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Evaluating sustainability of water-energy-food (WEF) nexus using an improved matter-element extension model: A case study of China

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ABSTRACT

The sustainability of the water-energy-food (WEF) nexus is a significant challenge faced by developing countries, especially China. Evaluating the sustainability status of China's water-energy-food, and improving its sustainable use, may provide good physical conditions to support China's future development. This paper applied the Pressure, State, and Response (PSR) model to select evaluation indexes. A combination weighting method was used to combine two objective weighting methods to determine index weights. The study constructed the classical field, the limited field, and the matter-element to be evaluated. This allowed the establishment of an improved matter-element extension model to evaluate the sustainability of the water-energy-food nexus; the model was then used to quantitatively evaluate the sustainability of China's water-energy-food nexus. The simulation results indicated that in 2005, the sustainability of China's water-energy-food was at a relatively low efficiency rank. By 2015, the sustainability of China's water-energy-food had reached a general efficiency rank. The results suggested that the sustainability of China's water-energy-food system significantly improved between 2005 and 2015; however, the improved sustainability remained at a general status (The general status means that the sustainability of water-energy-food nexus in China can meet the basic development needs, but it is far from the optimal state and needs further adjustment and improvement). Thus, China should improve its current utilization patterns for the three resources and consider them as a whole. This would help realize synergistic resource use and enhance their sustainability.

1. Introduction

The resources and environmental conditions in a country impact its development, and play a decisive role in realizing sustainable economic and social development. More specifically, water, energy, and food (WEF) are the three most fundamental resources for human society (Elst and Davis, 2011; The Food and Agriculture Organization, 2014). China currently has the largest population in the world, with approximately 1.4 billion people, or 19% of the world's population (World-Bank, 2017). China lacks resources of the water, energy and food. Its per capita farmland area is less than 50% of the world average (World-Bank, 2017), its per capita water resources make up approximately 25% of the world average (Wang et al., 2018), and its per capita hold of energy is less than 50% of the world average (Wang and Chen, 2015). However, China leads the world in its speed of development. In 2017, China individually contributed nearly 33% of worldwide economic growth (UNCTAD, 2017).

In some sense, China's further development is constrained by the three resource – water, energy, and food. The sustainable utilization of the three resources directly impacts China's national security and social stability. Given this background, this study investigated the overall sustainability of WEF. The research applied an improved matter-element extension method to evaluate the sustainability status of China's WEF system, and proposed new ways to resolve the conflict among the three resources. In addition, the evaluation results provide a certain reference values for countries or regions in similar situations.

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2. Literature review

2.1. Research status of WEF

Water, energy, and food are irreplaceable in the development of human society. They constitute the material basis that impacts national security and regional stability. Thus, policy-makers must consider the development status of all three resources. In 2011, the Bonn Conference (Water-Energy-Food Security Nexus Conference) was held in Germany. At the conference, the relationship between water, energy and food was first summarized as a "WEF-Nexus". The "WEF-Nexus" provides a transparent, reasonable, and sagacious framework. Based on the premise of not jeopardizing resource sustainability, efforts are needed to resolve mutual competition between different resource uses, and accounting for an overall resource shortage. Since then, there has been an increase in the number of studies in this field.

In terms of qualitative studies, Rasul et al. propose that the problems and challenges associated with water, energy, and food are interwoven in complicated ways. Effectively managing the three requires a cross-departmental management pattern (Rasul, 2014). Zhan notes that water, energy, and food are correlated and interact with each other in complicated relationships. It remains difficult to produce freshwater resources, and producing energy and food consumes large amounts of water resources. Similarly, using water resources consumes a lot of energy. Producing food requires energy and water, and food supports the existence and development of a major workforce (human resources) employed to produce water and energy (Zhan and Wu, 2014). D Conway et al. use South Africa as an example to describe the influence of climate change on the WEF system (Conway et al., 2015). Ozturk et al. applied principal component analysis to conduct an overall analysis of BRICS (Brazil, Russia, India, China and South Africa). They note that energy and water resource shortages have significantly influenced the food security of these countries (Ozturk, 2015). Alloisio elaborates on the relationships among WEF, proposing strategies to address the increasing future demands for water, energy, and food. The study also recommends that natural resources should be harmoniously managed and used (Alloisio, 2015). Gallagher argues that studies on "WEF-Nexus" can help determine the forces critical for realizing sustainable development, highlighting the importance of both policy and practical studies (Gallagher et al., 2016). Gondhalekar et al. conducted a case study of Munich, Germany. They investigated the applications of "WEF-Nexus," and discussed the operability of a "Nexus City" and its facilitative effect on sustainable development (Gondhalekar and Ramsauer, 2016). Chang et al. have sorted out the emergence and development of "WEF-Nexus," summarize possible extensions and related applications by the international community, and pose suggestions and implications for policy-making in related fields in China (Chang et al., 2016). Li et al. proposed two basic viewpoints regarding "WEF-Nexus" studies: the "slow variable viewpoint" and the "resources integration viewpoint." This study encouraged future studies to shift from summaries of practical experience to the construction of theoretical frameworks (Li et al., 2016a). Endo et al. reviewed and analyzed existing studies on the relationships among WEF, proposing that a unified relationship study framework be constructed to increase the degree of synergistic use of the three resources (Endo et al., 2017). Abou Najm et al. proposed an integrated mathematical framework (roadmap) to create connection and feedback loops among those connections. This framework could be used to investigate the relations among WEF (Abou Najm and Higgins, 2016). Jia et al. used the case study of Ordos to analyze the interactions among water, energy, and food; they proposed strategies for realizing the synergistic development of these resources (Jia et al., 2017). Sperling et al. applied an analysis of "WEF-Nexus" to the sustainable development of cities, and proposed the framework of "urban contact science" (Sperling and Berke, 2017).

