between the internal resources and this external environment. The synergetic development of the WEF nexus relies on not only the balanced development of water, energy, and food resources, but also on the mutual coordination between these and the external environment. Symbiosis theory can therefore provide a new perspective for the study of WEF nexus synergies.

Symbiotic systems are generally composed of four elements: symbiotic units, symbiotic relationships, symbiotic interfaces, and symbiotic environments. In the symbiotic system of the WEF nexus, as approached in this study, the three systems of water, energy, and food were called symbiotic units and were important subjects in the symbiotic system. The interactions and mutual transformations between the three systems composed of the symbiotic units—water–energy, water–food, and energy–food—have been referred to as symbiotic relationships,

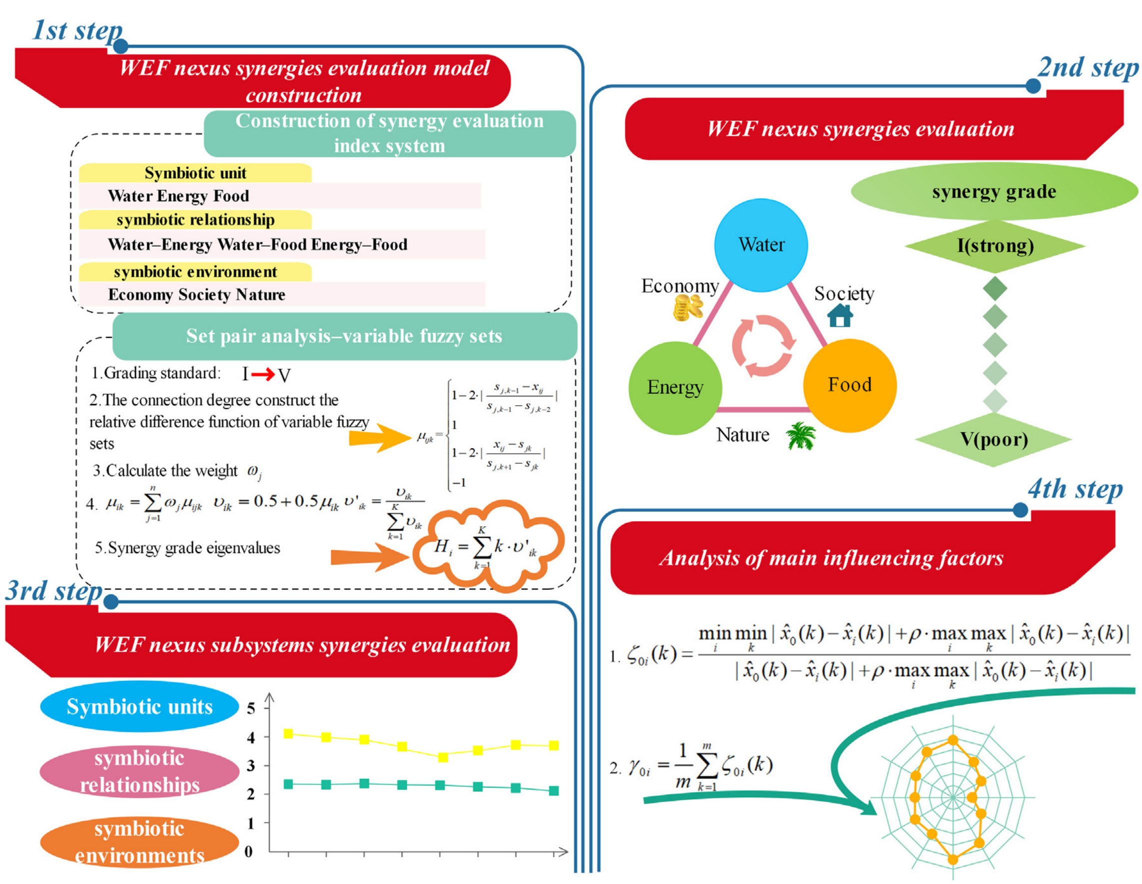


**Fig. 2.** The research process used in this study.

which contributed conditions necessary for the symbiotic system. Materials transfers and energy movements between symbiotic units have been referred to as symbiotic interfaces, which include elements such as social systems, industrial structures, and technology levels, and supply important support for coordinating developments between symbiotic units and the outside world. Symbiotic interfaces play significant roles in improving symbiotic relationships. In our work, the WEF nexus was a symbiotic interface in the WEF symbiosis system, and economy, society and nature were referred to in our symbiotic environments as the external connections among symbiotic relationships. The symbiotic system applicable to the WEF nexus has been illustrated in Fig. 3.

The WEF nexus synergies mean that, from a symbiosis perspective, in developing the symbiotic environment consisting of economic, social, and natural conditions, the three systems of water, energy and food transform each other, and operate in a coordinated manner. In this way, the development and exploitation of various resources can be maintained within their carrying capacity, while fulfilling social development needs. Thus, the WEF nexus and social development form a virtuous cycle of mutual promotion and maintain a sustainable development state. In studying WEF nexus synergies, since the symbiotic interface has been represented as the carrier of materials and energy between symbiotic units, it can be combined with symbiotic relationships.

In the study described here, discussion of WEF nexus synergies has been incorporated into this theoretical framework using symbiosis theory. WEF nexus synergies have been examined based on the symbiotic unit synergies of the individual subsystem of water, energy and food, the symbiotic relationship synergies between each two subsystems, and the symbiotic environment synergies comprising economic, social, and natural conditions. From this symbiosis perspective, the synergy evaluation index system of WEF nexus can be divided into three criteria using the three elements: symbiotic units, symbiotic relationships, and symbiotic environments. Symbiotic unit synergies reflect the carrying capacity, supply, and demand balance among WEF symbiotic units. Symbiotic relationship synergies reflect the state of mutual coordination and transformation among the water–energy, water–food, and energy–food symbiotic relationships, while the symbiotic environment synergies reflect the overall sustainability status of the system under the

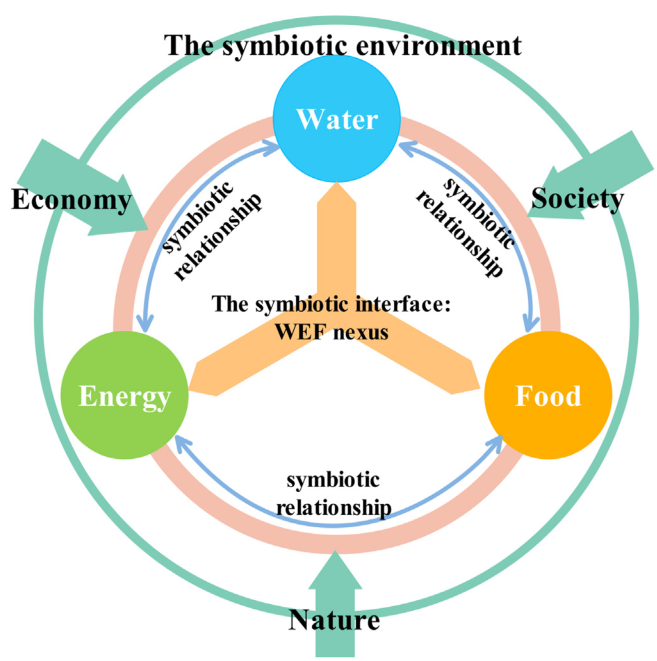


**Fig. 3.** The WEF nexus symbiotic system.

economic, social, and natural symbiotic environment constraints. WEF nexus synergies can be comprehensively evaluated using synergies between the symbiotic unit, symbiotic relationship, and symbiotic environmental criteria.

Using this theoretical analysis, in combination with data for the BTH, an evaluation index system of WEF nexus synergies was constructed and corresponding grade classification standards were determined for each indicator (Table 2). The synergy evaluation grade for each WEF nexus indicator was divided into five: I (strong), II (slightly strong), III (medium), IV (weak), and V (poor). The stronger the synergy, the higher the sustainable development level of the WEF nexus. The evaluation grading standards for each indicator were combined with existing research (Li and Chen, 2021; Yin et al., 2020; Peng and Qin, 2019), the evaluation standards for Chinese 'livable cities' (Chinese Society for Urban Studies, 2007), the evaluation standards for Chinese model cities in terms of environmental protection (Ministry of Ecology and Environment of the People's Republic of China, 2011) and the development levels of advanced cities in China and abroad.

