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Network analysis of the food–energy–water nexus in China's Yangtze River Economic Belt from a synergetic perspective

Rihui An[1,2,3], **Pan Liu**[1,2,3], **Lei Cheng**[1,2,3], **Minglei Yao**[1], **He Li**[1,2,3] **and Yibo Wang**[1,2,3]

[1] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, People's Republic of China
[2] Research Institute for Water Security (RIWS), Wuhan University, Wuhan 430072, People's Republic of China
[3] Hubei Provincial Key Lab of Water System Science for Sponge City Construction, Wuhan University, Wuhan 430072, People's Republic of China

E-mail: liupan@whu.edu.cn

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Abstract

Economic development, resource scarcity and climate change pose enormous challenges to the food–energy–water (FEW) nexus, calling for integrative resources governance to improve the synergy between subsystems. However, it is unclear about the synergy evolution of the FEW nexus in temporal and spatial scales. This paper uses the network analysis to explore the FEW nexus in China's Yangtze River Economic Belt. First, the comprehensive index system containing subsystems, order parameters and eigenvectors are determined in causal paths. Second, the synergetic network among order parameters is developed, and the centrality analysis is then conducted to identify the influencing factors. Third, the Bayesian network among eigenvectors is constructed to analyze the sensitivity of the dominant influencing factors. The results show that: (a) Energy subsystem has the highest centralities and dominates the FEW nexus. (b) From the perspective of time variability, the network centralization reaches the highest in 2007, but reaches the lowest in 2013, showing a downward trend, so we should adhere to the national strategy of synergetic development to realize the resource sustainability. (c) From the perspective of spatial sensitivity, upper reach (UR) is sensitive to food-related factors while lower reach (LR) is sensitive to energy-related factors. Therefore, the development of agriculture in upper UR should focus on protection, and the development of industry in LR should focus on remediation. The significance of the research is to construct a network analysis framework for better understanding the spatio-temporal variability of the FEW nexus in Yangtze River Economic Belt.

1. Introduction

Food–energy–water (FEW) are three essential resources for human society, but facing the problem of increasing demand and limited supply (Karabulut *et al* 2016, Cai *et al* 2018). Global human consumption of FEW resources will increase 35%, 50% and 40% respectively by 2030 (United States National Intelligence Council 2012). The looming food security, fossil energy exhaustion and fresh water shortage have attracted the attention of governments and scholars all over the world (Jiao 2010). The FEW nexus was first proposed in Bonn Conference (Hoff 2011), and nearly 43 organizations launched FEW nexus projects in the following 5 years (Endo *et al* 2017). The FEW nexus constitutes a framework for analyzing the dynamic interactions between three interdependent subsystems and developing strategies for resource sustainability and effective governance (Cai *et al* 2018).

Restrictions on one resource may limit the availability of the other resources (Efteliogl *et al* 2017, Ming *et al* 2018). For example, at a watershed scale, the reducing discharge in upstream can increase the power generation, but it will affect the irrigation water quantity and ecological flow in downstream (Shi *et al* 2020), leading the crop loss and fish extinction. Solutions implemented in one sector can also have consequences in other sectors. For example, the 10 year fishing ban policy in Yangtze River will restore fish

stocks and biodiversity (Brainard 2020), increase the food production and furtherly protect the security of water system. As a result, FEW nexus should be analyzed in a holistic and integrated way.

Three main types of approaches have been used to model the interconnections of the FEW nexus: footprint quantification, system simulation, and optimizing management (Zhang *et al* 2019). (a) The footprint method is widely used to quantify the resource and economic efficiency, aiming at understanding and quantifying the interdependence property of FEW subsystems. Typical methods contain input–output analysis (Feng *et al* 2019a), life cycle assessment (Chen *et al* 2020) and data envelopment analysis (Li *et al* 2016). (b) System simulation focuses on assessing and forecasting. System dynamic model (Feng *et al* 2016, 2019b) and network analysis (Kharanagh *et al* 2020, Shi *et al* 2020) are two common methods to evaluate the system performance. (c) Some optimization models have been developed specifically to address the FEW nexus besides traditional stochastic multi objective optimization (Li *et al* 2020). For example, Long-Range Energy Alternatives Planning model, Water Evaluation and Planning model model, and Soil and Water Assessment Tool. Integrated models include the CLEW model (Sridharan *et al* 2020), the WEF Tool 2.0 (Daher and Mohtar 2015) and the WELF model (Ibrahim *et al* 2019).

Despite the fact that all these three approaches have the capability of modeling FEW nexus, the network analysis is adopted to simulate the coupled system for reduction of data requirements, characterization of causality and simulation of uncertainty: (a) the type and quantity of data determine the applicable method. The detailed data during different production and consumption processes are needed in footprints quantification. Lots of observations are required to calibrate the physical models. The missing data imposes great difficulties to the application of footprint quantification and optimizing management methods. (b) The stability of social development can greatly affect the FEW nexus, but the difference in evolution is often ignored (Shi *et al* 2020). The interactions across the FEW nexus are highly complex, and there are many uncertainties in the future development of the society, environment and economy (Perrone and Hornberger 2014, Chai *et al* 2020). High uncertainty of multi-system brings difficulties in applying integrated models. (c) The model structure and the spatio-temporal scale do not always match well, because integrating models contain knowledge from different fields (Shi *et al* 2020). For example, the precipitation and runoff data from hydrological station is in daily scale, which is controlled by a natural boundary (i.e. aquifers and river basins). Crop water consumption and yield obtained from irrigation districts are in 10 day scale, which is influenced by administrative boundaries (Cai *et al* 2018). (d) In essence, the traditional methods do not reveal the conditional correlation and its strength among subsystems from a synergetic perspective.

The method of network analysis, including synergetic network and Bayesian network analysis, provides possible solution for the above issue. When compared with the traditional nexus modeling, the synergetic network (Bodin and Crona 2009, Weiss *et al* 2012, Hauck *et al* 2016) can select the dominant influencing factors with a high synergy degree, and provide a classification based on their positions in a network. For example, Li *et al* (2019) studied the FEW nexus from the view of urban resources governance, and found the synergy in Shenzhen can be maximized by reducing the crops sown areas, coordinating the energy imports and exports, and stabilizing water supply. Kharanagh *et al* (2020) analyzed the actors' power across FEW nexus in the Yazd-Ardakan aquifer, Iran, and found that the sectors act alone and do not exploit the maximum organizational capacities. Bayesian network (Poppenborg and Koellner 2014, Phan *et al* 2016, Taner *et al* 2019) simulates the complex system with the simplest structure and presents probabilistic predictions instead of a single prediction. It can be used to solve the problem of loosening the constraints, due to the lack of causality restrictions in traditional resources optimization. For example, Shi *et al* (2020) analyzed and optimized the water resource use in Syr Darya River basin by coupling the Water–Energy–Food–Ecology nexus in Bayesian network. Chai *et al* (2020) proposed a quantitative Bayesian network analysis framework based on the Water–Energy–Food–Economy–Society–Environment nexus of China.

This paper develops an integrated approach by combining the synergetic network with Bayesian network analysis to reveal the synergies of the FEW nexus in China's Yangtze River Economic Belt (YREB). The potential contributions of this paper are as follows: (a) to find out what role each subsystem plays in nexus, (b) to identify the influencing factors in the FEW nexus, (c) to analyze the time variability and spatial sensitivity based on the dominant influencing factors.