In terms of quantitative studies, Villamayor-Tomas et al. used an IAD framework and value chain analysis to study the relationship among WEF (Villamayor-Tomas et al., 2015). Talozi et al. introduced a GIS model and virtual method to provide policy input about the relationships among WEF (Talozi et al., 2015). Al-Ansari et al. proposed a comprehensive tool for life cycle evaluations of water, energy, and food; and applied the tool to investigate the status of WEF in Qatar (Al-Ansari et al., 2015). Li et al., based on system dynamics, simulated the WEF system of Beijing, and forecasted changing WEF trends in Beijing (Li et al., 2016b). Jalilov et al. applied a water conservancy economy model to probe the relationships among WEF in the Amu Darya Basin, stressing the importance of the cross-basin comprehensive utilization of WEF to achieve a win-win situation (Jalilov et al., 2016). Hang et al. designed an optimization model, and used it to study the relationships among WEF in the local environment (Hang et al., 2016). Karabulut et al. introduced the SWAT model to create a comprehensive framework to evaluate water supply services, and used a water resources perspective to address the complicated relationships associated with ecosystem-water-food-energy (Karabulut et al., 2016). Peng et al. followed the synergistic principle to perform a synergistic optimization for WEF in the Yellow River Basin. They proposed an integrated layout scheme for water resource allocation, energy development, and food production (Peng et al., 2017). Li et al. used the DEA method to analyze and evaluate the input-output efficiency of WEF in different parts of China (Li et al., 2017). Kurian reviewed recent "WEF-Nexus" studies, introducing scientific methods to investigate WEF (Kurian, 2017). Hussien et al. created a WEF risk evaluation model, and applied it to evaluate the influence of seasonal changes on WEF demands (Hussien et al., 2017, 2018). White et al. adopted the input-output method to analyze the relationships among WEF in East Asia, and to provide policy input about ways to realize sustainable development (White et al., 2018). Yang et al. used the Great Ruaha River of Tanzania as an example to build a coupling model for analyzing WEF (Yang and Wi, 2018). Guijun Li et al. created a simulation model based on Agent and combined with NetLogo, and used it to explore how to effectively allocate the three resources in urban development (Guijun et al., 2017). Hussien et al. built an integrated simulation model, and evaluated the relationships among WEF on a family scale (Hussien et al., 2017, 2018). Martinez-Hernandez et al. used NexSym (a system simulation tool) to investigate the interactions among water, energy, food, and ecosystem (Martinez-Hernandez et al., 2017).

This literature review showed the following. ① In terms of qualitative studies, scholars have mainly focused on discussing the internal relationships of the "WEF-Nexus" system. These studies provide opinions and references for policy makers, by analyzing external influences. ② In terms of quantitative studies, existing studies remain in the initial stage; to be specific, the studies elaborate the relationships among WEF, quantify these relationships, and construct study frameworks and models. ③ Few quantitative studies have explored the overall sustainability of WEF. For WEF, sustainability is the priority for their development. Whether their sustainable development can be realized or not relates to the present situation and future of the three resources, as well as the prospect and destiny of regional development. ④ China's water resources quantity (per capita) and per capita hold of energy are both at a relatively low level in the world. The country's food resources are at a medium level; however, its reliance on imports is relatively high, making the sustainable development of WEF particularly important for China. Given this, it is of vital practical significance to analyze the relationships among the three, and investigate their sustainable development status.

2.2. Research status of matter-element extension model

The matter-element extension method, proposed by Chinese scholar Cai Wen, is a comprehensive evaluation method that solves practical contradictions from both qualitative and quantitative perspectives (Cai, 1999). The main idea of this analysis theory is to use elements to describe things. Its core value lies in solving the problem of incompatibility, and promoting the conversion of things.

The specific principle of matter-element extension theory is: the theory uses the corresponding methods to analyze things, summarize the nature and connotation of things, and choose indicators that can represent the characteristics of things. Use indicators and corresponding data as input to the model to combine qualitative analysis and quantitative calculations. Use a reasonable weight calculation method to determine the weight of the indicator. The degrees of closeness and evaluation level are calculated by establishing the classical field matter-element, the limited field matter-element, and the matter-element to be evaluated. The evaluation results of things are reflected by specific values. Finally, through the analysis of the calculation results, the comprehensive evaluation results of things are obtained. So the model applies to multi-index evaluation problems (Liu et al., 2017), and has been applied to many specific problems. He et al. used the matter-element extension method to evaluate the risks of an urban power grid (He et al., 2011). Li et al. adopted the matter element extension method to evaluate the external economy of wind power projects in Inner Mongolia (Li and Guo, 2013). The matter-element extension method does have certain limitations and disadvantages. First, when an index value exceeds the limited field, it's impossible to obtain the correlation function value. Second, the model's evaluation principle is equivalent to the maximum subordination principle in the fuzzy comprehensive evaluation model. It is susceptible to information losses under some circumstances. To solve this problem, scholars have proposed an improved matter-element extension method; this extension method has been widely applied (Zhao and Li, 2013). The main improvements of the improved matter-element extension method (Li et al., 2013) are as follows. ① Normalization processing is provided for the classical field and the matter-element to be evaluated. This overcomes the first disadvantage of the above matter-element extension method. ② The degree of closeness is introduced as a substitute for the degree of association to overcome the second disadvantage. The improved matter-element extension method is based on the matter-element extension method, but mitigates the limitations of the matter-element extension method. Scholars have applied it widely to comprehensively evaluate multi-factor problems (Feng et al., 2015).