### *2.2. WEF nexus synergies evaluation: the set pair analysis-variable fuzzy sets model*

#### *2.2.1. Set pair analysis*

Set pair analysis refers to constructing two sets, $A$ and $B$, which have some connection, into a set pair in a specific problem context, and quantitatively portraying the characteristics of the two sets, in terms of identity, discrepancy, and opposite—before obtaining the expression of the connection degree between these two sets. Using this approach allows related problems of a system to be studied in depth. In the WEF nexus synergy evaluation system, set $A$ represented the sample data set for each evaluation indicator, while set $B$ represented the evaluation indicator grade classification standards set. Set pair analysis could then be used to analyze and process various uncertain information effectively, and reveal potential process rules from the perspective of object interrelationships.

When the state space (evaluation index system) was divided into three grades, the connection degree was defined as shown in Eq. (1):

$$\mu = \frac{S}{N} + \frac{F}{N} i + \frac{P}{N} j = a + bi + cj \tag{1}$$

Eq. (1) is the expression for three-element connection degree. Here, $\mu$ indicates the connection degree, $N$ represents the total number of features of the set pair, $S$ and $P$ represent the number of identifying characteristics of the set pair and the number of opposite characteristics of the set pair, respectively. $F = N - S - P$, and represents the number of discrepant characteristics for the set pair. Here, $a = \frac{S}{N}, b = \frac{F}{N}, c = \frac{P}{N}$, and represent the identity degree, discrepancy degree, and opposite degree, respectively. $a, b, c \in [0, 1]$, and $a + b + c = 1$. Symbol $i$ indicates the coefficient of discrepancy degree, and $i \in [-1, 1]$. Symbol $j$ represents the coefficient of the opposite degree and $j = -1$.

In practical problems, it is relatively crude to divide the state space into three grades, so we considered how to subdivide the discrepancy degree according to different situations, to conduct a more accurate analysis of related problems. When the state space was divided into five grades, Eq. (1) could be extended to a five-element connection degree expression, as shown in Eq. (2):

$$\mu = a + b_1 i_1 + b_2 i_2 + b_3 i_3 + cj \tag{2}$$

where $i_1$, $i_2$, and $i_3$ represent the uncertainty component coefficients of the discrepancy degree, and $i_1$, $i_2$, $i_3 \in [-1, 1]$. Symbols $a$ and $c$ represent the identity degree and opposite degree, respectively, while $b_1$, $b_2$, and $b_3$ represent the components of the discrepancy degree, and $a + b_1 + b_2 + b_3 + c = 1$.

**Table 2**
WEF nexus synergy evaluation index system and grade classification standards.

| Criteria | Subsystem | Indicators (units) | Grade classification standard | | | | |
|---|---|---|---|---|---|---|---|
| | | | I | II | III | IV | V |
| Symbiotic units | Water subsystem | $c_1$ Per capita water resources ($m^3$/person) | 3000–8000 | 2000–3000 | 1000–2000 | 500–1000 | <500 |
| | | $c_2$ Water resource development and utilization rate (%) | 0–10 | 10–20 | 20–40 | 40–80 | 80–1000 |
| | | $c_3$ Groundwater supply ratio (%) | 0–15 | 15–30 | 30–45 | 45–60 | 60–100 |
| | | $c_4$ Unconventional water ratio (%) | 20–40 | 15–20 | 10–15 | 5–10 | 0–5 |
| | | $c_5$ Water consumption per $10^4$ yuan of GDP ($m^3/10^4$ yuan) | 0–50 | 50–100 | 100–300 | 300–600 | 600–1500 |
| | Energy subsystem | $c_6$ Per capita energy production (tons standard coal/person) | 7–30 | 3–7 | 1.5–3 | 1–1.5 | 0–1 |
| | | $c_7$ Energy consumption elasticity coefficient | 0–0.3 | 0.3–0.5 | 0.5–0.7 | 0.7–1 | 1–2 |
| | | $c_8$ Percentage of clean energy use (%) | 100–80 | 50–80 | 30–50 | 15–30 | 0–15 |
| | | $c_9$ Energy self-sufficiency rate (%) | 200–500 | 100–200 | 60–100 | 20–60 | 0–20 |
| | | $c_{10}$ Energy consumption per $10^4$ yuan of GDP (tons standard coal/$10^4$ yuan) | 0–0.3 | 0.3–0.6 | 0.6–1 | 1–2 | 2–5 |
| | Food subsystem | $c_{11}$ Per capita arable land area ($m^2$/person) | 1500–4500 | 1000–1500 | 500–1000 | 200–500 | 0–200 |
| | | $c_{12}$ Per capita food production (kg/person) | 700–1500 | 500–700 | 400–500 | 300–400 | 0–300 |
| | | $c_{13}$ Proportion of crop affected area (%) | 0–5 | 5–8 | 8–10 | 10–20 | 20–100 |
| | | $c_{14}$ Food self-sufficiency rate (%) | 200–400 | 100–200 | 90–100 | 50–90 | 0–50 |
| symbiotic relationships | Water–energy subsystem | $c_{15}$ Energy consumption water intensity ($m^3$/ton standard coal) | 0–0.5 | 0.5–1 | 1–1.5 | 1.5–2 | 2–4 |
| | | $c_{16}$ Proportion of water used in energy production (%) | 0–0.2 | 0.2–0.5 | 0.5–1 | 1–2 | 2–7 |
| | | $c_{17}$ Industrial water reuse rate (%) | 90–100 | 85–90 | 75–85 | 50–75 | 0–50 |
| | Water–food subsystem | $c_{18}$ Proportion of agricultural water (%) | 0–20 | 20–40 | 40–65 | 65–85 | 85–100 |
| | | $c_{19}$ Irrigation water consumption per hectare ($m^3$/ha) | 0–3000 | 3000–4500 | 4500–7500 | 7500–12,000 | 12,000–15,000 |
| | | $c_{20}$ Effective irrigated area ratio (%) | 80–100 | 70–80 | 50–70 | 30–50 | 0–30 |
| | Energy–food subsystem | $c_{21}$ Agricultural machinery power per unit cultivated area (kw/ha) | 15–20 | 10–15 | 5–10 | 3–5 | 0–3 |
| | | $c_{22}$ Agricultural energy consumption ratio (%) | 0–1 | 1–2 | 2–3 | 3–4 | 4–7 |
| | | $c_{23}$ Agricultural energy utilization efficiency index ($10^4$ yuan/ton standard coal) | 15–20 | 10–15 | 5–10 | 3–5 | 0–3 |
| symbiotic environments | Economic subsystem | $c_{24}$ Per capita GDP ($10^4$ yuan/person) | 10–15 | 8–10 | 5–8 | 2–5 | 0–2 |
| | | $c_{25}$ GDP growth rate (%) | 20–50 | 12–20 | 8–12 | 4–8 | 0–4 |
| | | $c_{26}$ Percentage of tertiary industry added value in the GDP (%) | 70–100 | 60–70 | 40–60 | 30–40 | 0–30 |
| | | $c_{27}$ Ratio of R&D expenditure to GDP (%) | 5.5–10 | 4–5.5 | 2.5–4 | 1–2.5 | 0–1 |
| | | $c_{28}$ Proportion of investment in environmental restoration and protection to GDP (%) | 3.5–5 | 2.5–3.5 | 1.5–2.5 | 1–1.5 | 0–1 |
| | Social subsystem | $c_{29}$ Urbanization rate (%) | 80–100 | 60–80 | 40–60 | 20–40 | 0–20 |
| | | $c_{30}$ Population density (people/$km^2$) | 0–500 | 500–1000 | 1000–1500 | 1500–2000 | 2000–4000 |
| | | $c_{31}$ Aged population percentage (%) | 0–2 | 2–5 | 5–7 | 7–14 | 14–18 |
| | | $c_{32}$ Number of college students per $10^4$ people (person/$10^4$ people) | 600–1000 | 400–650 | 200–400 | 100–200 | 0–100 |
| | Natural subsystem | $c_{33}$ Urban sewage treatment rate (%) | 90–100 | 80–90 | 70–80 | 60–70 | 0–60 |
| | | $c_{34}$ Forest coverage (%) | 50–70 | 40–50 | 30–40 | 20–30 | 0–20 |
| | | $c_{35}$ Annual rainfall (mm) | 800–2000 | 600–800 | 400–600 | 200–400 | 0–200 |
| | | $c_{36}$ Sulfur dioxide emissions per $10^4$ yuan of GDP ($m^3/10^4$ yuan) | 0–0.3 | 0.3–0.7 | 0.7–1 | 1–5 | 5–10 |
| | | $c_{37}$ Fertilizer application per unit cultivated area (tons/ha) | 0–0.2 | 0.2–0.4 | 0.4–0.6 | 0.6–0.8 | 0.8–2 |

### *2.2.2. The variable fuzzy sets model*

The variable fuzzy sets model has been a breakthrough; it has enabled the development of absolute and static fuzzy sets, which can accurately reflect the fuzziness of things, while effectively dealing with uncertainty problems—including information fusion of index data in the evaluation system, and interactions between individual evaluation indictors. Two aspects have been central to the model—the relative membership degree and relative difference degree.

