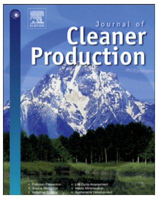
Journal of Cleaner Production xxx (xxxx) xxx

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro



Assessment on the features of coupling interaction of the food-energy-water nexus in China

Dongni Han [a], Deyong Yu [a, *], Qian Cao [b]

[a] Center for Human-Environment System Sustainability (CHESS), State Key Laboratory of Earth Surface Processes and Resource Ecology (ESPRE), College of Resources Science & Technology, Faculty of Geographical Science, Beijing Normal University, Beijing, 100875, China
[b] Institute of Ecology and Biodiversity, School of Life Sciences, Shandong University, Qingdao, 266237, China

ARTICLE INFO

Article history:
Received 28 June 2019
Received in revised form
4 November 2019
Accepted 18 November 2019
Available online xxx

Handling editor: Panos Seferlis

Keywords:
Data envelopment analysis
Coupling degree
Coupling coordination degree
Sustainable resource utilization
Trade-off
Synergy

ABSTRACT

Food, energy and water are critical resources for human well-being. A prerequisite for achieving the sustainable utilization of these resources is how to identify and manage the synergies and trade-offs within the food-energy-water (FEW) nexus. This study considered multiple combinations of dimensions, including economic benefits, social benefits and negative environmental impacts, to assess the performance of China's FEW nexus system. The efficiency of the FEW nexus from 2005 to 2017 was evaluated in 30 provinces across China using a multiplicative environmental data envelopment analysis (ME-DEA) model. The coupling interaction among the FEW nexus was investigated from the perspectives of the coupling degree and coupling coordination degree. Finally, five efficiency bundles of the FEW nexus were identified using the K-means clustering method. Our results showed that 78% of the provinces with high- and sub-high efficiency were distributed in eastern and central China. Conversely, 86% of the low-efficiency provinces were concentrated in western China. Additionally, the coupling coordination degree of most provinces (63%) generally decreased from 2005 to 2017. These results revealed irreconcilable trade-offs among the subsystems of the FEW nexus. Some valuable suggestions for the sustainable use of resources were proposed according to the characteristics of the five efficiency classes. Class 1 performed well in the water, food and labor dimensions. To balance the FEW nexus, we recommend adjusting energy-related policies. Class 2 showed inefficiency in all dimensions, particularly for labor and social efficiencies. Therefore, the government should provide more employment opportunities and improve social benefits for households. A gap in economic efficiency was found in Class 3. Thus, policies and funding support for the economic dimension are recommended. Class 4 had lower efficiency values than the average, particularly in terms of energy and environmental aspects. The government should pay more attention to pollution treatment. For Class 5, synergies were found in all partial efficiencies; thus, the current development strategies should be adhered. These findings are helpful for developing policies that enhance the sustainability of the FEW nexus.

1. Introduction

As basic resources for human survival and development, food, energy and water supply key ecosystem services, such as provisioning, regulating and cultural services, to meet human well-being (Wu, 2013). There are interconnections among these subsystems in the biophysical and socioeconomic dimensions. For example, hydropower requires water to provide power, and water plays a key role in producing fuel and transporting energy (Xie et al., 2018). In turn, intensive desalinization uses energy to produce drinkable water. Food production requires energy and water to irrigate, plant and harvest. Thus, the concept of the food-energy-water (FEW) nexus was proposed (Hoff, 2011). The supply, distribution and flow of ecosystem services are affected by the interrelationships within the nexus.

However, with rapid population growth, land use change, and climate change, the utilization and distribution patterns of water, energy and food resources have been affected on local, regional and

---

* Corresponding author. State Key Laboratory of Earth Surface Processes and Resource Ecology (ESPRE), College of Resources Science & Technology, Faculty of Geographical Science, Beijing Normal University, No. 19 XinJieKouWai Street, Haidian District, Beijing, 100875, China.
E-mail address: ydy@bnu.edu.cn (D. Yu).

https://doi.org/10.1016/j.jclepro.2019.119379
0959-6526/© 2019 Elsevier Ltd. All rights reserved.

Please cite this article as: Han, D et al., Assessment on the features of coupling interaction of the food-energy-water nexus in China, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2019.119379

even global scales. This situation has posed substantial pressure on human well-being because of the competing needs for limited resources. It is predicted that global labor will increase to 10 billion by 2100, and the consequences relate to changes in water, energy and food availability. The water supply shortage will reach 40% by 2030, the food demand will increase by 50%, and the demand for energy will increase three-fold (CNA, 2014). The global water cycle, food production and climate change are inextricably linked. Under global climate change, the water distribution patterns will change significantly and further intensify the water stress in developing countries and poverty-stricken areas (Forman and Wu, 2016). Climate change and labor growth may have significant implications for agricultural production, especially for irrigated agriculture, which provides approximately 40% of global food production. Rainfed food production will experience intense pressure due to shifts in weather patterns and a greater dependency on land and water resources (Khan and Hanjra, 2009). Thus, because the availability and productivity of water, food and energy are increasingly limited, the demands of billions of people are barely being met (Hoff, 2011). Specifically, 30% of arable land and 70% of fresh water resources of the world will be used to produce 2.5 billion tons of grain (Forum, 2011; Zhang, 2013). In this situation, nearly 2 billion people are still undernourished or malnourished, and nearly 2.8 billion people are suffering from water shortages in physical or economic terms (Howells et al., 2013). Under current resource utilization patterns, it will become more challenging to obtain adequate food, energy and water resources for sustainable development (Obersteiner et al., 2016). The insecurity of food, energy and water has seriously threatened ecosystem health and human well-being (Biggs et al., 2015).