As a comprehensive evaluation method suitable for dealing with multi-factors, the matter-element extension method is suitable for studying sustainability issues. In terms of the sustainability of things, the sustainability of everything involves the impact and balance in three aspects of social, environmental and economic. These three concepts contain a large number of influencing factors, and different factors are interrelated and conflicting. The advantage of the matter-element extension theory lies in the handling of complex things with multiple factors and their incompatibility. Therefore, it is very suitable to use the matter-element extension method to study the sustainability of things. In addition, a large number of scholars have used the matter-element extension method to study the sustainability of things (An et al., 2018; Dai and Niu, 2017; Huang and Mai, 2015; Li et al., 2016; Li et al., 2015; Ren et al., 2017; Zhong et al., 2017), which also shows that the method is widely recognized as suitable for studying sustainability issues. Thus, the WEF system is complicated and comprehensive, and its sustainability also has multi-factor characteristics. Thus, the improved matter-element extension method applies to the evaluation of WEF system sustainability.

When applying the improved matter-element extension method, determining the weights is a critical aspect, because the final evaluation result is directly influenced by the weight of the index. The objective weighting method bases its analysis on data and determines weights using specific calculations. The subjective weighting method determines weights through subjective judgment, based on the importance that people attach to indexes. They both have their disadvantages. First, the weights determined by the subjective weighting method reflect the inclination of decision-makers; as such, the results are significantly influenced by the subjectivity of evaluation subjects. This method does not use data-driven information. Second, the objective weighting method mainly relies on a complete set of mathematical theories and methods. It starts with objective data, and does not consider the subjective information from decision makers. In addition, the method omits differences in the indexes themselves, and can very easily overlook the true status (Shan et al., 2012). The combination weighting method that integrates the two methods has received wide attention. By synthesizing the weights obtained by the subjective weighting method and the objective weighting method in specific ways, the respective advantages are maximized (Cui et al., 2012), leading to the extensive application of the method (Zhang et al., 2013).

However, with respect to the "WEF-Nexus," current explorations remain in a start-up stage, and consensus has not yet been reached among scholars. If subjective judgment is used to determine the weights of indexes, there will be significant differences and uncertainties. For this reason, this paper extended the scope of application of the combination weighting method, combining two objective weighting methods. That is, the coefficient of variation method and the entropy method were used to determine the weights of indexes. The combination weighting method was then used to synthesize the results of the two methods, to minimize the influence of human factors and highlight the information contained in the data. The obtained weights could better reflect the different degrees of index importance.

To summarize, this study considered WEF as a whole, using a combination weighting method to calculate the weights of indexes. It also applied an improved matter-element extension method to evaluate the sustainability of China's WEF system. This paper offers many improvements upon existing studies on WEF systems. First, it used the combination weighting method to combine two objective weighting methods, minimizing the influence of human factors. Second, it extended the scope of application of the improved matter-element extension method to evaluate the WEF system, quantitatively determining the sustainability level of China's WEF system. The study also compared the status of China's WEF system in 2005 with its status in 2015. The results suggest that the method can correctly evaluate the sustainability of the WEF system. It also generated new ideas for WEF system studies, and offers a reference for improving the utilization efficiency of WEF and developing regional policies for sustainable development. There is no doubt that people should play closer attention to the WEF system to realize the sustainable use of these resources.

3. Methods

3.1. Index system

The pressure, state, response (PSR) model was first proposed by Canadian scholars David J. Rapport and Tony Friend. It was later developed by OECD and UNEP, and is used to study environmental issues (Benites and Tschirley, 1997; Walz, 2000). The PSR model consists of three major indexes: pressure, state, and response. These indexes interact with and mutually restrict each other. The model emphasizes the relationships between environmental pressure and environmental degradation, and influences the entire decision-making process (Qiu, 2006). As such, it has been extensively applied in China to evaluate ecological environments and other fields.

Yan et al. used the PSR model to create an index system and evaluation model, and to evaluate the health status of the ecosystem in the Dongxi River Basin of Zhao'an, Fujian Province (Yan et al., 2008). Feng et al. adopted the PSR model and a geographical information system (GIS) model to study the differences in the intensive use of urban land in Zhejiang Province (Feng et al., 2007). Zhang et al. used a PSR model to evaluate the ecological security of land in the Three Gorges area (Zhang et al., 2011). Bai et al. used a PSR model to evaluate the ecological security of Tianjin (Bai and Tang, 2010). This paper borrowed the PSR model concept, and combined the indexes selected from the Literature [24] with practical situations to determine an index system that could evaluate WEF system sustainability. Fig. 1 shows the details (C_i represents index number, $i = 1, 2, \ldots \ldots, 13$). On the other hand, the concept of sustainability essentially integrates checks and balances among society, economy, and environment. Proceeding with this perspective, the representative indexes related to these three dimensions are selected in the index system above. To be specific, the social indexes include water consumption, energy consumption, urban residents' food consumption (per capita), permanent resident population, and water resource quantities (per capita). The economic indexes include per capita gross domestic product (GDP), total energy production, and food yield. The environmental indexes include wastewater and sewage discharge, SO_2 emission, smoke (dust) emissions, industrial solid waste discharge, and total investment in environmental pollution control.

3.2. Determination of weights

3.2.1. The coefficient of variation method

The coefficient of variation method is an objective method to determine index weights. The basic premise of the method is that in a comprehensive evaluation index system, the greater the variation of an index, the better the ability of index reflects the evaluation object. Thus, the index is assigned a higher weight (Cheng, 2008; Sun et al., 2007). This objective method has been applied in many case studies. Chu et al. used the coefficient of variation method to investigate and evaluate the energy-saving and emission-reduction status of Anhui Province (Chu and Chen, 2011). When introducing the security access evaluation methods for facilities in chemical industry parks, C Qian et al. adopted the coefficient of variation method to determine the weights of related indexes (Qian et al., 2014).

The specific steps of weight determination are as follows:

(1) Non-dimensionalization processing of data

Reverse index:

$$Y'_{ij} = \frac{\max_i [Y_{ij}] - Y_{ij}}{\max_i [Y_{ij}] - \min_i [Y_{ij}]} \quad (1)$$

Forward index:

$$Y'_{ij} = \frac{Y_{ij} - \min_i [Y_{ij}]}{\max_i [Y_{ij}] - \min_i [Y_{ij}]} \quad (2)$$

$i = 1,2, \ldots,n;\ j = 1,2, \ldots,m.$

The variable Y_{ij} represents the actual data before non-dimensionalization processing; Y'_{ij} represents the data of the jth index in the ith year after non-dimensionalization processing.