To explain this process, in this development, we define $A$ as a fuzzy concept in a theoretical domain $U$. $A$ and $A^C$ denote attraction and repulsion properties, respectively. On the continuous number axis of the relative membership function, for any element, $u(u \in U)$ in $U$, $\mu_{\underset{\sim}{A}}(u)$ and $\mu_{\underset{\sim}{A}^c}(u)$ represent the relative membership degrees of $u$ to $A$ and $A^C$, and $\mu_{\underset{\sim}{A}}(u) + \mu_{\underset{\sim}{A}^c}(u) = 1$. $D_{\underset{\sim}{A}}(u) = \mu_{\underset{\sim}{A}}(u) - \mu_{\underset{\sim}{A}^c}(u)$ indicates the relative difference in the degree of $u$ to $A$. Mapping $\begin{cases} D_{\underset{\sim}{A}} : D \to [-1,1] \\ u | D_{\underset{\sim}{A}}(u) \in [-1,1] \end{cases}$ is a relative difference function of $u$ to $A$, while $V = \left\{ (u,D) | u \in D, D_{\underset{\sim}{A}}(u) = \mu_{\underset{\sim}{A}}(u) - \mu_{\underset{\sim}{A}^c}(u), \text{and } D \in [-1,1] \right\}$ are variable fuzzy sets of $U$.

Since $\mu_{\underset{\sim}{A}}(u) + \mu_{\underset{\sim}{A}^c}(u) = 1$, then:

$$D_{\underset{\sim}{A}}(u) = 2\mu_{\underset{\sim}{A}}(u) - 1, \text{or} \mu_{\underset{\sim}{A}}(u) = \left(1 + D_{\underset{\sim}{A}}(u)\right)/2 \quad (3)$$

Suppose that $X_0 = [a,b]$ are the attraction domains of the fuzzy variable sets $V$ on the real axis, that is, the interval of $\mu_{\underset{\sim}{A}}(u) > \mu_{\underset{\sim}{A}^c}(u)$, and $X \in [c,d]$ is the range domain interval of a certain upper and lower bound containing $X_0 (X_0 \subset X)$, as shown in Fig. 4.

According to the definition of variable fuzzy sets, the intervals [$c$, $a$] and [$b$, $d$] are both repulsion domains of the variable fuzzy sets $V$, that is, the interval of $\mu_{\underset{\sim}{A}}(u) < \mu_{\underset{\sim}{A}^c}(u)$.

Suppose $M$ is the point value of $D_{\underset{\sim}{A}}(u) = 1 (\mu_{\underset{\sim}{A}}(u) = 1)$ in the attraction domain interval [$a$, $b$], and $x$ is the measured value of any point in the interval $X$. The difference function for the case where $x$ falls to the left of point $M$ can be described as shown in Eq. (4):

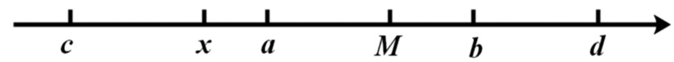


**Fig. 4.** Location relationship diagram.

**Table 3**
WEF nexus synergy grade eigenvalues and synergy grades for the BTH, individually and combined.

| Year | Beijing | | Tianjin | | Hebei | | The BTH as a whole | |
|---|---|---|---|---|---|---|---|---|
| | Grade eigenvalue | Synergy grade | Grade eigenvalue | Synergy grade | Grade eigenvalue | Synergy grade | Grade eigenvalue | Synergy grade |
| 2005 | 3.116 | III | 3.382 | III | 3.562 | IV | 3.370 | III |
| 2006 | 3.010 | III | 3.438 | III | 3.563 | IV | 3.378 | III |
| 2007 | 2.933 | III | 3.427 | III | 3.506 | IV | 3.298 | III |
| 2008 | 2.855 | III | 3.356 | III | 3.441 | III | 3.243 | III |
| 2009 | 2.863 | III | 3.327 | III | 3.490 | III | 3.312 | III |
| 2010 | 2.797 | III | 3.251 | III | 3.370 | III | 3.186 | III |
| 2011 | 2.869 | III | 3.188 | III | 3.303 | III | 3.135 | III |
| 2012 | 2.825 | III | 3.212 | III | 3.334 | III | 3.139 | III |
| 2013 | 2.809 | III | 3.198 | III | 3.302 | III | 3.117 | III |
| 2014 | 2.835 | III | 3.127 | III | 3.359 | III | 3.169 | III |
| 2015 | 2.694 | III | 3.126 | III | 3.333 | III | 3.168 | III |
| 2016 | 2.784 | III | 3.058 | III | 3.287 | III | 3.087 | III |
| 2017 | 2.651 | III | 3.061 | III | 3.201 | III | 3.019 | III |

$$\begin{cases} D_{\underset{\sim}{A}}(u) = \left[\frac{x-a}{M-a}\right]^{\beta} & x \in [a, M] \\ D_{\underset{\sim}{A}}(u) = -\left[\frac{x-a}{c-a}\right] & x \in [c, a] \end{cases} \quad (4)$$

The difference function for the case when $x$ falls to the right of point $M$ can therefore be described as shown in Eq. (5):

$$\begin{cases} D_{\underset{\sim}{A}}(u) = \left[\frac{x-b}{M-b}\right]^{\beta} & x \in [M, b] \\ D_{\underset{\sim}{A}}(u) = -\left[\frac{x-b}{d-b}\right] & x \in [b, d] \end{cases} \quad (5)$$

$$D_{\underset{\sim}{A}}(u) = -1, x \notin [c, d] \quad (6)$$

In Eqs. (4)–(5), $\beta$ indicates a non-negative exponent, and usually $\beta = 1$. Eqs. (4)–(5) meet the following conditions: 1) when $x = a = b$, $D_{\underset{\sim}{A}}(u) = 0$; 2) when $x = M$, $D_{\underset{\sim}{A}}(u) = 1$; 3) when $x = c = d$, $D_{\underset{\sim}{A}}(u) = -1$.