Many studies have explored the FEW nexus from various aspects. Based on existing research topics, the current literature can be divided into three categories: (1) internal relationship analysis towards evaluating the interactions among subsystems, (2) external impact analysis oriented at identifying influential factors, and (3) assessment of the whole coupling system performance.

In interrelationship analysis, quantifying the interactions and interdependence of the FEW nexus has helped improve the safety of food, energy and water as well as the resource utilization efficiency (Endo et al., 2015; Scott et al., 2015), reduce trade-offs among subsystems, and promote synergy across subsystems (Machell et al., 2015). For example, Karan and Asadi (2018) measured the sustainability of a FEW system using the integrated FEW sustainability index and formulated the interconnections associated with the FEW components, which helps us better understand how each subcomponent affects the overall sustainability of the system. Using Beijing as an example of a typical fast-growing mega city, Wang et al. (2019a) established a FEW impact model to analyze how the spatial patterns of water system elements influence rice production and energy.

In external impact analysis, external environmental changes can influence the performance of the nexus by reshaping the supply and utilization of water, energy and food through interconnected processes (Zhang et al., 2018). Thus, understanding the changing mechanism of the system is vitally important to ensure the supply of water, food and energy. Conway et al. (2015) analyzed how climate change affected the relationships among the FEW nexus in southern Africa by changing the spatial and subsystem interdependence. However, the mechanisms of the changes among the subsystems were not declared. Hussien et al. (2018) assessed the impacts of seasonal variability on the demand for water, energy and food using a developed FEW model to find the most effective strategy, which provided scientific evidence for risk management.

In the assessment of system performance, sustainability and resilience are usually discussed. For example, Wang et al. (2018) evaluated the sustainability of the FEW nexus in China using an improved matter-element extension model. Namany et al. (2019) considered multiple technological options in three food scenarios to find optimization schemes for the environment and economy.

However, current studies still present several shortcomings: (1) The interaction mechanism among the subsystems of the FEW nexus needs to be interpreted. There is a lack of consideration of the concrete biophysical and chemical processes among food, water and energy subsystems. (2) The evaluation of the coupled system is inadequate. The changes in one subsystem can cascade to others through the coupled system (Zhang et al., 2018); thus, neglecting to consider the coupling interactions among the FEW system may cause imperfectness. (3) There is a lack of research that considers multiple combined dimensions, such as economic benefits, social benefits, environmental impacts, and human well-being. Finally, (4) few studies have been conducted at the national scale due to the lack and uncertainty of data. Indeed, most previous studies have been conducted on small or local scales (e.g., Wang et al., 2018; Conway et al., 2015; Hussien et al., 2018).

With only 7% of the world's freshwater resources, China has supported one-fifth of the global population (Gu et al., 2016). China's per capita water resources are only one-fourth of the world's per capita water resources, ranking 121th in the world. The scarcity of water resources in the country may be illustrated by comparing values with neighboring Russia, where approximately 2% of the global population is supported by 10% of the world's freshwater resources (Proskuryakova et al., 2018). China's cultivated land is mainly distributed in the arid and semiarid northern areas, and the country's grain supply mainly originates from the northern regions where water resources are relatively scarce. Grain production in these areas is heavily dependent on groundwater irrigation, which greatly increases the burden on natural ecosystems (Jiang et al., 2009). Meanwhile, with population growth and ongoing urbanization, residents' diets tend to be more water-intensive, including meat, vegetables, and fruits (Wu et al., 2006). Climate change will increase the need for irrigation, further exacerbating the water crisis (Jiang, 2015; Wang et al., 2013). The amount of water available for food production will be severely limited due to water competition among water-intensive crops and water requirements of domestic and industrial development. For example, the coal industry is the second largest consumer of water in China, accounting for 20% of water consumption (Zheng et al., 2016). However, the distribution of freshwater resources in China is unbalanced, particularly in coal- and gas-rich regions (Zheng et al., 2016). The three coal-richest regions (Shanxi, Shaanxi and Inner Mongolia) occupy only approximately 3% of the nation's water resources (Zheng et al., 2016). The coal-based industries developing in coal-rich regions are facing great constraints on water resources (Xie et al., 2018). In addition, the consumption of energy can have an adverse effect on the environment. China had the highest coal consumption and largest CO_2 emissions worldwide. The electricity sector mainly relies on coal-fired thermal generation (Xie et al., 2018). Therefore, the dilemma in terms of trade-offs in the FEW nexus is quite serious in China. Studying the interactions of the FEW nexus is vitally important for improving water, energy and food securities and management levels across subsystems.