(2) Calculation of each index's mean value $\overline{c_j}$ and standard deviation s_j

$$\overline{c_j} = \frac{1}{n} = \sum_{i=1}^{n} Y'_{ij} [j = 1, 2, .., m] \quad (3)$$

$$s_j = \sqrt{\frac{\sum_{i=1}^{n} \left(Y_{ij} - \overline{C_j}\right)^2}{n - 1}} [j = 1, 2, .., m] \quad (4)$$

(3) Calculation of each index's coefficient of variation v_j

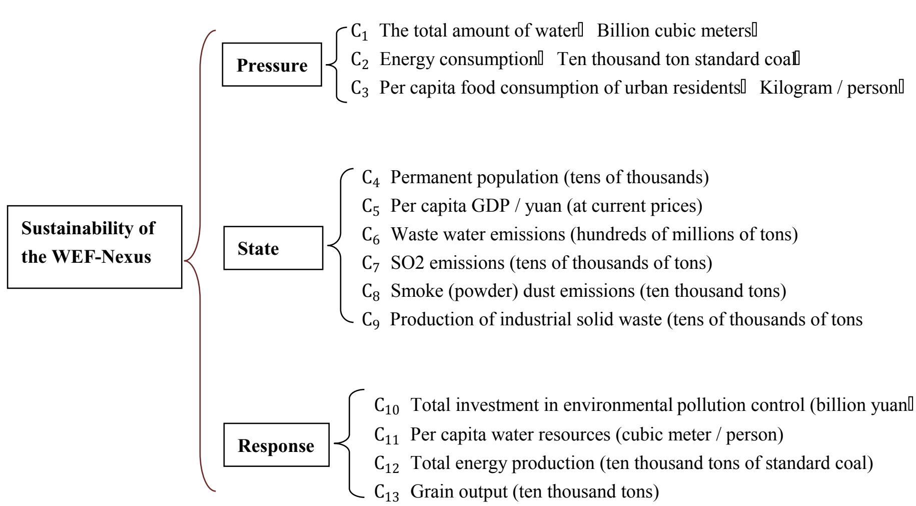

Fig. 1. Index system evaluating the sustainability of the WEF system.

$$v_j = \frac{s_j}{c_j} [j = 1, 2, ..., m] \quad (5)$$

(4) Calculation of each index's weight w_j

$$w_j = \frac{v_j}{\sum_{i=1}^{n} v_j} [j = 1, 2, ..., m] \quad (6)$$

3.2.2. The entropy method

The entropy method is an objective weighting method that has been extensively applied to matter-element evaluations (Qiao, 2004; Zhou et al., 2006). Entropy is a measure of the degree of the disorder of a system; the entropy weight reflects the amount of useful information carried and transported by each index. That is, the higher the amount of useful information carried and transported by an index, the higher the index's entropy weight, and vice versa (Yang et al., 2016). Xiao et al. applied the entropy method to adjust the weights of performance indexes, and have overcome disadvantages of previous weight determination methods (Xiao et al., 2005). Han et al. applied the entropy method to urban ecological security evaluations, and used it to determine index weights (Han et al., 2015).

The specific steps to determine weights are as follows:

(1) Non-dimensionalization processing of data

For the-smaller-the-better indexes, we first provide forward processing for the convenience of analysis:

$$X_{ki} = (V_{ki})_{max} - V_{ki} \quad (7)$$

In the expression, V_{ki} represents the actual value of the kth index in the ith year.

Non-dimensionalization processing is provided for all indexes:

$$Y_{ki} = \frac{X_{ki}}{\sum_{i=1}^{n} X_{ki}} = [i = 1, 2, ..., n; k = 1, 2, ..., m] \quad (8)$$

The variable X_{ki} represents the actual data before processing; and Y_{ki} represents the data of the kth index in the ith year after non-dimensionalization processing.

(2) Calculation of the entropy values of the different indexes:

$$f_{ik} = \frac{1 + y_{ki}}{\sum_{k=1}^{s} (1 + y_{ki})} \quad (9)$$

$$t = -\frac{1}{\text{Ink}} \quad (10)$$

$$H_i = -t \sum_{k=1}^{s} f_{ik} \ln f_{ik} \quad (11)$$

In the expression, i = 1,2, …,n; k = 1,2, …,s; $0 \leqq H_i \leqq 1$.

(3) Calculation of the weights of various indexes:

$$W_i = \frac{1 - H_i}{n - \sum_{i=1}^{n} H_i} \quad (12)$$

In the expression, $\sum_{i=1}^{n} W_i = 1$ $(0 \leqq W_i \leqq 1)$

3.2.3. The combination weighting method

The combination weighting method is a widely used weight determination method. It is usually used to combine subject and objective weighting methods to determine synthetic weights. It has been applied to many problems (Pan et al., 2014). However, as noted in section 2.2, current research in WEF remains underdeveloped, and scholars have not reached consensus about its application. Based on this, in this research the combination weighting method are used to combine the two objective weighting methods. The goal was to eliminate the influence of subjective factors as much as possible, and more scientifically and reasonably determine index weights. Considering the real-world situation at hand, this study used the combination weighting method to combine the two objective weighting methods and obtain the synthetic weights. The weights were then substituted into the improved matter-element extension method for evaluation.

The specific steps to determine weights are as follows:

$$\varphi_i = \frac{\omega_i' \omega_i''}{\sum_{i=1}^{n} \omega_i' \omega_i''} (i = 1, 2, ..., n) \quad (13)$$

In the expression, ω_i' and ω_i'' represent the index weights determined by the two different methods.