The sample data $\{x_{ij}(i = 1,2,\ldots,m; j = 1,2,\ldots,n)\}$ were identified according to the standard characteristic values of $n$ indexes, and $k$ index grades. The attraction $[a_{jk}, b_{jk}]$ and range domains, $[c_{jk}, d_{jk}]$, of the variable sets, and the point value, $M_{jk}$, of $[c_{jk}, d_{jk}]$ in the attraction domain, were determined by referring to the standard value matrix of the evaluation index, and the actual situation of the synergy evaluation objective. Symbol $m$ indicates the number of evaluation samples, that is, the number of evaluation years, where $n$ stands for the number of evaluation indicators, $k$ represents the indicator evaluation grade, and $k = 1, 2, \ldots, K$. Thus, the difference degree, $D_{\underset{\sim}{A}}(x_{ij})_k$, and the relative membership degree, $\mu_{\underset{\sim}{A}}(x_{ij})_k$, of the sample $i$ index $j$ to the $k$ grade were

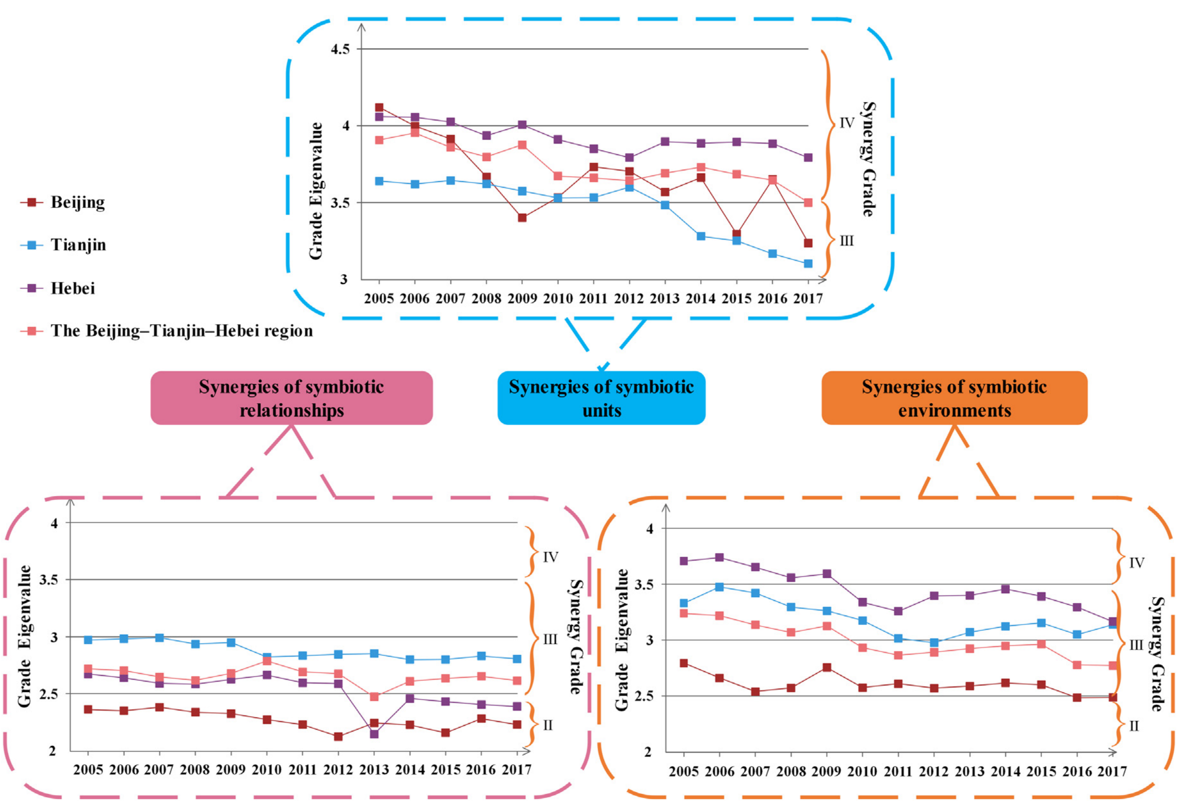


**Fig. 5.** The synergy grade eigenvalues, and symbiotic unit, symbiotic relationship and symbiotic environment synergy grades, for the BTH WEF nexus.

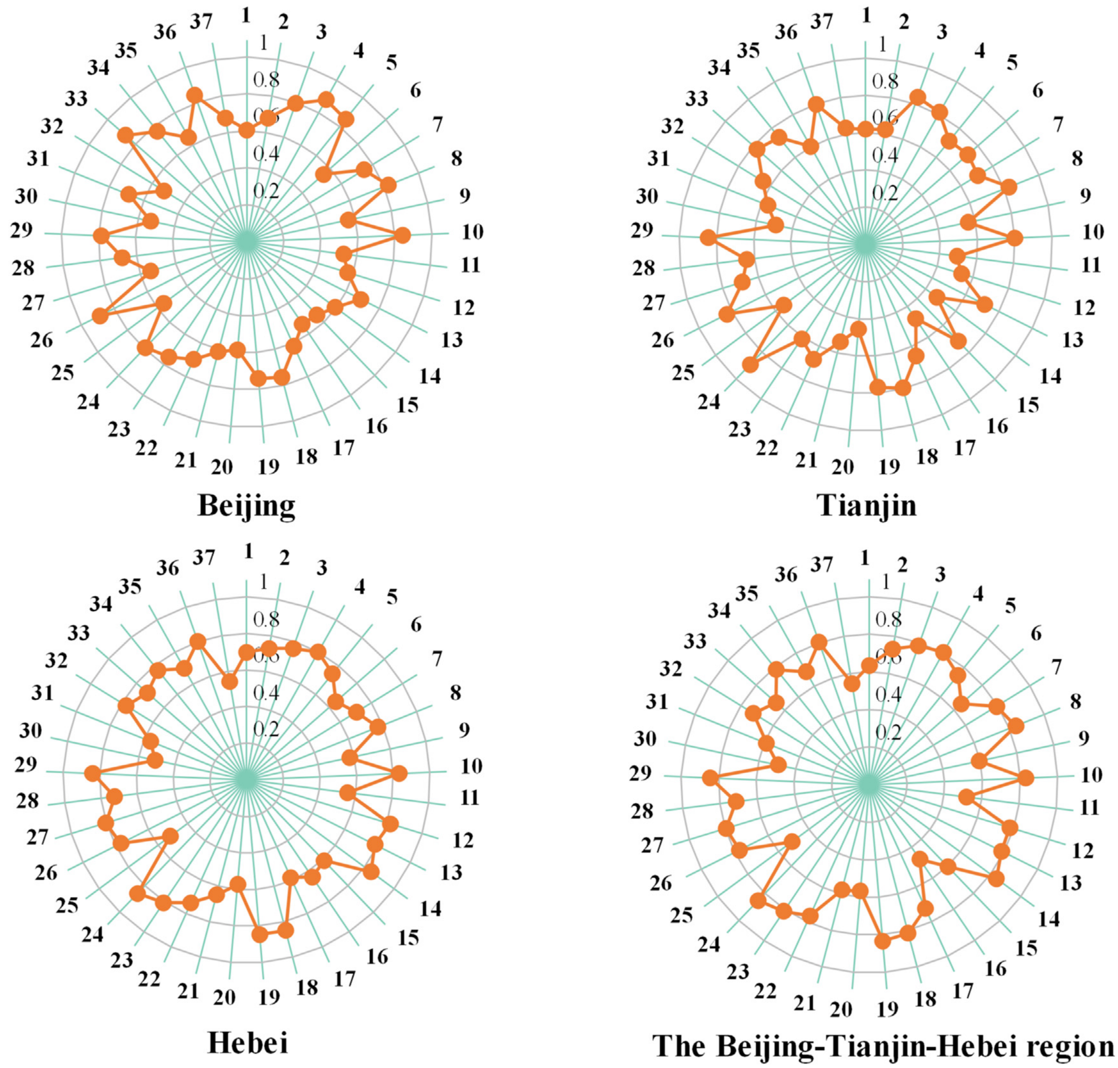


**Fig. 6.** Grey correlation degrees between the WEF nexus synergy grade eigenvalues and evaluation indicators.

obtained, and the comprehensive relative membership degree, $v'_{ik}$, could be obtained, as shown in Eq. (7):

$$v'_{ik} = 1 / \left[ 1 + \left[ \frac{\sum_{j=1}^{n} \left[ \omega_j \left( 1 - \mu_{\underset{\sim}{A}}(x_{ij})_k \right)^p \right]}{\sum_{j=1}^{n} \left( \omega_j \mu_{\underset{\sim}{A}}(x_{ij})_k \right)^p} \right]^{\alpha/p} \right] \tag{7}$$

where $\omega_j$ indicates the index weight, $\alpha$ represents the model optimization criterion parameter, and $p$ denotes the distance parameter with $p = 1$ being the Hamming distance, and $p = 2$ being the Euclidian distance.