To conquer these limitations in the current literature, this study made efforts to consider multiple combinations of dimensions to assess the performance of China's FEW nexus system from 2005 to 2017; the dimensions included the economic benefits, social benefits and negative environmental impacts. In addition, we considered the FEW nexus as a coupled system to detect the coupling interactions among the FEW nexus. To do so, (1) the overall and individual efficiencies of the FEW nexus were measured using the

Please cite this article as: Han, D et al., Assessment on the features of coupling interaction of the food-energy-water nexus in China, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2019.119379

ME-DEA method in a holistic perspective; (2) the coupling interactions among subsystems were analyzed using the coupling degree and coupling coordination degree models; (3) the trade-offs and synergies were evaluated to provide a co-optimization base for different stakeholders with different benefit concerns; and (4) the FEW nexus bundles were identified to provide corresponding suggestions for specific decision-making.

2. Methodology

The methodology section included four parts: 1) the ME-DEA model, which was used to evaluate the efficiency of the FEW nexus; 2) the coupling degree and coupling coordination degree models, which were used to analyze the coupling interaction among subsystems; 3) the Mann-Kendall test and Sen's slope method, which were used to test the changing trends of interactions between the subsystems of the FEW nexus; and 4) the study area and data sources.

2.1. Data envelopment analysis

The traditional radial or non-radial DEA model performs in different pursuits of maximizing the inputs or outputs and adopts strong disposable assumptions. Thus, the evaluations often deviate from the actual production process. In this paper, a multiplicatively non-radial DEA model was chosen, which can be regarded as a multiplicative version of a group of DEA models (ME-DEA) known as slack-based measures. The ME-DEA model (Valadkhani et al., 2016) was used to measure the efficiency of the FEW nexus. The ME-DEA model was chosen due to its multiplicative environmental technology. The efficiency of any decision-making unit (DMU) was obtained as the maximum of a ratio of weighted outputs to weighted inputs. The condition needed is that the similar ratios for every DMU are less than or equal to unity (Charnes et al., 1978).

The overall efficiency index was decomposed to compile eight partial efficiency scores. Thus, the independent efficiency scores of water, food and energy can reflect the comprehensive development levels of each subsystem, which can serve as the inputs of the coupling degree and coupling coordination degree models.

As a non-parametric model, the DEA estimates the effective production frontier based on a set of input-output observations to evaluate the relative efficiency of a set of DMUs. There is a set of DMU$_j$ (j = 1,2,…n) that use m input indicators x_{ij} (i = 1,2,…m) to generate s output indicators y_{rj} (r = = 1,2,…s). Here, x_j and y_j are both larger than zero (j = 1,2,…n). In this study, the assumption is that there are n homogeneous DMUs, corresponding to the $n = 30$ provincial administrative units employed in the sample.

The multiplicative environmental (ME) DEA technology was presented as:

$$P_{DEA}^{ME}(X) = \left\{ \left(y^D, y^U\right) \in R_+^{p+q} \,\middle|\, \begin{array}{l} \prod_{j\in J} x_{ij}^{\lambda_j} \le x_i, i = 1, \dots, m, \\ \prod_{j\in J} y_{rj}^{D^{\theta_j \lambda_j}} \le y_r^D, r = 1, \dots, p, \\ \prod_{j\in J} y_{tj}^{U^{\theta_j \lambda_j}} = y_t^U, t = 1, \dots, q, \\ \sum_{j\in J} \lambda_j = 1, \\ \lambda_j \ge 0, 0 \le \theta_j \le 1, j = 1, \dots, n \end{array} \right. \tag{1}$$

The multiplicative weak disposability assumption was restated from Shephard (1970):

$$\left(y^D, y^U\right) \in P(X), 0 < \theta \le 1 \Rightarrow \left(y^{D\theta}, y^{U\theta}\right) \in P(X) \tag{2}$$

Applying the transformation (Kuosmanen and Podinovski, 2009), we can obtain an equivalent linear programming model:

$$\begin{array}{l} \log \rho_O^{ME} = Max \sum_{i=1}^{m} u_i \log\alpha_i + \sum_{r=1}^{p} v_r \log\beta_r + \sum_{t=1}^{q} w_t \log\gamma_t \\ s.t. \sum_{j\in J} (\mu_j + \eta_j) \log x_{ij} \le \log x_{io} - \log\alpha_i, i = 1, \dots, m, \\ \sum_{j\in J} \mu_j \log y_{rj}^D \ge \log y_{ro}^D + \log\beta_r, r = 1, \dots, p, \\ \sum_{j\in J} \mu_j \log y_{tj}^U = \log y_{to}^U - \log\beta_t, t = 1, \dots, q, \\ \sum_{j\in J} (\mu_j + \eta_j) = 1, \\ \sum_{j\in J} \mu_j \ge 0, \eta_j \ge 0, \log\alpha_i \ge 0, \log\beta_r \ge 0, \log\gamma_t \ge 0, \forall i, r, t, j \end{array} \tag{3}$$

where u_i=(u_1,…u_m), v_r=(v_1, …v_p) and w_t=(w_1, …w_q) are the user-specified weights assigned to the inputs, desirable outputs and undesirable outputs, respectively, and α_i (i = 1,2,…m), β_r (r = 1,2,…p) and γ_t (t = 1,2,…q) are the efficiencies of the i_{th} input indicator, the r_{th} desirable output and the t_{th} undesirable output, respectively. The optimal goal of the objective function is to find the maximum value of these variables related to one certain product.