3.3. The improved matter-element extension method

The improved matter-element extension method adopts the evaluation index system and its eigenvalue as matter-elements. By evaluating level and measured data, the method generates the classical field, the limited field, and the degree of closeness. In the end, the constructed model is used to conduct a comprehensive quantitative evaluation (Kong et al., 2007). This paper used the improved matter-element extension method to evaluate the WEF system's sustainability.

3.3.1. Determination of evaluation criteria and ranking

Data were collected based on the index system adopted in this study. The study also applied the method of determining the classical field proposed in Literature (Zhang et al., 2015), adjusting the method based on the real-world situation. The method measured sustainability using five ranks: N_1 represents high efficiency (I); N_2 represents general efficiency (II); N_3 represents critical efficiency (III); N_4 represents relatively low efficiency (IV); and N_5 represents low efficiency (V). Table 2 provides details about the rankings.

3.3.2. Construction of the improved matter-element extension model

(1) Determination of the matter-element to be evaluated ($\mathbf{R}_0$)

$$R_0 = (P_0, C_i, V_i) \begin{bmatrix} P_0 & c_1 & v_1 \\ & c_2 & v_2 \\ & \vdots & \vdots \\ & c_n & v_n \end{bmatrix} \quad (14)$$

In the expression, $\mathbf{R}_0$ represents the matter-element to be evaluated; P_0 represents the rank of the matter-element to be evaluated; $c_1 c_2$, …,c_n represent the n characteristics of the matter-element to be evaluated (for instance, c_1 represents water consumption); and $v_1 v_2$, …, v_n represent the measured values of the n characteristics of the matter-element to be evaluated.

(2) Determination of the classical field ($\mathbf{R_j}$)

$$R_j=(P_j,C_i,V_{ij})=\begin{bmatrix}P_j & c_1 & v_{1j}\\ & c_2 & v_{2j}\\ & \vdots & \vdots\\ & c_n & v_{nj}\end{bmatrix}=\begin{bmatrix}P_j & c_1 & (a_{1j},b_{1j})\\ & c_2 & (a_{2j},b_{2j})\\ & \vdots & \vdots\\ & c_n & (a_{nj},b_{nj})\end{bmatrix} \tag{15}$$

In the expression, P_j represents the rank of the jth evaluation (for instance, P_1 represents level I); v_{ij} represents the value range of the rank of the jth evaluation about c_i; a_{ip} and b_{ip} represent the upper limit and lower limit, respectively, of the values of v_{ip}.

(3) Determination of the limited field ($\mathbf{R_p}$)

$$R_p=(P,C_i,V_{ip})=\begin{bmatrix}P & c_1 & v_{1p}\\ & c_2 & v_{2p}\\ & \vdots & \vdots\\ & c_n & v_{np}\end{bmatrix}=\begin{bmatrix}P & c_1 & (a_{1p},b_{1p})\\ & c_2 & (a_{2p},b_{2p})\\ & \vdots & \vdots\\ & c_n & (a_{np},b_{np})\end{bmatrix} \tag{16}$$

In the expression, P represents the overall rank of the evaluation object; v_{ip} represents the value range of the corresponding characteristic c_i; and (a_{ip},b_{ip}) represents the specific values of the range (from minimum to maximum values).

(4) Normalization processing

Normalization processing is provided for the classical field matter-element and the matter-element to be evaluated, to avoid circumstances where the measured data exceed the range of the limited field.

$$R'_0=((P_0,C_i,V_i)=\begin{bmatrix}P_0 & c_1 & \frac{v_1}{b_{1p}}\\ & c_2 & \frac{v_2}{b_{2p}}\\ & \vdots & \vdots\\ & c_n & \frac{v_n}{b_{np}}\end{bmatrix} \tag{17}$$

$$R'_j=\left(P_j,C_i,\ V'_{ij}\right)=\begin{bmatrix}P_j & c_1 & \left(\frac{a_{1j}}{b_{1p}},\frac{b_{1j}}{b_{1p}}\right)\\ & c_2 & \left(\frac{a_{2j}}{b_{2p}},\frac{b_{2j}}{b_{2p}}\right)\\ & \vdots & \vdots\\ & c_n & \left(\frac{a_{nj}}{b_{np}},\frac{b_{nj}}{b_{np}}\right)\end{bmatrix} \tag{18}$$

In the expression, $\mathbf{R'_0}$ represents the matter-element to be evaluated after normalization; $\mathbf{R'_j}$ represents the classical field matter-element after normalization; and b_{ip} represents the corresponding right-end value of the limited field in Formula (16).

(5) Determination of degree of closeness

$$D_j(v'_i)=\left|v'_i-\frac{a'_{ij}+b'_{ij}}{2}\right|=-\frac{1}{2}\left(b'_{ij}-a'_{ij}\right) \tag{19}$$

$$N_j(R'_0)=1-\frac{1}{n(n+1)}\sum_{i=1}^{n}D_j(v'_i)\omega_i(X) \tag{20}$$

In this expression, $D_j(v'_i)$ represents the distance between the classical field and the matter-element to be evaluated; $\omega_i(X)$ represents the synthetic weights of evaluation indexes; n represents the number of indexes; and $N_j(R'_0)$ represents the degree of closeness.

(6) Rank evaluation

$$N_m(R'_0)=\max[N_j(R'_0)] \tag{21}$$

After obtaining the degree of closeness for each rank, Formula (21) can be used to judge whether the matter-element to be evaluated belongs to rank m.

$$\overline{N}_j(R'_0)=\frac{N_j(R'_0)-\min[N_j(R'_0)]}{\max[N_j(R'_0)]-\min[N_j(R'_0)]} \tag{22}$$

$$j^*=\frac{\sum_{j=1}^{m}j^*\,\overline{N}_j(R'_0)}{\sum_{j=1}^{m}\overline{N}_j(R'_0)} \tag{23}$$

In this expression, j^* represents the rank variable eigenvalue of the matter-element to be evaluated R'_0.
Formulas (22) and (23) can be used to judge the degree of trending of the matter-element to be evaluated towards an adjacent rank.