The normalized comprehensive relative membership degree, $v_{ik}$, can then be obtained using Eq. (7), as shown in Eq. (8):

$$v_{ik} = v'_{ik} / \sum_{k=1}^{K} v'_{ik} \tag{8}$$

Finally, the grade eigenvalue can be derived, as shown in Eq. (9):

$$H_i = \sum_{k=1}^{K} k \cdot v_{ik} \tag{9}$$

*2.2.3. The set pair analysis-variable fuzzy sets model*

The variable fuzzy sets construction process was relatively complicated and included several instances of applying subjective judgment to obtain difference degree functions, which were tedious to calculate. In this study, by combining the theory of set pair analysis with the theory of variable fuzzy sets, the coupled set pair analysis-variable fuzzy sets model was established, and the set pair analysis connection degree was taken as the difference degree of variable fuzzy sets, to simplify difference degree calculations and to improve the objectivity and reliability of the calculation results.

The following steps were used to evaluate WEF nexus synergies, using the set pair analysis-variable fuzzy sets model:

(1) Construct a synergy evaluation index system, and determine its grade classification standards (see Table 1). Sample data $\{x_{ij}$ $(i = 1,2,\ldots,m; j = 1,2,\ldots,n)\}$ for each index constituted set $A$, and the threshold values of the indicator grade classification standards constituted set $B$. Symbol $m$ indicates the number of evaluation samples, that is, the number of evaluation years, where $n$ represents the number of evaluation indicators, and $k$ denotes indicator evaluation grades. We have seen that, in this work, $m = 13$, $n = 37$, and $k = 5$.
(2) The single index connection degree, $\mu_{ijk}$, between the index, $x_{ij}$,

**Table 4**
Principal research conclusions derived from this study.

| Aspect | Conclusions | |
|---|---|---|
| Evaluating WEF nexus synergies | (1) Beijing demonstrated the best WEF nexus, followed by the BTH as a whole, then Tianjin and Hebei. WEF nexus synergy grades improved over time, with Beijing improving the most, and Tianjin the least.<br>(2) WEF nexus symbiotic unit, symbiotic relationship, and symbiotic environment synergy grade eigenvalues showed fluctuating decreasing trends in each region, while the synergy grades gradually increased. Symbiotic relationship synergies achieved better results than symbiotic environment synergies than symbiotic unit synergies.<br>(3) Tianjin achieved the best results with respect to symbiotic unit synergies, followed by Beijing, the BTH as a whole, and then Hebei; the symbiotic relationship synergies results were the highest in Beijing, followed by Hebei, the BTH as a whole, and then Tianjin; the symbiotic environment synergies results had Beijing performing the best, followed by the BTH as a whole, Tianjin, and then Hebei. | |
| The main factors influencing of WEF nexus synergies | Beijing | Percentage of tertiary industry added value in the GDP, the unconventional water ratio, the urban sewage treatment rate, the water consumption per $10^4$ yuan of GDP, the energy consumption per $10^4$ yuan of GDP, the sulfur dioxide emissions per $10^4$ yuan of GDP, and the percentage of clean energy use. |
| | Tianjin | Per capita GDP, the urbanization rate, the groundwater supply ratio, the percentage of tertiary industry added value in the GDP, the percentage of clean energy use, and the unconventional water ratio. |
| | Hebei | Per capita GDP, the proportion of agricultural water, the irrigation water consumption per hectare, the food self-sufficiency rate, the urbanization rate, the energy consumption per $10^4$ yuan of GDP, the per capita food production, the agricultural energy utilization efficiency index, the ratio of R&D expenditure to GDP, the sulfur dioxide emissions per $10^4$ yuan of GDP, and the unconventional water ratio. |
| | The BTH as a whole | Per capita GDP, the urbanization rate, the food self–sufficiency rate, the percentage of clean energy use, the irrigation water consumption per hectare, the energy consumption per $10^4$ yuan of GDP, the proportion of agricultural water, the agricultural energy utilization efficiency index, the unconventional water ratio, and the sulfur dioxide emissions per $10^4$ yuan of GDP. |

and evaluation grade $k$ was constructed, based on the set pair analysis concept. When $x_{ij}$ was in grade $k$, the set pair relationship was expressed as the identity relationship, and $\mu_{ijk} = 1$; when $x_{ij}$ was in the grade adjacent to grade $k$, the set pair relationship was expressed as the discrepancy relationship, and $\mu_{ijk} \in [-1,1]$; for other cases, the set pair relationship was expressed as the opposition relationship and $\mu_{ijk} =$ - 1.

The expression of single index connection degree, $\mu_{ijk}$, could therefore be described as shown in Eq. (10):

$$\mu_{ijk} = \begin{cases} 1-2\cdot\left|\dfrac{s_{j,k-1}-x_{ij}}{s_{j,k-1}-s_{j,k-2}}\right| & \text{if } x_{ij} \text{ locates in the adjacent } k-1 \text{ grade} \\ 1 & \text{if } x_{ij} \text{ locates in the discussed } k \text{ grade} \\ 1-2\cdot\left|\dfrac{x_{ij}-s_{jk}}{s_{j,k+1}-s_{jk}}\right| & \text{if } x_{ij} \text{ locates in the adjacent } k+1 \text{ grade} \\ -1 & \text{if } x_{ij} \text{ locates in other intensity grades} \end{cases} \tag{10}$$

(3) The weights of each index were calculated using the entropy weight method.

The dimensionless processing of data could be described using Eqs. (11) and (12):

$$\text{Positive index}: x'_{ij} = \frac{x_{ij} - \min\{x_j\}}{\max\{x_j\} - \min\{x_j\}} \tag{11}$$

$$\text{Negative index}: x'_{ij} = \frac{\max\{x_j\} - x_{ij}}{\max\{x_j\} - \min\{x_j\}} \tag{12}$$

In Eqs. (11) and (12), $x'_{ij}$ indicates the standardized value of the index $x_{ij}$, $\max\{x_j\}$ represents the maximum value of the index $j$, and $\min\{x_j\}$ represents the minimum value of the index $j$.

The information entropy of index $j$ could be described by Eq. (13):

$$e_j = -\frac{1}{\ln(m)} \sum_{i=1}^{m} \frac{x'_{ij}}{\sum_{i=1}^{m} x'_{ij}} \ln\left(\frac{x'_{ij}}{\sum_{i=1}^{m} x'_{ij}}\right), 0 \le e_i \le 1 \tag{13}$$

While the weight of index $j$ could be described using Eq. (14):

$$\omega_j = \frac{1 - e_j}{\sum_{j=1}^{n} (1 - e_j)} \tag{14}$$

(4) The comprehensive connection degree, $\mu_{ik}$, the relative membership degree, $\upsilon_{ik}$, and the normalized relative membership degree, $\upsilon'_{ik}$, between sample $i$ and evaluation grade $k$, were as follows:

$$\mu_{ik} = \sum_{j=1}^{n} \omega_j \mu_{ijk} \tag{15}$$

$$\upsilon_{ik} = 0.5 + 0.5\mu_{ik} \tag{16}$$

$$\upsilon'_{ik} = \frac{\upsilon_{ik}}{\sum_{k=1}^{K} \upsilon_{ik}} \tag{17}$$

(5) The synergy grade eigenvalue, $H_i$, of the sample was then calculated, and the synergy grade determined, according to the rounding principle, as shown in Eq. (18):

$$H_i = \sum_{k=1}^{K} k \cdot \upsilon'_{ik} \tag{18}$$

### 2.3. Influencing factor identification using the grey correlation degree model

The correlation degree is a measure of the correlation between two sequences that change over time. The clearer the level of synchronous change in the two sequences over time, the higher the grey correlation degree between the two. In the process of identifying the main WEF nexus synergy influencing factors, the synergy grade eigenvalue was used as the reference sequence, and the evaluation index system was used as the comparison sequence. The higher the grey correlation value between the two sequences, the stronger the correlation is, that is, the greater the influence of the particular indicator on WEF nexus synergies.