2. Study area and data sources

As shown in figure 1, 11 provinces and municipalities can be divided into three areas according to the geographical location in YREB, i.e. upper reach (UR), middle reach (MR) and lower reach (LR) (The State Council of the People's Republic of China 2014). YREB produces one-third food, one-third GDP, one-third water resources and one-third population with one-fifth land area (Environmental protection plan for the Yangtze River Economic Belt 2017). (a) In terms of food, YREB is one of the most important grain producing areas, occupying six (Chengdu Plain, Jianghan Plain, Dongting Lake Plain, Poyang Lake Plain, Jianghuai region and Taihu Lake Plain)

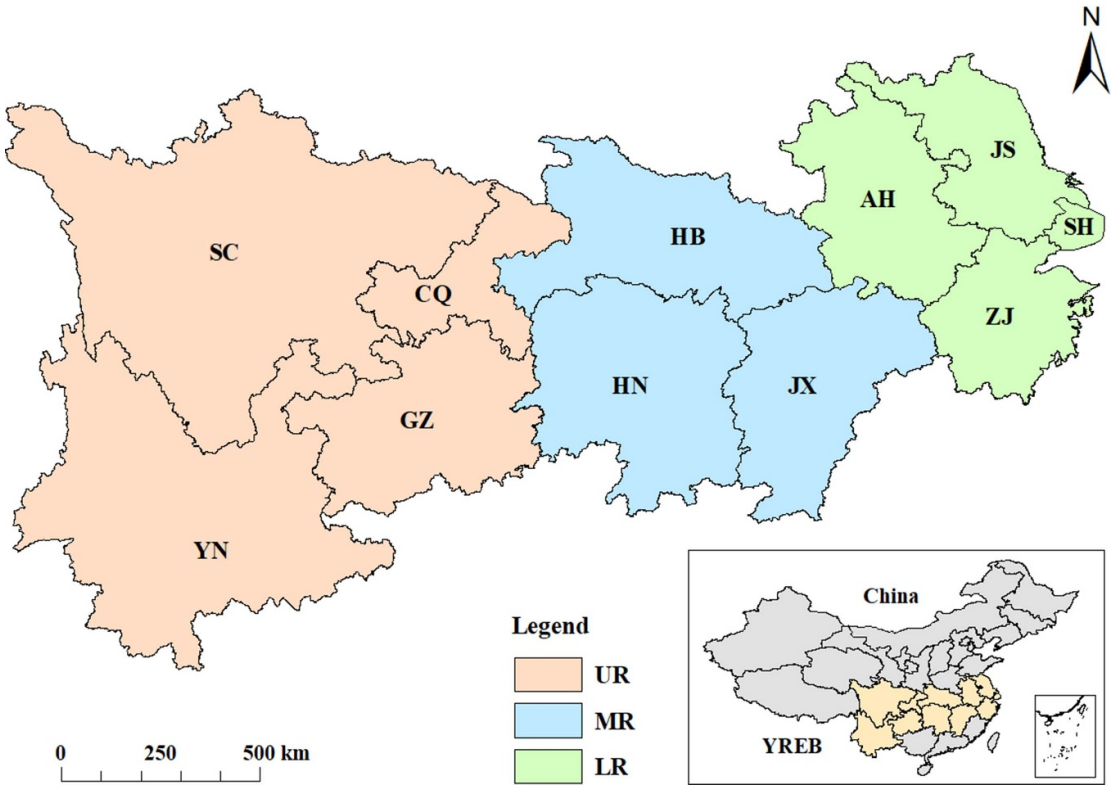

Figure 1. Location of the Yangtze River Economic Belt. Upper reach (UR) contains Shanghai (SH), Jiangsu (JS), Zhejiang (ZJ) and Anhui (AH); middle reach (MR) contains Jiangxi (JX), Hubei (HB) and Hunan (HN); lower reach (LR) contains Chongqing (CQ), Sichuan (SC), Guizhou (GZ) and Yunnan (YN).

of the nine major commodity grain bases in China (Xu *et al* 2019). Besides, there are 378 species of fish distributed in the Yangtze River, accounting for 33% of the total number of freshwater fish, ranking the first in all rivers in China (Luo *et al* 2019). (b) In terms of energy, YREB is the busiest inland waterway in the world with the largest industrial agglomeration scale. There are important steel and petrochemical bases along the Yangtze river. The output of 12 industrial products in YREB is more than the half of the total output in China. (c) In terms of water, as the third longest river in the world and the longest river in China, the Yangtze River is an important strategic water source, hydropower base and biological treasure. It has important functions of soil and water conservation, flood regulation and storage (Liu *et al* 2015). The hydraulic exploitable capacity of the Yangtze River Basin is 281 million KW, accounting for 53.4% of the national exploitable capacity. (d) As an economic center in China, YREB is a dense urban zone with an area of about 2.05 million km^2, whose population and economic output both exceed 40% of the whole country.

However, YREB is facing with the contradictions between high-speed economic growth and limited environmental carrying capacity (Xu *et al* 2018). The resource and development in UR, MR and LR are extremely unbalanced. For example, (a) the development of hydropower in UR has seriously affected the environment, lead to the biodiversity degradation and soil erosion (Yang and Ma 2009, Chen *et al* 2017); (b) fossil energy in MR are relatively scarce, and more than 90% of coal and almost all oil and gas are imported from outside; (c) energy consumption in LR is large, the food security and water quality deterioration problems are prominent (Chen *et al* 2017). Comparison of basic information of different reaches in 2013 is shown in table S1 (available online at stacks.iop.org/ERL/16/054001/mmedia) of supplementary information (Liang 2015). It is important to distinguish the spatial differences of regional FEW development so as to make reasonable decision for policymakers and practitioners.

The data describing FEW nexus is explained in section 3.1 and derived from China National Bureau of Statistics (www.stats.gov.cn/), China Economic and Social Development Statistics Database (http://tongji.cnki.net/kns55/index.aspx) and Easy Professional Superior (http://olap.epsnet.com.cn/login.html). A small amount of missing data is supplemented by interpolation.

3. Methodology

The following steps are performed to analyze the FEW network from a synergetic perspective. (a) The hierarchical structure and the causal paths are determined in the FEW nexus. (b) The synergetic network is

constructed by the synergy degree between every two order parameters to identify the influencing factors. (c) The Bayesian network is developed to illustrate the interconnection between eigenvectors and analyze the sensitivity of the dominant influencing factors.

3.1. Determination of the FEW nexus

3.1.1. Subsystems, order parameters and eigenvectors

As shown in table 1, 12 order parameters and 33 eigenvectors are chosen in the comprehensive FEW index system (the detailed description can be seen in section S1 of supplementary information). First, the FEW nexus is divided into FEW subsystems. Second, each subsystem is described by four order parameters, according to the supply, demand, benefit and pollution caused by related resources. Order parameters describe the ordered structure of the system and contribute to understand the tradeoff and synergy in the FEW nexus. The fluctuation of order parameters can change the stability of the FEW coupled system and increase the complexity of resource governance (Li *et al* 2019). Third, each order parameter is decomposed into a set of eigenvectors. Multidimensional eigenvectors are combined to form a vector space to calculate the synergy degree among every two order parameters (Li *et al* 2019).

3.1.2. Causal paths in the FEW nexus

The causal paths qualitatively show the interconnections among eigenvectors, which are integrated and visualized in figure S1. Three kinds of causal paths are considered in the FEW nexus, including constitutive causality, direct causality and indirect causality (Shi *et al* 2020). Constitutive causality is determined by composition relationship. For example, agricultural, industrial, domestic and ecological water consumption per capita constitute the total water consumption per capita. Direct causality is based on physical processes. For example, the increase of agricultural water consumption per capita promotes the increase of grain production per capita. Indirect causality is driven by demand, such as the relationship between machine power per unit area and grain yield per unit area.

3.2. Synergetic network among order parameters

3.2.1. Construction of synergetic network

The core of synergetic network is to calculate the synergy degree among order parameters. The synergy degree reflects the associative strength between any two order parameters, which can be obtained by the variations of multiple eigenvectors. The dominant order parameters in synergetic network can be further identified for more effective policy making (Li *et al* 2019). Synergetic network can be constructed in the following three steps.