Therefore, the reciprocals of the optimal values of these variables can be interpreted as partial efficiencies, including labor, water, food, energy, capital, economic, social and environmental efficiencies. In economics, partial efficiency is defined as measuring the performance of each resource from the perspective of input-output (Bosseboeuf et al., 1997). The overall efficiency is the full measurement of inputs, desirable outputs and undesirable outputs.

Multiplicative environmental measures of efficiency can be defined based on partial efficiencies. In this study, each DMU consumes five inputs (labor, capital, water, food and energy) to jointly yield two desirable outputs (GDP and household consumption) and undesirable environmental outputs. Socioeconomic efficiency, environmental efficiency, energy efficiency, and the geometric mean of the above three measures were calculated using the equations (4)–(7), which were based on partial efficiencies associated with these factors (Valadkhani et al., 2016).

Multiplicative socioeconomic efficiency is equal to the geometric mean of the partial efficiencies related to labor (α_1*), food (α_2*), capital (α_5*), GDP (β_1*) and household consumption (β_2*).

$$e_o^{M-Econ} = \left(\alpha_1^* \times \alpha_2^* \times \alpha_5^* \times \beta_1^* \times \beta_2^*\right)^{-1/5} \tag{4}$$

Multiplicative environmental efficiency is equal to the geometric mean of the partial efficiencies associated with water (α_4*) and environment (γ_1*).

$$e_o^{M-\text{Evir}} = \left(\alpha_4^* \times \gamma_1^*\right)^{-1/2} \tag{5}$$

Multiplicative energy efficiency is equal to the partial efficiency of energy (α_3*).

$$e_o^{M-Ener} = \left(\alpha_3^*\right)^{-1} \tag{6}$$

The geometric mean of the above three measures was further defined as the unified overall efficiency.

$$e_o^{ME} = \left(e_o^{M-\text{Evir}} \times e_o^{M-\text{Econ}} \times e_o^{M-\text{Ener}}\right)^{-1/3} \tag{7}$$

Please cite this article as: Han, D et al., Assessment on the features of coupling interaction of the food-energy-water nexus in China, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2019.119379

2.2. Quantifying the interaction of the FEW nexus

The coupling degree and coupling coordination degree were usually used to measure the interactions among the systems or the elements (Deng et al., 2017). The former highlights the interaction strength, while the latter emphasizes the positive interaction (Xiong et al., 2014). In this section, the coupling degree and coupling coordination degree were used to quantify the interactions among the energy, water and food subsystems.

2.2.1. Coupling degree model

Based on the research of Liao (1999), we constructed the coupling degree model as follows:

$$C = 3\sqrt[3]{f(x)g(y)h(z)} \Big/ (f(x) + g(y) + h(z)) \tag{8}$$

where C refers to the coupling degree among the water, energy and food subsystems. $f(x)$, $g(y)$, and $h(z)$ are the efficiency scores of the water, energy and food subsystems evaluated from the DEA model, respectively, reflecting the comprehensive development levels of these three subsystems.

Based on a previous study (Guan and Xu, 2014), we divided the coupling degree into four levels as follows: 1) separated coupled phase (0–0.25); 2) antagonistic coupled phase (0.25–0.5); 3) barely coupled phase (0.5–0.75); and 4) superior coupled phase (0.75–1).

2.2.2. Coupling coordination degree model

The coupling degree model alone cannot judge whether the coupling is positive or negative. Based on the physical concept of coupling coordination (Li et al., 2012), we constructed a FEW nexus coupling coordination degree model as follows:

$$D = \sqrt{C \times T} \tag{9}$$

$$T = \alpha f(x) + \beta g(y) + \gamma h(z) \tag{10}$$

where D is the coupling coordination degree, C is the coupling degree, and T represents the integrated evaluation index of the FEW nexus, reflecting the contribution of water, energy and food. α, β and γ are the weights indicating the importance of each subsystem, respectively. In the FEW nexus, each subsystem is considered equally important; thus, $\alpha = \beta = \gamma = 1/3$ was set.

The coupling coordination degree was classified into four categories based on the study of Xing et al. (2019), as follows: 1) low coupling coordination phase (0–0.25); 2) moderate coupling coordination phase (0.25–0.5); 3) high coupling coordination phase (0.5–0.75); and 4) extreme coupling coordination phase (0.75–1).

2.2.3. Analyzing the efficiency bundles of the FEW nexus

Spearman's rank correlation of each partial efficiency was calculated using SPSS (IBM SPSS 20), indicating the strength and direction of the relationship.