4. Empirical analysis of Chinese WEF nexus

4.1. Creation of the index system and determination of the weights

As described in section 3.1, a corresponding evaluation index system was created, and data from 2000 to 2015 were collected based on the selected indexes (data derived from *China Statistical Yearbook* (NBS, 2016)). After that, the coefficient of variation method and the entropy method were used to calculate the index weights. The combination weighting method was used to calculate the synthetic weights. Table 1 provides the synthetic weights of specific indexes.
The data were derived from the *China Statistical Yearbook* (NBS, 2016); data from 2000 to 2015 were used to calculate the weights of indexes.

4.2. Evaluation ranking

As described in section 3.3.1 above, the evaluation ranking used a scientific determination method, and also accounted for real-world regional situations. This study measured sustainability by

Table 1
wt of indexes.

index c	Coefficient of variation method ω'_i	Entropy method ω''_i	Combination weighting method ω_i
c_1	0.0845	0.1354	0.1410
c_2	0.0843	0.1346	0.1397
c_3	0.0809	0.0081	0.0081
c_4	0.0702	0.0936	0.0809
c_5	0.0931	0.0764	0.0876
c_6	0.0865	0.1411	0.1503
c_7	0.0575	0.0644	0.0456
c_8	0.0685	0.0893	0.0753
c_9	0.0821	0.1289	0.1303
c_{10}	0.0944	0.1028	0.1195
c_{11}	0.0549	0.0014	0.0009
c_{12}	0.0699	0.0209	0.0180
c_{13}	0.0732	0.0031	0.0028

Table 2
Five ranks of sustainability.

Rankindex	N_1(I)	N_2(II)	N_3(III)	N_4(IV)	N_5(V)	N_p
c_1	(0,0.9092)	(0.9092,0.9319)	(0.9319,0.9546)	(0.9546,0.9773)	(0.9773,1)	(0,1)
c_2	(0,0.5734)	(0.5734,0.6801)	(0.6801,0.7867)	(0.7867,0.8933)	(0.8933,1)	(0,1)
c_3	(1,0.9256)	(0.9256,0.8512)	(0.8512,0.7768)	(0.7768,0.7024)	(0.7024,0.6281)	(0.6281,1)
c_4	(0,0.9509)	(0.9509,0.9632)	(0.9632,0.9755)	(0.9755,0.9877)	(0.9877,1)	(0,1)
c_5	(1,0.8251)	(0.8251,0.6502)	(0.6502,0.4753)	(0.4753,0.3004)	(0.3004,0.1256)	(0.1256,1)
c_6	(0,0.8611)	(0.8611,0.8958)	(0.8968,0.9305)	(0.9305,0.9653)	(0.9563,1)	(0,1)
c_7	(0,0.8288)	(0.8288,0.8716)	(0.8716,0.9144)	(0.9144,0.9572)	(0.9572,1)	(0,1)
c_8	(0,0.4834)	(0.4834,0.6125)	(0.6125,0.7417)	(0.7417,0.8708)	(0.8708,1)	(0,1)
c_9	(0,0.4561)	(0.4561,0.5921)	(0.5921,0.7280)	(0.7280,0.8640)	(0.8640,1)	(0,1)
c_{10}	(1,0.7546)	(0.7546,0.5092)	(0.5092,0.2638)	(0.2638,0.0183)	(0.0183,0)	(0,1)
c_{11}	(1,0.9639)	(0.9639,0.9278)	(0.9278,0.8917)	(0.8917,0.8556)	(0.8556,0.8195)	(0.8195,1)
c_{12}	(1,0.8313)	(0.8313,0.6625)	(0.6625,0.4938)	(0.4938,0.3250)	(0.3250,0.1563)	(0.1563,1)
c_{13}	(1,0.9493)	(0.9493,0.8987)	(0.8987,0.8480)	(0.8480,0.7973)	(0.7973,0.7467)	(0.7467,1)

In this table, N_p represents the overall range of ranks, that is, the limited field.

Table 3
Distances for the matter-element to be evaluated.R_0'

Index	high efficiency(I)$\mathbf{D}_1(\mathbf{v}_i')$	general efficiency (II)$\mathbf{D}_2(\mathbf{v}_i')$	critical efficiency(III)$\mathbf{D}_3(\mathbf{v}_i')$	relatively low efficiency(IV)$\mathbf{D}_4(\mathbf{v}_i')$	low efficiency(V)$\mathbf{D}_4(\mathbf{v}_i')(V)\mathbf{D}_5(\mathbf{v}_i')$
C_1	−0.0078	0.0078	0.0305	0.0532	0.0759
C_2	0.0140	−0.0140	0.0926	0.1992	0.3059
C_3	0.2396	0.1652	0.0908	0.0579	0.1323
C_4	0.0007	−0.0007	0.0116	0.0238	0.0361
C_5	0.6344	0.4595	0.2846	0.1097	0.2400
C_6	0.0189	−0.0158	0.0158	0.0505	0.0853
C_7	0.1884	0.1456	0.1028	0.0601	0.0173
C_8	0.3506	0.2215	0.0923	−0.0368	0.0368
C_9	−0.0642	0.0642	0.2002	0.3362	0.4721
C_{10}	0.8005	0.5551	0.3096	0.1812	0.1995
C_{11}	0.0211	0.0511	0.0872	0.1232	0.1593
C_{12}	0.4968	0.3281	0.1593	0.1782	0.3469
C_{13}	0.1652	0.1145	0.0639	0.0375	0.0882

five ranks (I-V), detailed in Table 2.