The basic steps used in applying the grey correlation degree model were as follows:

(1) Suppose the number of observation years is $m$, and there is one reference sequence (using synergy grade eigenvalues of the WEF nexus as the reference sequence) and $n$ comparison sequences (using evaluation indicators as comparison sequences). Where, $m = 13$, and $n = 37$, the reference and comparison sequences can be described as shown in Eqs. (19) and (20):

Reference sequence:

$$X_0 = \{x_0(1), x_0(2), \ldots, x_0(13)\} \tag{19}$$

Comparison sequence:

$$X_i = \{x_i(1), x_i(2), \ldots, x_i(13)\}, (i = 1, 2, \ldots, 37) \tag{20}$$

(2) Complete dimensionless processing of the reference sequence and comparison sequences:

Reference sequence:

$$\widehat{X_0} = \{\hat{x}_0(1), \hat{x}_0(2), \ldots, \hat{x}_0(13)\} \tag{21}$$

Comparison sequence:

$$\hat{X}_i = \{\hat{x}_i(1), \hat{x}_i(2), \ldots, \hat{x}_i(13)\}, (i = 1, 2, \ldots, 37) \tag{22}$$

(3) Calculate the difference sequence for the corresponding elements between each evaluation indicator sequence (comparison sequence) and the reference sequence, and then determine the two-level maximum and two-level minimum differences.

The difference sequence:

$$\Delta_{0i}(k) = |\hat{x}_0(k) - \hat{x}_i(k)|, k = 1, 2, \ldots, m; i = 1, 2, \ldots, n \tag{23}$$

The two-level maximum difference:

$$\max_{i=1}^{n} \max_{k=1}^{m} |\hat{x}_0(k) - \hat{x}_i(k)| \tag{24}$$

The two-level minimum difference:

$$\min_{i=1}^{n} \min_{k=1}^{m} |\hat{x}_0(k) - \hat{x}_i(k)| \tag{25}$$

(4) The grey correlation coefficient, $\zeta_{0i}(k)$, can then be calculated, using Eq. (26):

$$\zeta_{0i}(k) = \frac{\min_i \min_k |\widehat{x}_0(k) - \widehat{x}_i(k)| + \rho \cdot \max_i \max_k |\widehat{x}_0(k) - \widehat{x}_i(k)|}{|\widehat{x}_0(k) - \widehat{x}_i(k)| + \rho \cdot \max_i \max_k |\widehat{x}_0(k) - \widehat{x}_i(k)|} \tag{26}$$

where $\rho$ represents the resolution coefficient, which is typically taken as $\rho = 0.5$ (Zhang et al., 2019).

(5) Quantify the grey correlation, $\gamma_{0i}$, using Eq. (27):

$$\gamma_{0i} = \frac{1}{m} \sum_{k=1}^{m} \zeta_{0i}(k) \tag{27}$$

(6) Determine the main WEF nexus synergy influencing factors using the grey correlation degree. The greater the degree of grey correlation, the greater the impact of the indicator on WEF nexus synergies. As a guide, when $\gamma_{0i} > 0.8$, the correlation was high (Pan et al., 2018), and the indicator has significantly influenced WEF nexus synergies.

### 2.4. Data sources

The 2005–2017 data used in this study were obtained from the China Statistical Yearbook, the China Energy Statistical Yearbook, the China Environment Statistical Yearbook, the China Rural Statistical Yearbook, the Beijing, Tianjin, and Hebei Statistical Yearbook, the Statistical Bulletin of National Economic and Social Development, and the Water Resources Bulletin.

## 3. Evaluating WEF nexus synergies in the BTH

### 3.1. Evaluating BTH WEF nexus synergy grades

WEF nexus synergy grade eigenvalues and synergy grades for Beijing, Tianjin, Hebei, and the BTH as a whole, were calculated using the set pair analysis-variable fuzzy sets model, as shown in Table 3.

(1) The best WEF nexus synergies were seen in Beijing, followed by the BTH as a whole, Tianjin, and Hebei. The Beijing WEF nexus synergy grade eigenvalues ranged from 2.6–3.2, and the synergy grade was calculated as grade III (medium). The Beijing WEF nexus synergy grade eigenvalue was the lowest, and its synergy grade was the strongest. The relatively comprehensive economic and technological development in Beijing has improved resource utilization and transformation efficiency while contributing to environmental improvements and bringing considerable economic and social benefits. This relatively coordinated development in Beijing WEF nexus has also promoted the WEF nexus synergies over the entire BTH. The whole BTH and the Tianjin WEF nexus synergies were both graded at III (medium), although the synergy grade eigenvalues for the whole BTH ranged from 3.01–3.38, while the Tianjin synergy grade eigenvalues ranged from 3.06–3.39. Compared with the whole BTH, the Tianjin WEF nexus synergy grade eigenvalues were higher, and the synergy grade weaker. The Hebei WEF nexus synergy grade eigenvalues ranged from 3.2 to 3.6, and its synergy grades were between IV (weak) and III (medium). The synergy grade eigenvalues for the Hebei WEF nexus were the highest, while its synergy grade was the weakest. The WEF nexus synergy grade eigenvalues in Tianjin and Hebei were both higher than those across the BTH as a whole, pulling down the WEF nexus synergies for the BTH overall. The poor performance of Hebei was quite clear, reflecting unbalanced development among its subsystems. These results made it apparent that it is important to seize the opportunity for the coordinated development of Beijing, Tianjin, and Hebei, to strengthen the environmental protection function, build a modern industrial system, and improve cooperation among the three centers, to make comprehensive improvements to their WEF nexus synergies.

(2) Overall, the WEF nexus synergy grade eigenvalues in each region showed a fluctuating downward trend, while the synergy grades gradually increased. The degree of change in the Tianjin WEF nexus synergy grade eigenvalues was the lowest, with the Beijing WEF nexus synergy grade eigenvalues changes being the highest. The Beijing WEF nexus synergy grades for 2005, 2010, and 2017 were all III (medium), and the corresponding synergy grade eigenvalues were 3.116, 2.797, and 2.651, respectively, with an average annual decrease of 0.039, which was the largest seen in this review. The Tianjin WEF nexus synergy grades for 2005, 2010, and 2017 were all III (medium), and the corresponding synergy grade eigenvalues were 3.382, 3.251, and 3.061, respectively, with an average annual decrease of 0.027, which was the smallest. The Hebei WEF nexus had the highest synergy grade eigenvalues, achieving 3.562, 3.370, and 3.201 in 2005, 2010, and 2017, respectively, with an average annual decrease of 0.030, and a gradual improvement in synergy grade from IV (weak) to III (medium). The 2005, 2010, and 2017 WEF nexus synergy grades for the entire BTH were all grade III (medium), while the synergy grade eigenvalues were 3.370, 3.186, and 3.019, respectively, decreasing by 0.029 annually. In recent years, steady improvement in the WEF nexus synergy grade for each region has been mainly due to the gradual increase in citizen awareness, in terms of saving resources and protecting the environment, and to the attention paid by the government to the improving resources use and to environmental protection. The unique political status, superior economic conditions, and advanced science and technology in Beijing have provided the conditions for its WEF nexus synergies. The corresponding synergies in Hebei have remained the weakest, while the average speed of its synergy improvement has been higher than that for Tianjin. Possible reasons for this include the face that despite resource shortages in Hebei—and the backwardness of its science and technology relative to Beijing and Tianjin—the recent background of coordinated BTH development and increased investment in environmental protection and improved governance have helped improve Hebei WEF nexus synergies to a certain extent. Although Tianjin WEF nexus synergies were better overall than those of Hebei, its synergy grade eigenvalues decreased the least, and the synergy gap between Tianjin and Hebei was seen to have gradually decreased over recent years.

### *3.2. Evaluating BTH WEF nexus symbiotic units, symbiotic relationships, and symbiotic environments synergy grades*

To grasp the synergetic development shortcomings of the BTH WEF nexus accurately, synergy grade eigenvalues for BTH WEF nexus symbiotic units, symbiotic relationships, and symbiotic environments, and the trends in their grades, were analyzed. The results can be seen in Fig. 5.