Efficiency bundles of the FEW nexus specialized in partial efficiencies. To better support the implementation of policy based on the efficiency results, the clustering method was used to identify the regions with similar efficiency aggregation. K-means clustering was performed to obtain the efficiency bundles corresponding to partial efficiency scores (labor, water, food, energy, capital, economic, social and environmental efficiencies). All partial efficiency scores were normalized before carrying out clustering analysis, and the K-means cluster was analyzed in R 3.6.1 (http://www.r-project.org/). The sum of squared error was used to identify the optimal number of clusters. The clustering method was used to identify the regions with similar efficiency aggregation, which depends on similar social-economic factors. Thus, policies can better target the particular problems in different regions.

Then, the efficiency bundles were mapped in the ArcGIS 10.2 platform (Esir, 2013) to show the spatial pattern and identify the spatial interactions. Furthermore, radar charts were used to show the characteristics of each bundle.

2.3. Mann-Kendall test and Sen's slope

The Mann-Kendall method (Mann, 1945) was used to analyze the changing trends of the coupling degree, coupling coordination degree, and partial efficiencies.

In the Mann-Kendall test, with the null hypothesis H_0, the time series data (x_1..., x_n) include a sample of n independent and random variables with the same distribution. With the alternative hypothesis H_1, there is an increasing or decreasing trend in the time series. The S statistic of the test is calculated as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i) \tag{11}$$

$$\mathrm{sgn}(x_j - x_i) = \begin{cases} +1, x_j - x_i > 0 \\ 0, \ \ x_j - x_i = 0 \\ -1, x_j - x_i < 0 \end{cases} \tag{12}$$

In this study, the time series length was $n = 13$, and the test was conducted using the Z value. At the given significance level of $\alpha = 0.05$, the null hypothesis is accepted when $|Z| \le Z_{1-\alpha/2}$, and the changing trend within the time series is considered to not be significant. When $|Z| > Z_{1-\alpha/2}$, the null hypothesis is rejected, and the trend is considered to be significant.

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{VAR(S)}}, S > 0 \\ 0, S = 0 \\ \dfrac{S+1}{\sqrt{VAR(S)}}, S < 0 \end{cases} \tag{13}$$

$$VAR(S) = \left(n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5) \right) \Big/ 18 \tag{14}$$

In Eq. (14), m is the number of nodes in the time series, and t_i is the width of the node.

Sen's slope (Gilbert, 1987) was used to calculate the slope of changes in the coupling degrees, coupling coordination degrees and efficiencies of the FEW nexus.

$$\beta = \mathrm{Median}\left(\frac{x_j - x_i}{j - i} \right) \tag{15}$$

2.4. Study areas and data sources

In this study, 30 provinces in China were chosen as study areas (Fig. 1). Because data for Tibet, Macao, Hong Kong, and Taiwan were unavailable, these provinces were excluded. The research period was from 2005 to 2017.

A detailed description of the input-output indicator system and data sources is provided in Table 1. Each province consumes 5 inputs (labor, capital, energy, food, and water) that jointly produce economic and social benefits as well as undesirable environmental

Please cite this article as: Han, D et al., Assessment on the features of coupling interaction of the food-energy-water nexus in China, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2019.119379

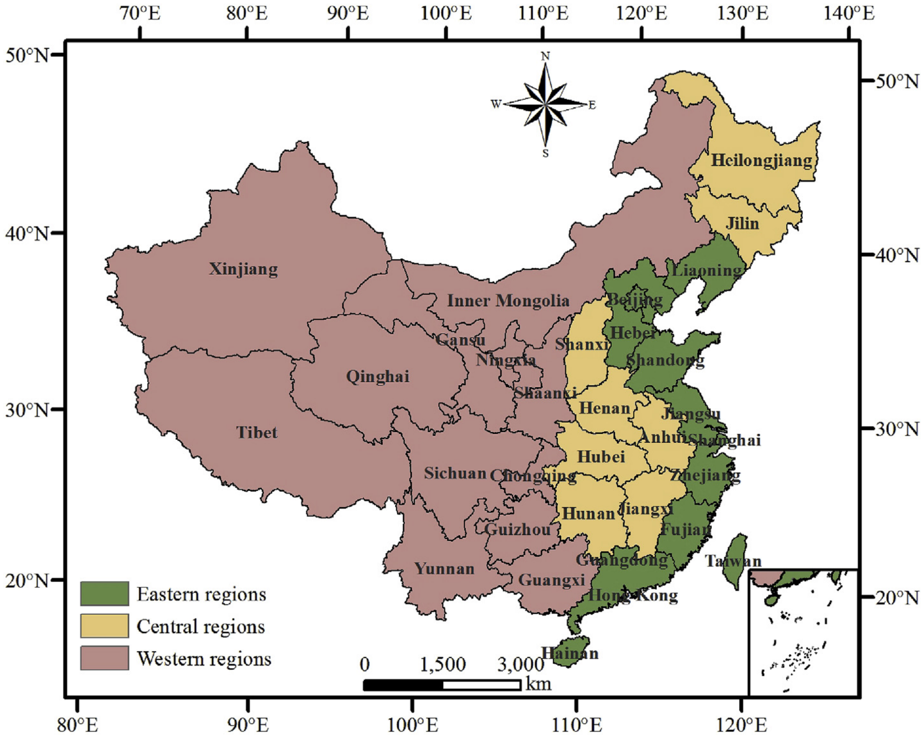


Fig. 1. Spatial distribution of the study areas, which are further classified into eastern regions, central regions and western regions.