First, each order parameter V in different time is represented by a set of eigenvectors v. V^i (the i-th order parameter) and V^j (the j-th order parameter) in year t and year $t+1$ are respectively defined as follows:

$$\begin{cases} V_t^i = (v_{1^t}^i, \cdots, v_{l^t}^i, \cdots, v_{n^t}^i) \\ V_{t+1}^i = (v_{1^{t+1}}^i, \cdots, v_{l^{t+1}}^i, \cdots, v_{n^{t+1}}^i) \\ l = 1, 2, \cdots, n \end{cases} \tag{1}$$

$$\begin{cases} V_t^j = (v_{1^t}^j, \cdots, v_{k^t}^j, \cdots, v_{m^t}^j) \\ V_{t+1}^j = (v_{1^{t+1}}^j, \cdots, v_{k^{t+1}}^j, \cdots, v_{m^{t+1}}^j) \\ k = 1, 2, \cdots, m \end{cases} \tag{2}$$

where $n(m)$ is the number of the eigenvectors $v^i(v^j)$ constituting the order parameter $V^i(V^j)$.

$$q_{l^t}^i = \frac{\left| v_{l^{t+1}}^i - v_{l^t}^i \right|}{v_{l^t}^i} \tag{3}$$

$$q_{k^t}^j = \frac{\left| v_{k^{t+1}}^j - v_{k^t}^j \right|}{v_{k^t}^j} \tag{4}$$

where $q_{l^t}^i$ and $q_{k^t}^j$ are respectively the variation of v^l (the l-th eigenvector) and v^k (the k-th eigenvector) between year t and year $t+1$.

Second, the synergy degree among any two order parameters in the same time interval is calculated (Salje and Devarajan 1986).

$$b_{lk,t}^{ij} = \frac{\min(q_{l^t}^i, q_{k^t}^j)}{\max(q_{l^t}^i, q_{k^t}^j)} \qquad 0 \leqslant b_{lk}^{ij} \leqslant 1 \tag{5}$$

where $b_{lk,t}^{ij}$ is the influence degree between eigenvector v^l and v^k. The closer the variation of two eigenvectors are, the higher synergetic effect will be, and $b_{lk,t}^{ij}$ will be closer to 1.

$$B_{n\times m,\,t}^{ij} = \begin{bmatrix} b_{11,\,t}^{ij} & b_{12,\,t}^{ij} & \cdots & b_{1m,\,t}^{ij} \\ b_{21,\,t}^{ij} & b_{22,\,t}^{ij} & \cdots & b_{2m,\,t}^{ij} \\ \cdots & \cdots & \cdots & \cdots \\ b_{n1,\,t}^{ij} & b_{n2,\,t}^{ij} & \cdots & b_{nm,\,t}^{ij} \end{bmatrix} \tag{6}$$

where $B_{n\times m,t}^{ij}$ is the synergy matrix between order parameter V^i and V^j. The synergetic matrix is in $n \times m$ dimension, because two order parameters are respectively composed of n and m eigenvectors.

$$r_{ij}(V_t^i, V_t^j) = \frac{\left| V_{t+1}^i - V_t^i \right| \cdot B \cdot \left| V_{t+1}^j - V_t^j \right|^T}{\left\| V_{t+1}^i - V_t^i \right\|_2 \cdot \|B\|_2 \cdot \left\| V_{t+1}^j - V_t^j \right\|_2}$$
$$0 \leqslant r_{ij}(V_t^i, V_t^j) \leqslant 1 \tag{7}$$

where $r_{ij}(V_t^i, V_t^j)$ is the synergy degree between order parameter V^i and V^j (Lee *et al* 1997). $|\bullet|$ means the absolute value of the vector, and $\|\bullet\|$ means the L2 norm of the vector or matrix.

Third, synergetic network is constructed based on the threshold of synergy degree $r_{\text{threshold}}$ (section

Table 1. Subsystems, order parameters and eigenvectors in the FEW nexus. The number of order parameter is uppercase and the number of the eigenvector is lowercase.

Subsystem	No.	Order parameter	No.	Eigenvector	Unit
Food system	F1	Food supply	f1	Grain production per capita	kg/capita
			f2	Grain yield per unit area	kg ha^{-1}
			f3	Aquatic production per capita	kg/capita
			f4	Aquatic production per unit area	kg ha^{-1}
	F2	Food demand	f5	Grain consumption per capita	kg/capita
			f6	Aquatic product consumption per capita	kg/capita
	F3	Food benefit	f7	Gross value of agriculture production per capita	yuan/capita
			f8	Gross value of aquatic product production per capita	yuan/capita
	F4	Pollution caused by food	f9	Fertilizer consumption per unit sown area	kg ha^{-1}
			f10	Pesticide consumption per unit sown area	kg ha^{-1}
Energy system	E1	Energy supply	e1	Energy production per capita	Ton standard coal/capita
			e2	Power generation per capita	kWh/capita
	E2	Energy demand	e3	Energy consumption per capita	Ton standard coal/capita
			e4	Machine power per unit area	10 kW ha^{-1}
	E3	Energy benefit	e5	Energy consumption per 10 000 yuan for GDP	Ton standard coal/10^4 yuan
			e6	Industrial added value per capita	10^4 yuan/capita
	E4	Pollution caused by energy	e7	Industrial waste water discharge per capita	T/capita
			e8	Industrial waste gas discharge per capita	10^4 m^3/capita
			e9	Industrial solid waste discharge per capita	T/capita
Water system	W1	Water supply	w1	Water supply per capita	m^3/capita
			w2	Surface water supply per capita	m^3/capita
			w3	Ground water supply per capita	m^3/capita
	W2	Water demand	w4	Water consumption per capita	m^3/capita
			w5	Agricultural water consumption per capita	m^3/capita
			w6	Industrial water consumption per capita	m^3/capita
			w7	Domestic water consumption per capita	m^3/capita
			w8	Ecological water consumption per capita	m^3/capita
	W3	Water benefit	w9	Water consumption per 10 000 yuan for GDP	m^3/10^4 yuan
			w10	Water consumption per 10 000 yuan for added value of primary industry	m^3/10^4 yuan
			w11	Water consumption per 10 000 yuan for added value of secondary industry	m^3/10^4 yuan
			w12	Water consumption per 10 000 yuan for added value of tertiary industry	m^3/10^4 yuan
	W4	Pollution caused by water	w13	COD emission	mg L^{-1}
			w14	Sewage treatment rate	%

S2 in supplementary information). Suppose there are N order parameters in total, C_N^2 synergy degree will be calculated. However, the connection between two order parameters only be established when the synergy degree r_{ij} is greater than the threshold $r_{\text{threshold}}$. If one order parameter has a strong synergetic correlation with others, it is considered dominant in the FEW nexus, and it is easy to affect or be affected by other order parameters.

3.2.2. Calculation of centrality indices

Centrality is an important structural attribute of the synergetic network. Freeman (1979) reviewed the previous studies and developed three distinct conceptions of centrality, i.e. degree centrality, betweenness centrality and closeness centrality. Two kinds of indices are considered for each concept, including point centrality and graph centralization. The former focuses on the description of individuals (node), while the latter focuses on the description of the whole (graph/network). In more detail, one absolute and one relative index form the point centrality (Freeman 1979, Liu 2009). The following steps are performed to analysis the centrality. First, the absolute point centrality for a specified node is calculated to show the node position in the network. Second, the relative point centrality is given according to the fraction of the absolute centrality of the node to the maximum centrality that may exist in other nodes. Finally, the graph centralization is calculated to reflect the irregularity of the entire network.

The detailed calculation and formulations can be found in section S3 of supplementary information. According to the network centralities, the status and significance of the order parameters in the FEW nexus can be demonstrated, and the order parameters can be ranked in synergetic network. The higher the ranking value is, the greater the influence of the order parameter will be. It is generally supposed that the top ranked order parameters contribute most to the network (Wang *et al* 2018).