4.3. Creation of the matter-element to be evaluated, the classical field matter-element and the limited field matter-element (all with normalized data)

As described above, the classical field matter-element and the limited field matter-element were created. To facilitate a contrast, data from 2005 to 2015 were used to create corresponding matter-elements to be evaluated. See details below:

(1) The matter-element to be evaluated

$$R_0' = \begin{bmatrix} P_0 & c_1 & 0.9014 \\ & c_2 & 0.5875 \\ & c_3 & 0.7604 \\ & c_4 & 0.9516 \\ & c_5 & 0.3656 \\ & c_6 & 0.8800 \\ & c_7 & 1.0173 \\ & c_8 & 0.8340 \\ & c_9 & 0.3919 \\ & c_{10} & 0.1995 \\ & c_{11} & 0.9789 \\ & c_{12} & 0.5032 \\ & c_{13} & 0.8348 \end{bmatrix} R_0'' = \begin{bmatrix} P_0 & c_1 & 0.9766 \\ & c_2 & 0.9665 \\ & c_3 & 1.1122 \\ & c_4 & 1.0004 \\ & c_5 & 1.2720 \\ & c_6 & 0.9450 \\ & c_7 & 0.7418 \\ & c_8 & 0.6126 \\ & c_9 & 0.9649 \\ & c_{10} & 0.7358 \\ & c_{11} & 0.9277 \\ & c_{12} & 0.7953 \\ & c_{13} & 1.0718 \end{bmatrix} \quad (24)$$

In this expression, R_0' represents the matter-element to be evaluated for 2005; R_0'' represents the matter-element to be evaluated for 2015.

(2) The classical field matter-element

The range of each rank is the classical field. Then, according to Table 2:

$$\mathbf{R}_1' = \begin{bmatrix} P_1 & c_1 & (0, 0.9092) \\ & c_2 & (0, 0.5734) \\ & c_3 & (1, 0.9256) \\ & c_4 & (0, 0.9509) \\ & c_5 & (1, 0.8251) \\ & c_6 & (0, 0.8610) \\ & c_7 & (0.0.8288) \\ & c_8 & (0, 0.4834) \\ & c_9 & (0, 0.4561) \\ & c_{10} & (1, 0.7546) \\ & c_{11} & (1, 0.9639) \\ & c_{12} & (1, 0.8313) \\ & c_{13} & (1, 0.9493) \end{bmatrix} \quad (25)$$

Using the same approach, we obtain R_2', R_3', R_4' and R_5'.

(3) The limited field matter-element

Table 4
Distances for the matter-element to be evaluated.R_0''

Index	high efficiency(I)$\mathbf{D}_1(\mathbf{v}_i')$	general efficiency(II)$\mathbf{D}_2(\mathbf{v}_i')$	critical efficiency(III)$\mathbf{D}_3(\mathbf{v}_i')$	relatively low efficiency(IV)$\mathbf{D}_4(\mathbf{v}_i')$	low efficiency(V)$\mathbf{D}_5(\mathbf{v}_i')$
$\mathbf{C}_1$	0.0674	0.0447	0.0220	−0.0007	0.0007
$\mathbf{C}_2$	0.3931	0.2864	0.1798	0.0731	−0.0335
$\mathbf{C}_3$	0.1866	0.2610	0.3354	0.4098	0.4842
$\mathbf{C}_4$	0.0495	0.0372	0.0250	0.0127	0.0004
$\mathbf{C}_5$	0.4469	0.6218	0.7967	0.9716	1.1465
$\mathbf{C}_6$	0.0840	0.0492	0.0145	−0.0145	0.0202
$\mathbf{C}_7$	−0.0870	0.0870	0.1298	0.1726	0.2154
$\mathbf{C}_8$	0.1293	0.0001	−0.0001	0.1290	0.2582
$\mathbf{C}_9$	0.5088	0.3728	0.2369	0.1009	−0.0351
$\mathbf{C}_{10}$	0.2642	0.2266	0.4720	0.7175	0.7358
$\mathbf{C}_{11}$	0.0723	0.0363	0.0359	0.0720	0.1081
$\mathbf{C}_{12}$	0.2047	0.1328	0.3016	0.4703	0.6390
$\mathbf{C}_{13}$	0.1225	0.1732	0.2238	0.2745	0.3251

Table 5
Rank variable eigenvalue.

Degree of closeness	**high efficiency**(I)	general efficiency(II)	critical efficiency(II)(III)	relatively low efficiency(IV)	low efficiency(V)	rank variable eigenvalue($\mathbf{j}^*$)
$\mathbf{N_j}(\mathbf{R}_0')$	0.99894	0.999217	0.999318	0.999320	0.998973	3.159656 (j'^*)
$\mathbf{N_j}(\mathbf{R}_0'')$	0.998739	0.998924	0.998878	0.998774	0.998748	2.634360(j''^*)

$$R_p = \begin{bmatrix} P & c_1 & (0,1) \\ & c_2 & (0,1) \\ & c_3 & (0.6281,1) \\ & c_4 & (0,1) \\ & c_5 & (0.1256,1) \\ & c_6 & (0,1) \\ & c_7 & (0,1) \\ & c_8 & (0,1) \\ & c_9 & (0,1) \\ & c_{10} & (0,1) \\ & c_{11} & (0.8195,1) \\ & c_{12} & (0.1563,1) \\ & c_{13} & (0.7467,1) \end{bmatrix} \tag{26}$$

4.4. Closeness degree calculation and rank evaluation

As described above, the distances between various indexes and the classical field can be calculated for the matter-elements to be evaluated, R_0' and R_0'', as detailed in Tables 3 and 4. Table 3 provides the distances for the matter-element to be evaluated, R_0'. Table 4 provides the distances for the matter-element to be evaluated, R_0''.

Tables 3 and 4 are used to calculate the degrees of closeness for the matter-elements to be evaluated, R_0' and R_0'', respectively. Meanwhile, Table 5 presents the calculation results of the rank variable eigenvalue $\mathbf{j}^*$ of R_0' and R_0''. Here, $\mathbf{j}'^*$represents the eigenvalue of R_0' and $\mathbf{j}''^*$represents the eigenvalue of R_0''.