Table 1
Input-output indicator system.

Types	Indices	Specific indicators	Units	Data sources
Input	Labor	Total population at year-end	10,000 people	Population at Year-end by Region, *China Statistical Yearbooks* (2005–2017)
	Water	Total water use	100 million m^3	Water Supply and Use by Region, *China Environmental Statistics Yearbooks* (2005–2017)
	Food	Intermediate consumption of agriculture, forestry, animal husbandry, and fishery	100 million Yuan (in constant price)	Gross output value, added value and intermediate consumption of agriculture, forestry, animal husbandry and fishery by Region, *China Rural Statistical Yearbooks* (2005–2017)
	Energy	Total energy consumption	10,000 tons of SCE	Energy Consumption by Region, *China Energy Statistics Yearbooks* (2005–2017)
	Capital	Real capital stock	100 million Yuan (in 2000 prices)	*China Statistical Yearbooks* (2005–2017)
Desirable output	Economic benefit	Real gross Regional Product (GDP)	100 million Yuan (in 2000 prices)	Gross Regional Product and Indices, *China Statistical Yearbooks* (2005–2017)
	Social benefit	Real household consumption	Yuan (in 2000 prices)	Final Consumption Expenditure and Its Composition by Region, *China Statistical Yearbooks* (2005–2017)
Undesirable output	Negative environmental impacts	Total Waste Water Discharged	10,000 tons	Main Pollutant Emission in Waste Water by Region, *China Environmental Statistics Yearbooks* (2005–2017)
		Sulphur Dioxide	10,000 tons	Main Pollutant Emission in Waste Gas by Region, *China Environmental Statistics Yearbooks* (2005–2017)
		Smoke and Dust	10,000 tons	Main Pollutant Emission in Waste Gas by Region, *China Environmental Statistics Yearbooks* (2005–2017)
		Total Solid Wastes Produced	10,000 tons	Disposal and Utilization of Industrial Solid Wastes by Region, *China Environmental Statistics Yearbooks* (2005–2017)

outputs.

Water, energy and food were the three natural resource inputs. Capital and labor were selected as the non-natural inputs. Specifically, the total consumption of water and energy was employed as the input of water and energy. To better measure the efficiency of food, the intermediate consumption of agriculture, forestry, animal husbandry, and fishery was chosen as the input of food. The amount of the labor force was represented by the number of persons at the end of the year. Capital stock was chosen as the fifth input indicator.

For desirable outputs, GDP, which is the direct reflection of production, represents the economic benefits in this study and was transformed into 2000 prices with GDP deflators. Social benefits are reflected by the living standards of local residents. Thus, the total household consumption was selected as another desirable output and was transformed into 2000 prices.

For undesirable outputs, the negative effects of excessive emissions on the environment as a consequence of food, energy and water resource consumption were considered. Four pollutants were selected as undesirable environmental outputs: waste water, solids, SO_2, and smoke and dust. Then, the data were normalized to

Please cite this article as: Han, D et al., Assessment on the features of coupling interaction of the food-energy-water nexus in China, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2019.119379

0–1, and the entropy method (Zhao et al., 2018) was used to determine the weights. Finally, a comprehensive environmental index was obtained to represent the integrated undesirable output.

3. Results

3.1. Efficiency of the FEW nexus

3.1.1. Spatial efficiency patterns of the FEW nexus

The spatial patterns of the average of the partial efficiencies of the FEW nexus during 2005–2017 are shown in Fig. 2. In general, the overall efficiency of the FEW nexus ranged from 0.5 to 1.

High-efficiency regions of the FEW nexus were mainly located in eastern China, including Beijing, Tianjin, Shanghai, Guangdong, Shandong, Hainan, and Qinghai (located in western China). These 7 provinces constituted the production frontier of the FEW nexus. Their water, food and energy efficiencies were all equal to 1.0, a value that was much higher than those of the other provinces. Compared with those of other provinces, the inputs of these 7 provinces were fully utilized, and the greatest output efficiency was achieved from 2005 to 2017. In addition, no efficiency loss was caused by excessive inputs (energy, water, and food), excessive undesirable outputs (waste water, waste gas, and waste solid) and improper resource allocation. In this case, economic, social and environmental benefits were realized at the same time. Other provinces did not achieve high efficiency, indicating that the combination of input and output factors was not optimal. Input redundancy and undesirable outputs were relatively high.