(1) The synergies of the WEF nexus symbiotic units were found to have been improving gradually, with the best performance shown by Tianjin, followed by Beijing, the whole BTH, and Hebei, respectively. The Tianjin WEF nexus symbiotic unit synergy grades were grade IV (weak), from 2005 to 2012, and grade III (medium), from 2013 to 2017. The Beijing WEF nexus symbiotic unit synergy grade was IV (weak) most years, while those for the whole BTH and Hebei were both grade IV (weak). The symbiotic unit synergy grade eigenvalues were higher for Beijing than for the whole BTH and Hebei. The decreasing trend seen for the synergy grade eigenvalues of the Beijing WEF nexus symbiotic units was the fastest, followed by that of Tianjin, while the decreasing trends in the symbiotic unit synergy grade eigenvalues for the WEF nexus in both Hebei and the whole BTH were relatively slow. The large Hebei population, combined with the high levels of resource consumption by the agricultural and industrial production sectors, has led to a prominent contradiction between resource supply and demand. This caused the WEF nexus symbiotic unit synergies to be weak here. Relatively backward production technologies have slowed improvement in symbiotic unit synergies and also reduced the WEF nexus symbiotic unit synergies across the BTH as a whole. In contrast, although Beijing and Tianjin have high population densities and lack of resources, their symbiotic unit synergies have been improved by their advanced production technologies and higher quality management.

(2) WEF nexus symbiotic relationship synergies have been gradually improving, with the best performance achieved by Beijing, followed by Hebei, the BTH as a whole, and then Tianjin. The symbiotic relationship synergy grade for the Beijing WEF nexus was grade II (slightly strong), while that for the Hebei WEF nexus was grade III (medium), from 2005 to 2012, and grade II (slightly strong) from 2013 to 2017. The WEF nexus symbiotic relationship synergy grade for the BTH as a whole was grade II (slightly strong) in 2013, and grade III (medium) in other years, while that for the Tianjin WEF nexus was grade III (medium). Reviewing the data presented in Fig. 5 showed that the symbiotic relationship synergy grade eigenvalues for each regions' WEF nexus had very slowly declined over recent years. This trend could have been the results of the continuous improvement and strengthening in science and technology applications, in the transformation and usage efficiency of resources, and each system's symbiotic relationships. We also saw, however, that, due to the constraints of resource shortages, waste, large-scale exploitation, and social development factors, the system symbiotic unit and symbiotic environment synergies have been relatively weak, which has impacted symbiotic relationship synergy development. It could also be seen that the slow rate of system symbiotic relationship synergy improvement had restricted the enhancement of symbiotic unit and symbiotic environment synergies. In the future, while focusing on improving symbiotic unit and symbiotic environment synergies, to promote overall improvement in WEF nexus synergies, it will be necessary to continually strengthen environmental protection efforts, promote coordinated development among various resources, and pursue resource allocation balance.

(3) The results showed that WEF nexus symbiotic environment synergies have been gradually improving, with the best performance achieved in Beijing, followed by the whole BTH, Tianjin, and then Hebei. Symbiotic environment synergies for the WEF nexus in Beijing, the whole BTH, and Tianjin were all calculated to be grade III (medium), although the symbiotic environment synergy grade eigenvalues showed that Beijing was higher than the whole BTH, followed by Tianjin. The Hebei WEF nexus symbiotic environment synergy grade was IV (weak), during 2005–2009, and grade III (medium) during 2010–2017. Symbiotic environment synergies provide an assessment of the overall sustainability level of the WEF nexus and can be limited by economic, social, and natural factors. Beijing's high level of economic, social, and technological development resulted in it enjoying symbiotic environment synergies better than those achieved by both Tianjin and Hebei.

## 4. Analyzing factors influencing WEF nexus synergies

Grey correlation degrees between the WEF nexus synergy grade eigenvalues and evaluation indicators were determined, using the grey correlation degree model, with the outcomes shown in Fig. 6 (where the designations 1–37 correspond to the 37 evaluation indicators, $c_1$–$c_{37}$, in Table 2). When the grey correlation degree was >0.8, the correlation was good. In this study, evaluation indicators with grey correlation degrees >0.8 were considered to represent the main WEF nexus synergy influencing factors.

(1) Economic factors and symbiotic unit synergies were found to be the main WEF nexus synergy influencing factors in Beijing and Tianjin. The results showed that seven main indicators influenced Beijing WEF nexus synergies, including the percentage of tertiary industry added value in the GDP, the unconventional water ratio, the urban sewage treatment rate, the water consumption per $10^4$ yuan of GDP, the energy consumption per $10^4$ yuan of GDP, the sulfur dioxide emissions per $10^4$ yuan of GDP, and the percentage of clean energy use. There were six equivalent factors in Tianjin, including per capita GDP, the urbanization rate, the groundwater supply ratio, the percentage of tertiary industry added value in the GDP, the percentage of clean energy use, and the unconventional water ratio. The first point to note here was that Beijing and Tianjin both had relatively high levels of influence on the WEF nexus synergies in terms of the 'percentage of tertiary industry added value in the GDP' indicator, as the population has a high level of demand for culture and entertainment—allowing the associated tertiary industries to drive the WEF nexus synergies of the two cities. The second point was that water resource-related indicators played an important role in the WEF nexus synergies of the two cities, with Beijing being represented by the unconventional water ratio, water consumption per $10^4$ yuan of GDP, and urban sewage treatment rate, while Tianjin has important groundwater supply and unconventional water ratios. Finally, in terms of energy and environmental indicators, the data showed that Beijing had the percentage of clean energy use, energy consumption per $10^4$ yuan of GDP, and sulfur dioxide emissions per $10^4$ yuan of GDP as key indicators, indicating that energy and environmental security have both been important contributors to Beijing WEF nexus synergies in recent years. The high level of economic development and urbanization were the most important factors affecting Tianjin WEF nexus synergies. Rapid economic development has resulted in well-developed economic foundations and social vitality for Beijing and Tianjin. These cities do have low self-sufficiency levels in water, energy, and food resources, however, depending mostly on external supplies, indicating that they have been unable to maintain their resource supply and demand balance. The data also showed that in the pursuit of rapid social and economic development, resource conservation and recycling have been generally neglected, causing serious impacts to WEF nexus symbiotic unit synergies in the two cities.

(2) Economic factors, symbiotic unit synergies, and symbiotic relationship synergies were found to be the main factors influencing Hebei WEF nexus synergies. The results showed that Hebei WEF nexus synergies were mainly influenced by 11 indicators, which included: per capita GDP, the proportion of agricultural water, the irrigation water consumption per hectare, the food self-sufficiency rate, the urbanization rate, the energy consumption per $10^4$ yuan of GDP, the per capita food production, the agricultural energy utilization efficiency index, the ratio of R&D expenditure to GDP, the sulfur dioxide emissions per $10^4$ yuan of GDP, and the unconventional water ratio. As a large agricultural and industrial province, Hebei has more water-consuming and energy-consuming industries than most, creating high demands for water and energy resources. This has affected specific indicators such as the proportion of agricultural water, the irrigation water consumption per hectare, and the agricultural energy utilization efficiency index—and as a result, the agricultural water and energy resource input–output levels achieving prominence in the Hebei WEF nexus synergies. The food self-sufficiency rate and per capita food production indicators represented the overall food security level of Hebei, with the higher the level of food security, the stronger the WEF nexus synergies. The data also showed that per capita GDP and the urbanization rate were important areas in which Hebei WEF nexus synergies could be improved, revealing that more economic development and accelerated urbanization could significantly improve the Hebei WEF nexus synergies. Symbiotic relationship synergies were found to be the most influential aspect of Hebei WEF nexus synergies, with these found to be stronger than both the symbiotic unit and symbiotic environment synergies. This showed that Hebei should focus on maintaining the balance of resource supply and demand, by improving symbiotic unit and symbiotic environment synergies, to improve its symbiotic relationship synergies.

(3) Economic factors, symbiotic unit synergies, and symbiotic relationship synergies were found to be the main factors influencing WEF nexus synergies for the BTH as a whole. The main WEF nexus synergy influencing factors here included: per capita GDP, the urbanization rate, the food self-sufficiency rate, the percentage of clean energy use, the irrigation water consumption per hectare, the energy consumption per $10^4$ yuan of GDP, the proportion of agricultural water, the agricultural energy utilization efficiency index, the unconventional water ratio, and the sulfur dioxide emissions per $10^4$ yuan of GDP. The per capita GDP and urbanization rate occupied important positions in the BTH, indicating that economic development and urbanization were the most direct ways for its regional WEF nexus synergies to be improved. The related elements of water resources, energy, agricultural water, and agricultural energy, also exerted significant influence on BTH WEF nexus synergetic development. The three indicators, percentage of clean energy use, energy consumption per $10^4$ yuan of GDP, and sulfur dioxide emission per $10^4$ yuan of GDP, showed that energy and environmental security elements were also important BTH WEF nexus synergy influencing aspects.