4.5. Analysis of model calculation results

(1) Table 5 shows that in the degree of closeness for the matter-element to be evaluated, R_0': max $[N_j(R_0')]= N_4(R_0') = 0.993200$; the rank variable eigenvalue $j'^* = 3.159656$. As such, the sustainability of China's WEF system in 2005 belonged to rank IV, a relatively low efficiency rank. At the same time, the fact that $j'^* = 3.159656<3.5$ indicates that the sustainability trended towards the critical efficiency rank. In 2005, the sustainability of WEF nexus in China was low and it was unable to meet the basic requirements for sustainable development. The use of resources such as water, energy, and food lacks efficiency and the mode of development is extensive. The government needs to make timely policy adjustments.

(2) Table 5 also shows that for the degree of closeness for the matter-element to be evaluated, R_0'': max $[N_j(R_0'')]= N_2(R_0'') = 0.998924$. The rank variable eigenvalue $j''^* = 2.634360$. Thus, the sustainability of China's WEF system in 2015 belonged to rank II, the general efficiency rank. At the same time, the fact that $j''^* = 2.634360>2.5$ indicates that the sustainability trended toward the critical efficiency rank. In 2015, the sustainable efficiency of WEF nexus in China can meet the requirements for sustainable development in the region. However, far from reaching the optimal state of sustainable development, it is necessary to make further improvements to the status quo.

(3) According to the evaluation results of 2005 and 2015, the sustainability of China's WEF system shifted from a relatively low efficiency rank to a general efficiency rank. Its rank variable eigenvalue ($\mathbf{j}^*$) changed from $j'^* = 3.159656$ to $j''^* = 2.634360$. This suggests that, from 2005 to 2015, the sustainability of China's WEF system experienced significant progress, but still with some room for improvement.

(4) The evaluation results obtained using this method were relatively consistent with real-world situations. In 2005, China's emphasis on sustainable development and use of water, energy, and food resources was inadequate; at that time, the "WEF-Nexus" concept had not been formally proposed. In the supply and demand of resources, regional self-balance was the primary emphasis; there was no overall optimal national allocation. The relatively low utilization efficiency of water, energy, and food could not meet sustainable development demands. Thus, sustainability in 2005 belonged to a relatively low efficiency rank. Further, its trend towards to the critical efficiency rank suggested that China realized the importance of the sustainable development of the WEF system. In 2015, the concept of sustainable development has become known to people, and China has begun

to pay attention to achieving sustainable development. As a result, the utilization efficiency of water, energy, and food resources had improved, with further optimization of resource allocation. However, there was still a lack of an overall understanding and utilization of the three resources, with room to improve the degree of sustainable development. Thus, sustainability in 2015 belonged to the general efficiency rank. However, the trend towards critical efficiency suggested that the sustainable utilization of China's WEF system was unstable, with a risk of declining efficiencies.

5. Conclusions

As the largest developing country, China faces a contradiction between its relatively high speed of economic growth and its resource shortages. For this reason, China's development issues represent many countries in the world. In this sense, this study's evaluation of the sustainability of China's WEF system may also provide reference value for countries or regions with similar situations.

(1) This study combined the improved matter-element extension model with the combination weighting method to evaluate the sustainability of China's WEF system. The results suggests that evaluating the sustainability of China's WEF system using this method was scientific and reasonable. The results accurately reflected the current sustainability status of China's WEF system.

(2) Contribution to the literature: ① This study used the combination weighting method to combine two objective weighting methods; this method has historically been used to combine subjective and objective weighting methods. ② The study extended the scope of application of an improved matter-element extension method, and used it to quantitatively evaluate the sustainability level of China's WEF nexus. This approach fills the existing gap in quantitative studies about the sustainability of WEF nexus, and provides a new perspective to analyze and investigate the sustainability of the WEF nexus.

(3) This paper also compared the evaluation results of 2005 and 2015 in China and found that China has made considerable progress in the sustainable use of water, energy, and food. The sustainability of China's WEF system in 2005 belonged to rank IV (a relatively low efficiency rank), and the rank variable eigenvalue $j^{'*} = 3.159656$. The sustainability of China's WEF system in 2015 belonged to rank Ⅱ(the general efficiency rank), the rank variable eigenvalue $j^{''*} = 2.634360$. Level eigenvalues in 2015 decreased by 0.525296 from 2005. Further, to some degree and within certain regions, China has realized the imperfect sustainable use of single resources. However, there are still problems with current use, and there are still potential improvements to be explored. This situation is consistent with the current departmental management of resources. Although independent management of different resources can improve management efficiency, there are obstacles to realizing sustainable development. To achieve the sustainable use of the WEF resources, attention should also be paid to the overall understanding and use of the three resources. Furthermore, decision-makers should attach greater importance to coordinating these resources and cooperating with others, to improve the sustainability of China's WEF nexus.

Here, the relevant policy suggestions are proposed for reference:

(a) Effective links between planning and policies among different departments should be strengthened, and unreasonable management measures should be quickly adjusted.

(b) The level of cooperation between water, energy and food management departments should be improved, and the supervision and coordination between departments should be strengthened. The information sharing platform between different departments must be established and the integrity and timeliness of policy measures must be improved.

(c) Perfect supporting measures must be established and reasonable monitoring mechanisms must be established. Non-conforming resource utilization conditions must be punished, and wonderful communication channels between government and society should be established.

(d) Pay attention to the construction of ecological civilization, and the development mode of destroying the environment must be stopped in time. The utilization efficiency of resources should be improved to reduce waste, and investment and policy support for recycling technologies should be increased.

(e) Raise public participation and share information with the public. The public's awareness of resources and the awareness of environmental protection should be strengthened, and the understanding of the internal links between water, energy, and food should be improved. Encourage the public to participate in the process of improving the sustainability of the water-energy-food nexus and promote the implementation of relevant policies.

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