3.3. Bayesian network among eigenvectors

3.3.1. Construction of Bayesian network

Bayesian network is a probabilistic graphical model (Corporation 1998, Korb and Nicholson 2010, Nagarajan *et al* 2013, Chai *et al* 2020), which is constructed to describe the multiple probability relationships between variables under uncertainty (Pearl 1988). In a directed acyclic graph $G = (M, A)$, M refers to the nodes of random variables. Here, an eigenvector constitutes a node. A refers to the arcs of probabilistic dependencies between two arbitrary nodes. If an arc is from node v^l to v^k, then v^l is considered as the parent node of the child node v^k. $P(v^k|v^l)$ represents the conditional probability. The joint probability distribution of Bayesian network is expressed as follows:

$$P(v^1, v^2, \ldots, v^l) = \prod_{l=1}^{M} P(v^l | parents(v^l)) \quad (8)$$

Bayesian network consists of structure learning and parameter learning. Structure learning determines the graph structure in Bayesian network while parameter learning determines the joint probability distribution of the variables on a given network structure. The nodes and structures of the FEW nexus are identified in section 3.1.2, and the parameters are learned from data using EM (expectation-maximization) algorithm (Neal and Hinton 1998).

3.3.2. Evaluation of Bayesian network

The performance of Bayesian network is evaluated from two points. (a) The accuracy of the prediction and inference is assessed by calculating the confusion matrices. (b) The matching degree between the constructed network and the actual knowledge is evaluated by sensitivity analysis. The latter method is considered to be more effective (Shi *et al* 2020).

K-fold cross-validation (Marcot 2012) is used to evaluate the model outcome when there are a few data samples. The empirical data set is first divided into k subsets. One subset of the data is used to test the model with the remaining subsets parameterizing the model, and the confusion error rate of model simulation is recorded. The procedure is repeated for K times, and the confusion matrices are averaged to evaluate the overall model performance.

Furtherly, to assess whether output variable is sensitive to the changes of input nodes in Bayesian network, mutual information (MI) is introduced for sensitivity analysis. MI is based on entropy reduction, the formulation is as follows:

$$\begin{aligned} \text{MI} &= H(Q) - H(Q|E) \\ &= \sum_q \sum_e P(q,e) log_2 \left(\frac{P(q,e)}{P(q)P(e)} \right) \end{aligned} \quad (9)$$

where q represents the state of the output variable Q, and e represents the state of the input variable E. H is the entropy. $H(\cdot|\cdot)$ means the conditional entropy. Finally, MI is rescaled to relative values (between 0% and 100%) for the convenience of comparison.

4. Results and discussion

4.1. Centrality analysis of synergetic network

4.1.1. Synergy degree of order parameters

The synergy degree of order parameters varies with the time. Figure 2(a) shows the box diagram of synergy degree for each order parameter from 2004 to 2018. The order of average synergy degree in energy and food subsystem is similar, where the benefit (E3 and F3) ranks first, followed by demand (E2 and F2), pollution (E4 and F4), and finally supply (E1 and F1). However, there is a completely opposite order in water subsystem, where the supply (W1) is the first,

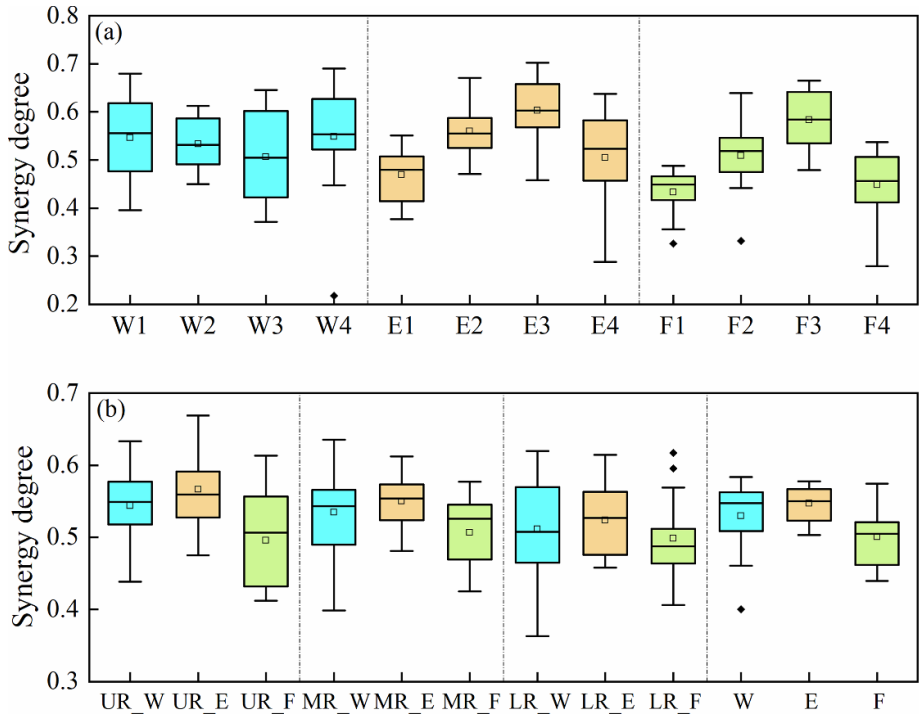

Figure 2. (a) The box diagram of synergy degree of 12 order parameters in YREB from 2004 to 2018. The line in the box represents the median value, and the square represents the mean value. Two ends of the box represent the first and third quartiles, the box whisker represent 1.5 times of the standard deviation, and the black diamond represents values exceeding 1.5 times of the standard deviation. Blue refers to the water subsystem, yellow refers to the energy subsystem and green refers to the food subsystem. (b) The box diagram of synergy degree of three subsystems in UR, MR, LR and YREB from 2004 to 2018.

followed by pollution (W4), demand (W2) and finally the benefit (W3). The significant difference is due to the different access to resources. Water is a resource that can be obtained directly from nature, while food and energy are resources produced or processed by human beings. The synergy degree of order parameters depends on the accessibility of resources. The supply ranks high in nature-oriented system, such as water subsystem; the benefit ranks high in human-oriented system, such as food and energy subsystems.

The synergy degree in subsystems varies with the space. Figure 2(b) shows the box diagram of synergy degree for each subsystem in UR, MR, LR and YREB respectively. From upstream to downstream, the average synergy degree of water subsystem gradually decreases, and so is energy subsystem. However, the synergy degree of food subsystem is highest in MR, but relatively low in the over developed LR and under developed UR. From the overall perspective of YREB, the average synergy degree in energy subsystem is the highest (0.54), followed by water subsystem (0.53) and food subsystem (0.50). It can be inferred that energy subsystem has the highest centralities and dominates the FEW nexus. Food subsystem is the bottleneck of synergetic development, so it is necessary to optimize and control the food subsystem to achieve overall synergy. Water subsystem is still critical to maintain the orderly operation of the FEW nexus, because water is taken as the constraint to determine the development of city, land, people and production according to the 18th National Congress of the Communist Party of China.

4.1.2. Evolution of synergetic network

The evolutionary synergetic network is visualized based on the synergy degree. Figure 3(a) shows the FEW synergetic network in YREB from 2004 to 2018. The node size indicates the average synergy degree between each specified order parameter and others. The node position is furtherly sorted based on the node size. During the evolutionary process of synergetic network, the size and position of nodes change constantly, meaning that each order parameter participates in the dynamics of the FEW nexus to some extent. In water subsystem, the node position of W1 (water supply) and W4 (polluted caused by water) is backward. In food subsystem, the node position of F1 (food supply) and F2 (food demand) is forward. In energy subsystem, the node position of E2 (energy demand) is forward, while the node position of E4 (polluted caused by energy) is backward.