## 5. Discussion and analysis

From the perspective of symbiosis, the set pair analysis-variable fuzzy sets model was used here to study WEF nexus synergies in the BTH, over the period 2005–2017, from the perspective of three criteria: symbiotic units, symbiotic relationships, and symbiotic environments. The main WEF nexus synergy influencing factors were also analyzed. The results showed that the BTH WEF nexus synergies have gradually improved, with those revealed for Beijing working the best, followed by the BTH as a whole, and the Tianjin, followed by Hebei. The WEF nexus symbiotic unit, symbiotic relationship, and symbiotic environment synergies for each region have gradually improved, with symbiotic relationship synergies performing better than symbiotic environment synergies than symbiotic unit synergies. Symbiotic unit synergies were revealed as the WEF nexus synergy aspects most in need of improvement. Symbiotic unit synergies were working the best in Tianjin, followed by Beijing, the BTH as a whole, and then Hebei, while symbiotic relationship synergies were working well in Beijing, followed by Hebei, the BTH as a whole, and then Tianjin. Symbiotic environment synergies were working the best in Beijing, followed by the BTH as a whole, Tianjin, and then Hebei. Economic factors and symbiotic unit synergies were found to be the main WEF nexus synergy influencing aspects for Beijing and Tianjin, while economic factors, symbiotic unit synergies, and symbiotic relationship synergies were seen as the most influential WEF nexus synergy aspects in both Hebei and the BTH as a whole. For evaluating the WEF nexus synergies using a set pair analysis-variable fuzzy sets model has been a key difference between this and the previous studies. The set pair analysis-variable fuzzy sets model is an uncertainty method and is more objective in evaluating the uncertainty issues (such as the level of system development); applying the combined model herein made estimating evaluation results faster and more efficient.

Indicators such as food import volume and the food consumption ratio of the energy system were not included in the evaluation index system here, as applicable data were unavailable—which may have impacted the empirical conclusions to some degree.

## 6. Conclusions and policy implications

Using symbiosis theory, the evaluation index system of WEF nexus synergies for this study involved applying three criteria: symbiotic units, symbiotic relationships, and symbiotic environments. The set pair analysis-variable fuzzy sets model was applied to calculate synergy grade eigenvalues and evaluate the WEF nexus synergy grades for 2005–2017 in the BTH. The grey correlation degree model was then used to determine the main BTH WEF nexus synergy influencing factors. The resulting conclusions presented in Table 4.

### 6.1. Main conclusions

Firstly, it was found that the WEF nexus synergy grade gradually increased over the study period in each region, with Beijing WEF nexus synergies showing the fastest improvement, followed by the BTH as a whole, Tianjin, and Hebei. The Beijing WEF nexus synergies also showed that the biggest improvement, while those for Tianjin improved the least. Secondly, the WEF nexus symbiotic unit, symbiotic relationship, and symbiotic environment synergy grade eigenvalues for each region exhibited a fluctuating decreasing trend, while synergy grades increased gradually. The symbiotic relationship synergies were found to be performing better than symbiotic environment synergies, and then symbiotic unit synergies. Thirdly, symbiotic unit synergies were performing best for Tianjin, followed by Beijing, the BTH as a whole, and then Hebei; the symbiotic relationship synergies showed the best results in Beijing, followed by Hebei, the BTH as a whole, and then Tianjin; the symbiotic environment synergies produced the best results in Beijing, followed by the BTH as a whole, Tianjin, and then Hebei. Finally, the results showed that economic factors and symbiotic relationship synergies were the most influential WEF nexus synergy factors for Beijing and Tianjin, while economic factors, symbiotic unit synergies, and symbiotic relationship synergies were the most influential WEF nexus synergy factors in both Hebei and the BTH as a whole. The main Beijing WEF nexus synergy influencing factors involved seven indicators: the percentage of tertiary industry added value in the GDP, the unconventional water ratio, the urban sewage treatment rate, the water consumption per $10^4$ yuan of GDP, the energy consumption per $10^4$ yuan of GDP, the sulfur dioxide emissions per $10^4$ yuan of GDP, and the percentage of clean energy use. The corresponding factors for Tianjin included six indicators: per capita GDP, the urbanization rate, the groundwater supply ratio, the percentage of tertiary industry added value in the GDP, the percentage of clean energy use, and the unconventional water ratio. The main Hebei WEF nexus synergy influencing factors included 11 indicators: per capita GDP, the proportion of agricultural water, the irrigation water consumption per hectare, the food self-sufficiency rate, the urbanization rate, the energy consumption per $10^4$ yuan of GDP, the per capita food production, the agricultural energy utilization efficiency index, the ratio of R&D expenditure to GDP, the sulfur dioxide emissions per $10^4$ yuan of GDP, and the unconventional water ratio. The main BTH WEF nexus synergy influencing factors included ten indicators: per capita GDP, the urbanization rate, the food self-sufficiency rate, the percentage of clean energy use, the irrigation water consumption per hectare, the energy consumption per $10^4$ yuan of GDP, the proportion of agricultural water, the agricultural energy utilization efficiency index, the unconventional water ratio, and the sulfur dioxide emissions per $10^4$ yuan of GDP.

### 6.2. Policy implications

There are interdependent relationships between water, energy, and food resources, and the improvements of WEF nexus synergies need to be adapted to local conditions. Based on the main factors influencing WEF nexus synergies in each region, the following policy implications have been derived from this work:

(1) Stable societal and economic development, combined with improving symbiotic unit synergies, have been the WEF nexus synergetic development focus for Beijing. The results indicate that Beijing should insist on the combination of water pollution prevention and water resources development and utilization, and promote the recycling of sewage. Beijing should also focus on progressing unconventional water resource usage, promoting rational water use while protecting unconventional water resources, and improving water use efficiency. At the same time, Beijing needs to strengthen the management and protection of coal to clean energy, increase investment in technology R&D, and reduce sulfur dioxide emissions.

(2) Stable economic and societal development, together with improving symbiotic unit synergies, should also be the WEF nexus synergetic development focus for Tianjin. Tianjin should review aspects relating to improved groundwater pollution monitoring, while researching unconventional water resource treatment processes, and should develop usage scenarios and resource dispatching systems to ensure unconventional water resource usage safety and efficiency are better managed. At the same time, to improve Tianjin WEF nexus synergies, Tianjin should focus on exploring innovative development modes, further reducing coal consumption, improving the quality of developments, and promoting urbanization.

(3) Stable economic and societal development, together with synergetic improvements to symbiotic units and symbiotic relationships, should also be the WEF nexus synergetic development focus in Hebei. Hebei should focus on promoting the development of the digital economy, on the digital transformation of industries, and on accelerating the digital transformation of urban public services. Hebei should also further strengthen agricultural science and technology innovation efforts, and strive to improve food production and ensure food security at source. In terms of agricultural water, Hebei should develop water-saving agriculture and promote efficient water-saving irrigation technology. The results also show a need to improve agricultural energy use efficiency. Agriculture should be developed simultaneously while increasing R&D investment relating to exploiting agricultural waste energy use (bioenergy) in the pursuit of sustainable resource utilization. Under a coordinated BTH development strategy, with Beijing as the center, WEF nexus synergy improvement will involve decentralizing non-capital functions, and constructing extensive transportation infrastructure in the cities surrounding Beijing. The strategy will also involve accelerating R&D investment in agriculture, energy, and water resource science and technology, to reduce overall agricultural production costs and improve production efficiency.

## CRediT authorship contribution statement

**Yong Wang:** Writing – original draft, Writing – review & editing, Supervision, Visualization, Funding acquisition. **Yanjing Xie:** Conceptualization, Software, Validation, Writing – original draft. **Lin Qi:** Supervision, Visualization, Validation, Writing – review & editing.

**Yuan He:** Methodology, Validation, Writing – original draft. **He Bo:** Methodology, Software, Data curation.

## Declaration of competing interest

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

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