3.1.2. Changing trends of the efficiency of the FEW nexus during 2005–2017

As Fig. 3 illustrates, the overall efficiency primarily decreased during 2005–2017. The overall efficiencies of 11 provinces significantly decreased, including those in Hebei, Shanxi, Inner Mongolia, Liaoning, Heilongjiang, Zhejiang, Anhui, Hunan, Yunnan, Shaanxi, and Xinjiang. The slopes of changes in Liaoning, Heilongjiang, Anhui, and Hunan were the largest (Table 2). In general, the water efficiency increased during 2005–2017. Concretely, the water efficiency of Jiangxi, Chongqing, Yunnan, and Gansu significantly increased. Chongqing (0.034) was a hotspot of increase (Table 2). Food and energy efficiency primarily decreased during 2005–2017. The food efficiency of 17 provinces significantly decreased. The

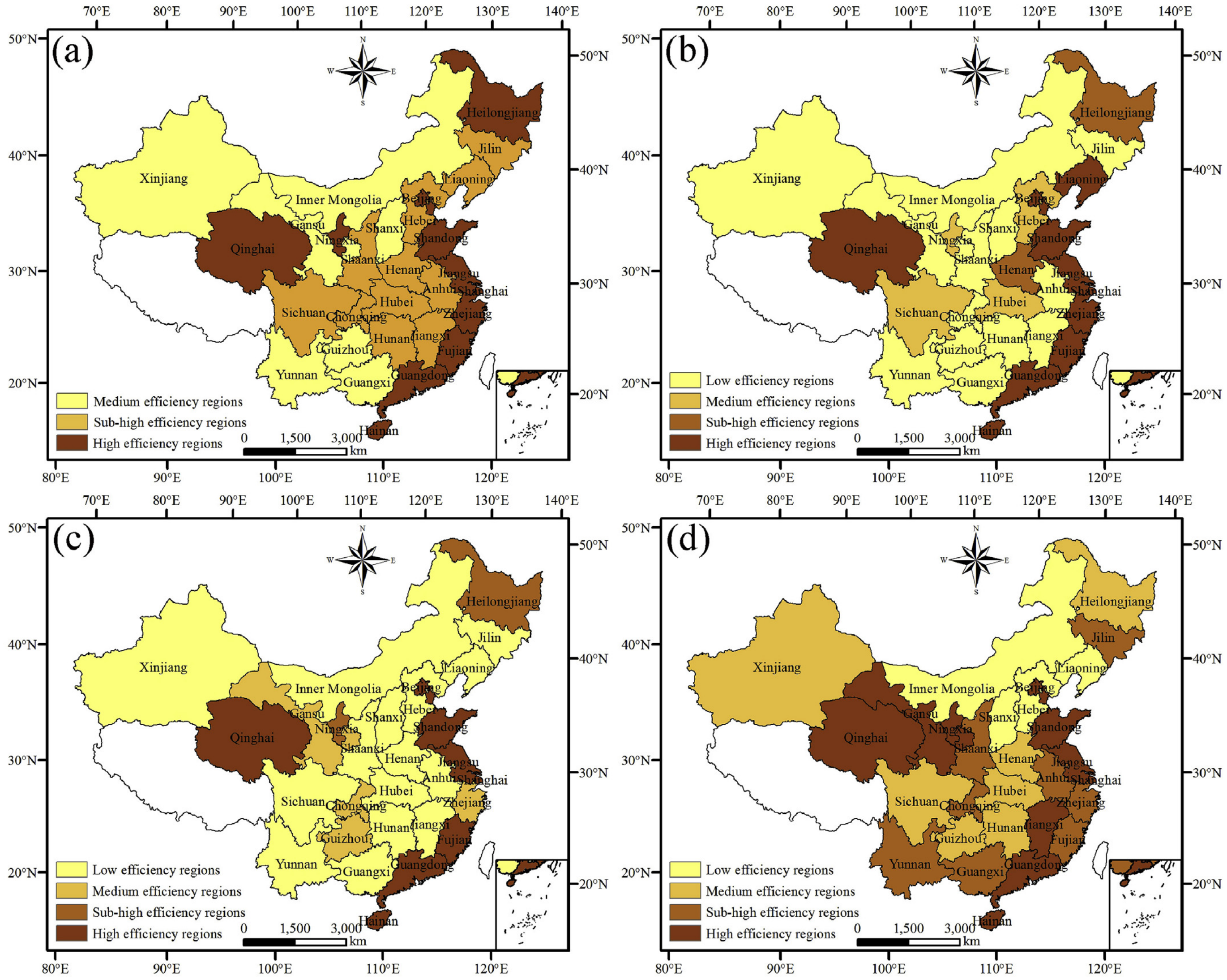


Fig. 2. Spatial patterns of the average a) overall efficiency, b) water efficiency, c) food efficiency, and d) energy efficiency of the FEW nexus in China. An efficiency score less than 0.5 was mapped to low efficiency, 0.5–0.7 to medium efficiency, 0.7–1.0 to sub-high efficiency, and 1 to high efficiency (the efficiency scopes were referenced from Li et al., 2016).