Figure 3(b) shows the average ordering value of 12 order parameters. The node positions of energy-related order parameters are relatively forward, those related to food are relatively backward, and the water-related order parameters are intermediate. Resource benefits occupy the dominate position in synergy network, mainly comes from E3 (energy benefit) and F3 (food benefit), thus ensuring a steady economic growth is critical to system development. F1 (food

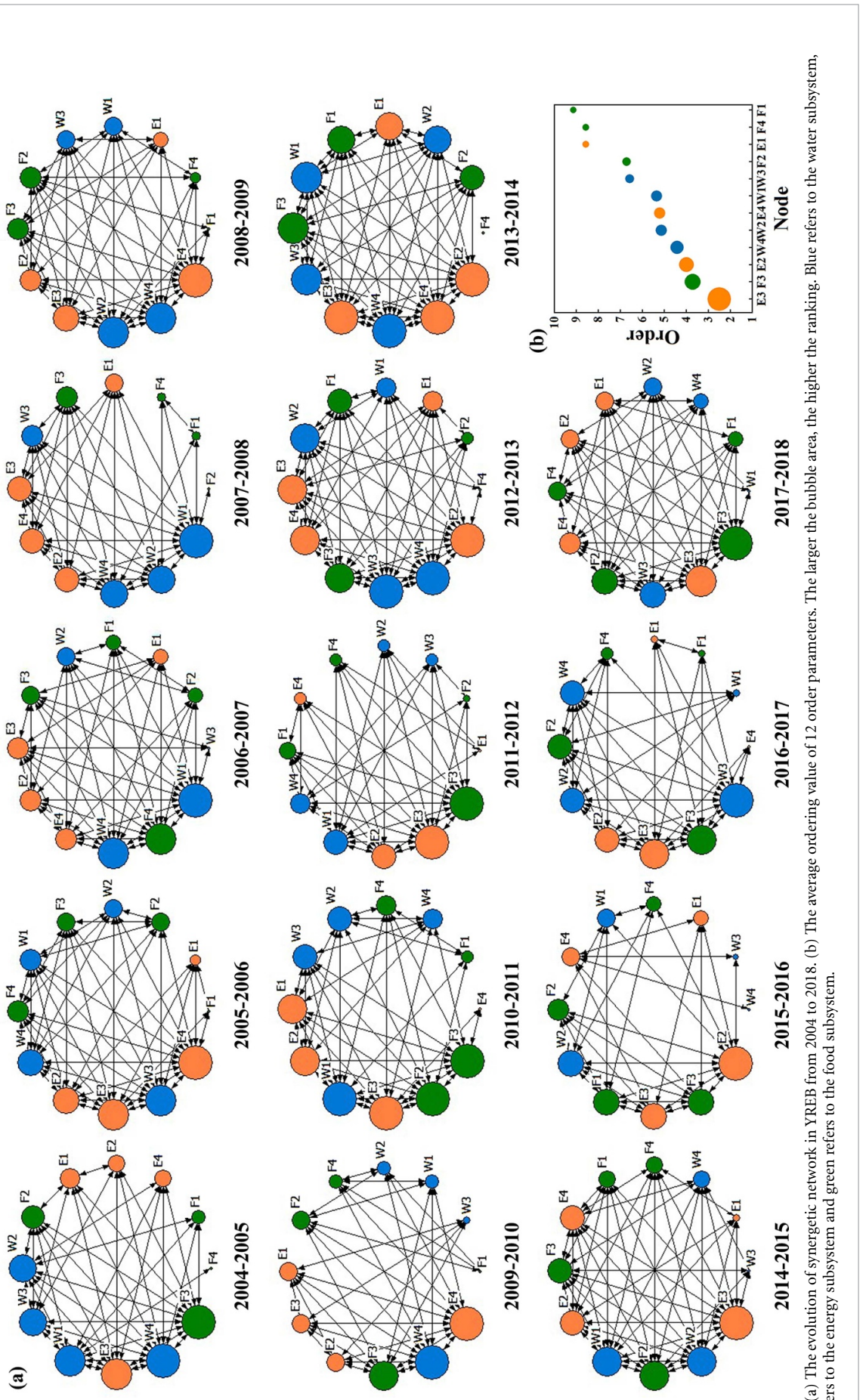

Figure 3. (a) The evolution of synergetic network in YREB from 2004 to 2018. (b) The average ordering value of 12 order parameters. The larger the bubble area, the higher the ranking. Blue refers to the water subsystem, yellow refers to the energy subsystem and green refers to the food subsystem.

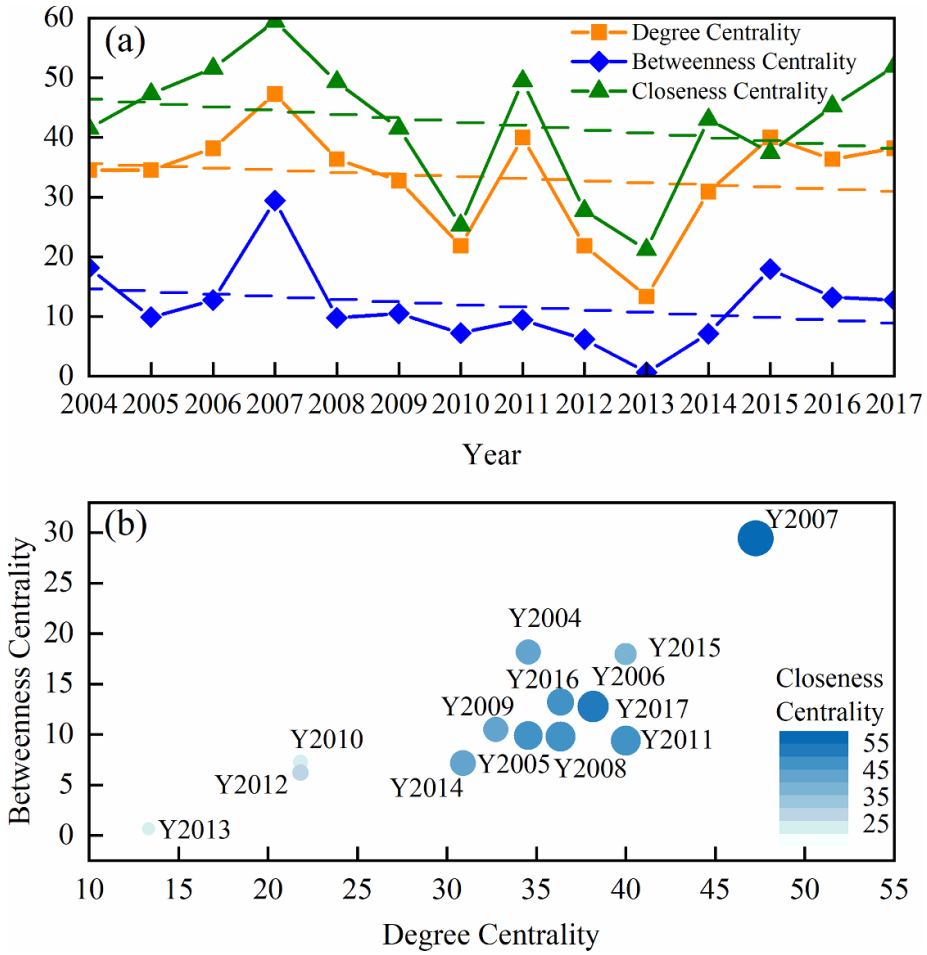

Figure 4. (a) The change of three graph centralization, i.e. the degree graph centralization, the betweenness graph centralization and the closeness graph centralization. The dotted line is the trend line, showing a downward trend. (b) The bubble diagram shows the relationship between the degree centrality, betweenness centrality and closeness centrality.

supply) ranks the last in the network and has strong independence, thus the changes of other order parameters have little driving effect on it. When compared with other supply nodes (F1 and E1), water supply (W1) has the highest ranking (Note that the smaller of the order value means the higher of the ranking), because it maintains both food production and energy generation.

4.1.3. Identification of the centrality

Table S3 and figure S4 of supplementary information shows the centrality indices of synergetic network from 2004 to 2018. (a) In figures S4(a) and (b), the degree point centrality of food subsystem reaches the minimum in 2007 mainly driven by food demand (F2), and water subsystem reaches the minimum in 2015 driven by water pollution (W4). (b) In figures S4(c) and (d), the betweenness point centrality of water subsystem reaches the maximum in 2007 mainly driven by water supply (W1), and energy subsystem reaches the maximum in 2015 driven by energy supply (E1). These two order parameters depend on the input of water and energy, and then affect the output of food products. They act as 'bridge' and show the important role in promoting the system synergy. (c) In figures S4(e) and (f), the closeness point centrality of three subsystems repeatedly fluctuates, and the direction of all subsystems is shown to be consistent. Three subsystems all reaches the minimum in 2013, meaning that the great instability within the FEW nexus happens. This is because the synergy degree between pollution caused by food (F4) and other order parameters is so small that it is removed from the network.

The degree graph centralization, the betweenness graph centralization and the closeness graph centralization are shown in figure 4(a). It is found that the changes of the three indices are similar. Network analysis can enhance the understanding of dynamic connections between interdependent subsystems. The temporal variations are observed in network centralization, because three resources (i.e. food, energy and water) compete and interact with each other, which constitute a dynamic network. As shown in figure 4(b), the graph centralization reaches the highest in 2007, reflecting that the synergy of the FEW nexus is the best; however the centralization

Table 2. Accuracy validation of the node w9 (water consumption per 10 000 yuan for GDP) based on the confusion matrix.

Actual value($m^3/10^4$ yuan)	Simulated value ($m^3/10^4$ yuan)			
	50–210	210–370	370–530	Sum
50–210	31	2	0	33
210–370	0	9	0	9
370–530	0	0	3	3
Sum	31	11	3	45
Total accuracy		95.56%		

reaches the lowest in 2013. Overall, it shows a downward trend. The Chinese government only started to take action in 2014, when the State Council proposed to take advantage of the golden waterway to build YREB. Since then, a series of development policies have been carried out. As a result, we should adhere to the national strategy to realize the resource sustainability and synergetic development.

4.2. Sensitivity analysis of Bayesian network

4.2.1. Model validation and evaluation

Bayesian network is parameterized with observational data. To assess the predictive accuracy of the model for w9 (water consumption per 10 000 yuan for GDP), the confusion matrix of the node is calculated by using three cross-validations of the data from 2004 to 2018. From table 2, the network has an overall accuracy of 95.56% when simulating, showing high accuracy and absolute reliability in simulating water benefit.

4.2.2. Description of regional FEW nexus

As shown in figure 5, the length of black horizontal bars varies in UR, MR and LR, meaning that there are significant regional differences in the characteristics of the FEW nexus. In water subsystem, node w6 (industrial water consumption per capita) and w7 (domestic water consumption per capita) increase from upstream to downstream, reflecting the more developed the zone is, the more intensive water use will be.

In energy subsystem, UR is rich in energy resources, because node e1 (energy production per capita) only occurs the highest state in UR. It is noted that UR accounts for 48% of the total water resources and contributes 72% of the hydropower installed capacity in the YREB. However, the advantage of resources has not been brought into play, the energy benefit is still low in UR. It can be inferred from node e6 that UR tends to be in low industrial added value. In order to promote the development of UR, the industry should be guided to transfer from downstream to upstream, according to *Guide to industrial transfer of Yangtze River Economic Belt* issued by MIIT (Ministry of Industry and Information Technology) in 2017.

In food subsystem, node f2 (grain yield per unit area) and f3 (aquatic production per capita) describing the food supply of MR and LR tend to in higher states than UR, which benefit from the agriculture and fishery in two Lake Plain, i.e. Poyang Lake Plain in Jiangxi Province and Dongting Lake Plain in Hunan Province. At the same time, the chemical fertilizers (f9) and pesticides (f10) caused by agricultural production also bring serious environmental pollution. Agricultural environmental governance should focus on the middle and lower reaches.

4.2.3. Contribution of influencing eigenvectors

Quantitative knowledge helps to understand the changes in the FEW nexus, while expert knowledge about the FEW nexus is often qualitative. The sensitivity analysis can help to generate quantitative insights in the absence of reliable expert knowledge, and identify the contributions of major factors that influence the FEW nexus. Based on the centrality analysis of synergetic network, the benefit impacts most in human-oriented system and occupies important position in the network. Therefore, node w9 (water consumption per 10 000yuan for GDP), e5 (energy consumption per 10 000 yuan for GDP) and f7 (gross value of agriculture production per capita) reflecting the impact of benefits are selected as target nodes.

The sensitivity analysis is carried out to assess the relative importance of input variables to target variables (w9, e5 and f7) in Bayesian network, figure 6 respectively shows the MI in different zones, and the greater MI means the greater sensitivity. Only variables with high sensitivity are shown here, and other variables with less influence are ignored. In figure 6(a), when considering the effect of e6 (industrial added value per capita) to w9, the impact is greatest in LR, followed by MR and UR. In terms of f7 (agricultural added value per capita), the impact is greatest in UR, while MR and LR are almost insensitive. This shows that different regions have different advantageous industries. LR is sensitive to energy-related factors, and it should promote the transformation of energy production and consumption patterns, thus the development of industry in LR should focus on remediation. UR is sensitive to food-related factors, and it should improve the food structure, increase the irrigation coefficient and yield, thus the development of agriculture in UR should focus on protection. In figure 6(b), the effect of e8 (industrial

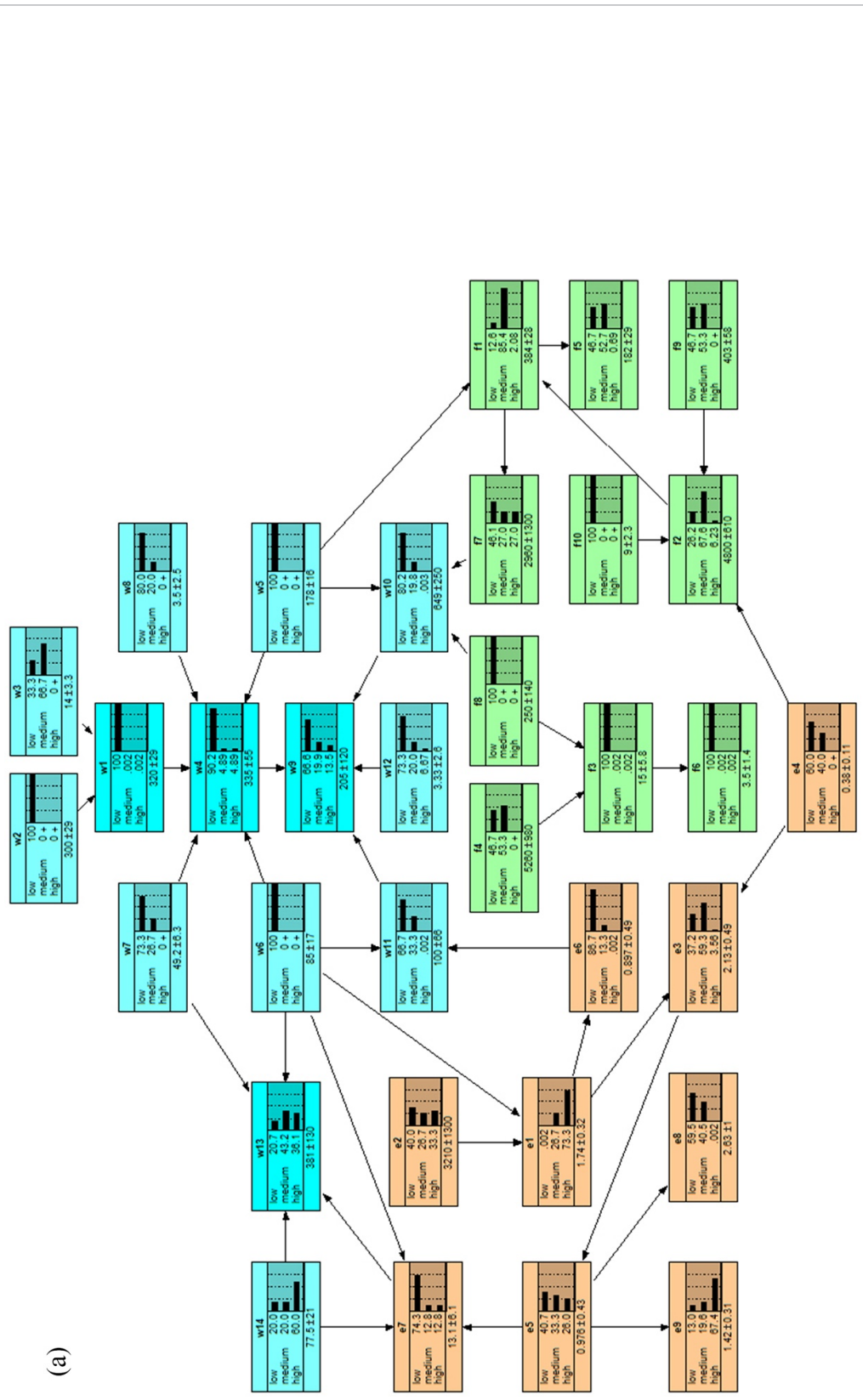

Figure 5. Parameterized Bayesian network in (a) UR, (b) MR and (c) LR. Blue nodes describes water subsystem, yellow nodes describes energy subsystem and green nodes describes food subsystem. Note that each noded (eigenvector) is divided into low, medium and high states. For each node, the black horizontal bar represents the probability distribution of the corresponding state, the values before and after the '±' respectively indicate the mean and standard deviation of the distribution.

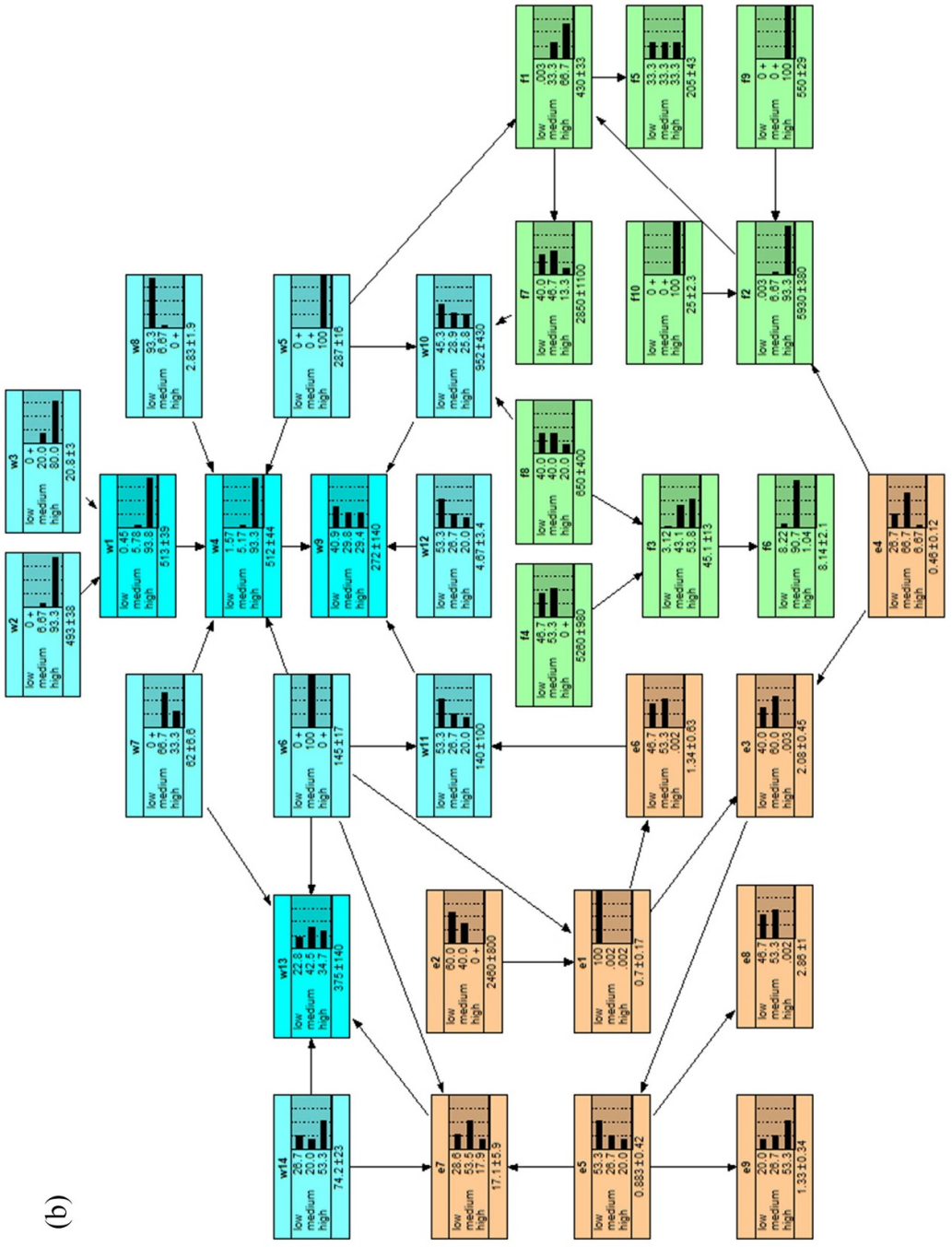

Figure 5. (Continued.)

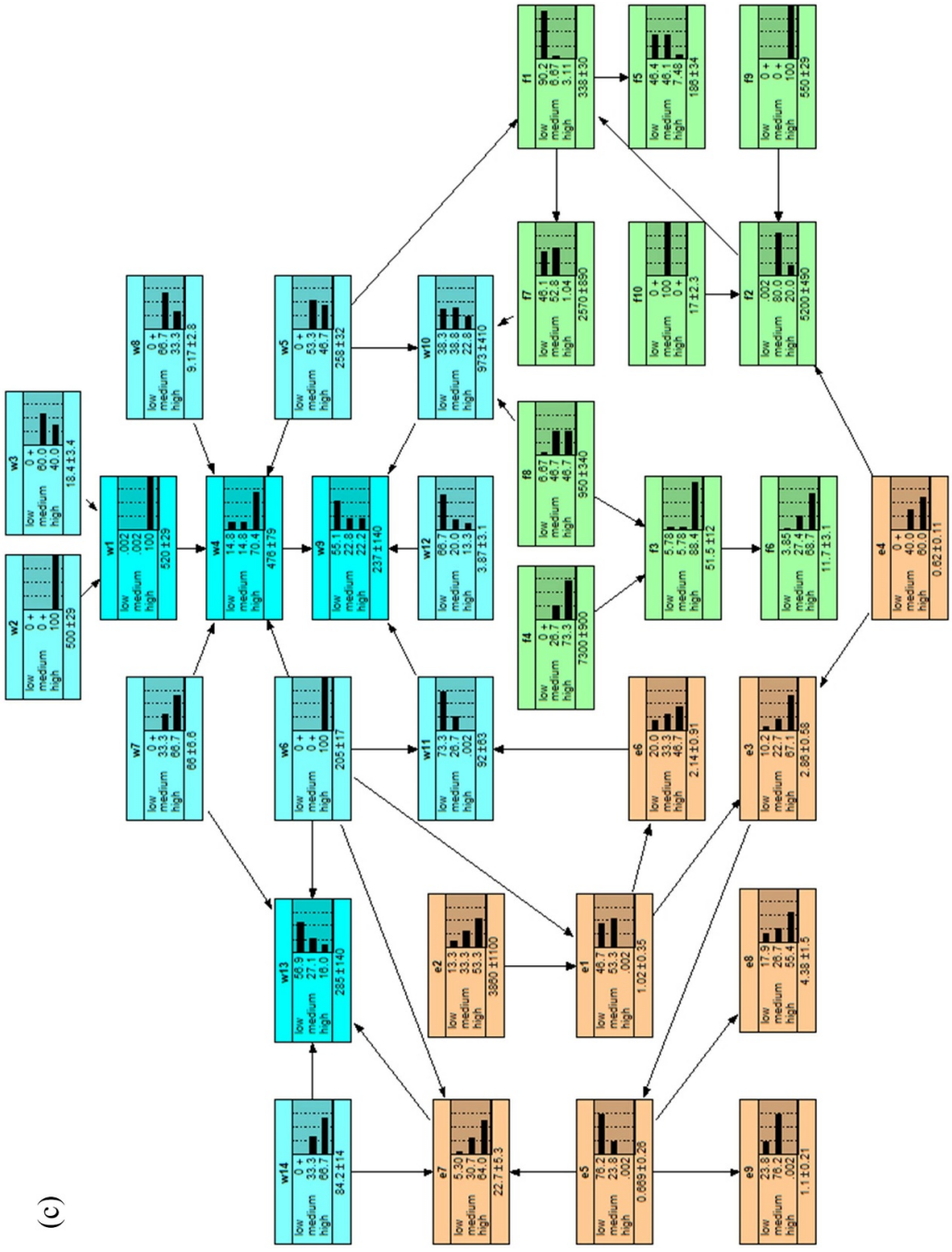

Figure 5. (Continued.)

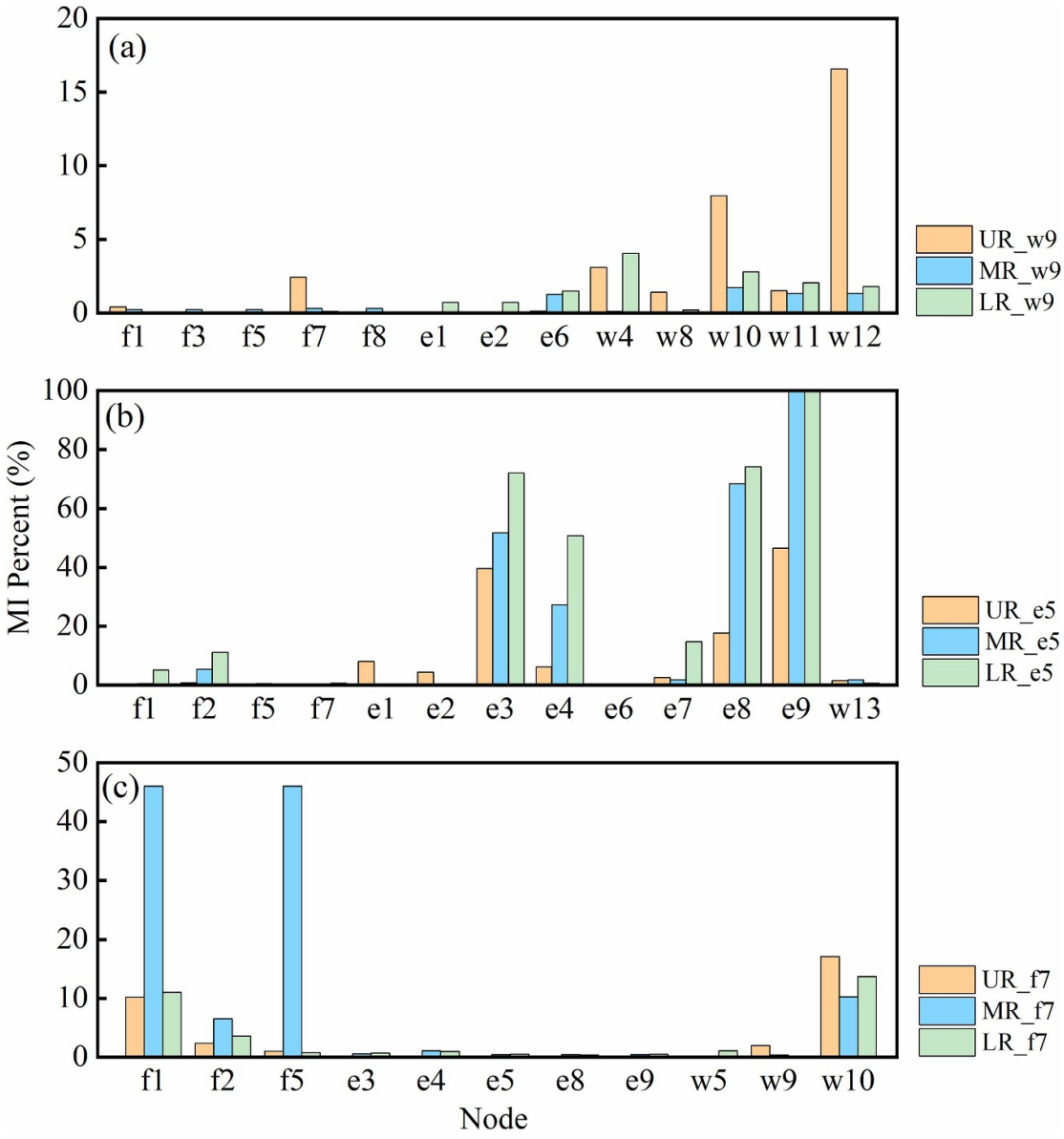

Figure 6. Sensitivity of spatial variability for node w9 (water consumption per 10 000 yuan for GDP), e5 (energy consumption per 10 000 yuan for GDP) and f7 (gross value of agriculture production per capita) in UR, MR and LR.

waste gas discharge per capita) and e9 (industrial solid waste discharge per capita) to e5 is apparent. In order to maintain the energy benefit, the pollution caused by related energy production, processing and transportation should be controlled. In figure 6(c), when considering the effect of e3, e4, e5, e8 and e9 to f7, the yellow vertical bars representing UR are missing, because the energy subsystem has little impact on the food subsystem, and the connection between food and energy in UR is not close.

The regional sensitivity is closely related to the advantageous resources. For example, economic developed provinces (GDP per capita is more than 5×10^4 yuan) mainly distribute in LR, where energy occupies the dominant position. Moderate developed provinces (GDP per capita is between 3×10^4 yuan and 5×10^4 yuan) mainly distribute in MR, where water resource is the most abundant. Less developed provinces (GDP per capita is less than 3×10^4 yuan) are distributed in UR, where agriculture promotes the development of local economy.

5. Conclusions

This study uses the network analysis by combining the synergetic network with Bayesian network to reveal the FEW nexus in China's Yangtze River Economic Belt. The subsystems, order parameters and eigenvectors describing FEW nexus are first determined in causal paths. The synergetic network among order parameters and Bayesian network among eigenvectors are then respectively developed to identify the influencing factors and analyze the sensitivity of the

dominant influencing factors. The derived conclusions are as follows:

(a) Food subsystem has the lowest centralities, thus becomes the bottleneck of the FEW nexus. It is necessary to optimize and control the food subsystem to achieve overall synergy. Energy subsystem has the highest centralities and dominates the FEW nexus. Water subsystem is critical to maintaining the orderly operation of the FEW nexus.
(b) From the perspective of time variability, the network centralization reaches the highest in 2007, but reaches the lowest in 2013, showing a downward trend. We should adhere to the national strategy of synergetic development to realize the resource sustainability. The resource benefits play an important role in promoting synergy of food and energy subsystems, and can be artificially managed.
(c) From the perspective of spatial sensitivity, LR is sensitive to energy-related factors. The development of industry in LR should focus on remediation, and promote the transformation of energy production and consumption patterns. UR is sensitive to food-related factors. The development of agriculture in UR should focus on protection, and improve the food structure, increase the irrigation coefficient and yield.

This study has some limitations. First, the selection of order parameters is mainly relied on the availability of data and some important order parameters in the FEW nexus are omitted. In addition, the synergetic degree is only relative value and there is still a lack of baseline for scenarios comparison.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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ORCID iD

Pan Liu https://orcid.org/0000-0002-3777-6561

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