Please cite this article as: Han, D et al., Assessment on the features of coupling interaction of the food-energy-water nexus in China, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2019.119379

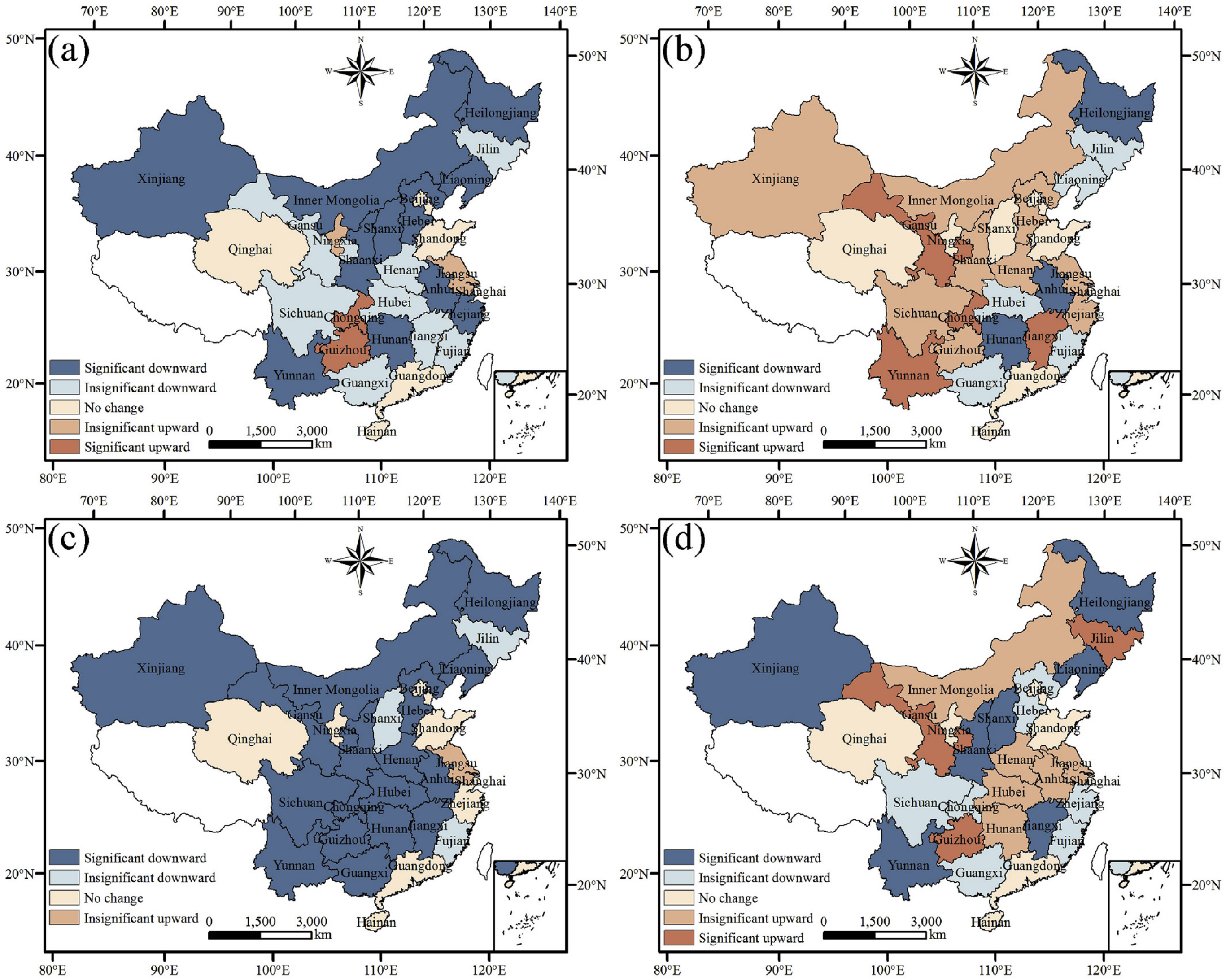


Fig. 3. Changing trends of a) overall efficiency, b) water efficiency, c) food efficiency, and d) energy efficiency from 2005 to 2017. The given significance level α is 0.05.

slopes of changes in the efficiency scores of Hunan (−0.061) and Hubei (−0.051) were the largest (Table 2). The changing trends of energy efficiency exhibited similar patterns with water efficiency. The energy efficiency of Jilin, Guizhou, and Gansu significantly increased. Jilin (0.017) was the hotspot of increase (Table 2). There were no changing trends of overall and these three partial efficiencies in Beijing, Tianjin, Shanghai, Shandong, Guangdong, Hainan, and Qinghai.

3.1.3. Congruence of the efficiency between water-energy, water-food and food-energy subsystems during 2005–2017

Fig. 4 shows the congruence of energy, water and food efficiencies of each province during 2005–2017. Using the medians of energy efficiency (0.79), water efficiency (0.64), and food efficiency (0.51) as the horizontal and vertical axes, respectively, all 30 provinces can be classified into four groups corresponding to four quadrants.

For the extent of water-food congruence, 12 provinces (Beijing, Tianjin, Shanghai, Shandong, Guangdong, Hainan, Qinghai, Ningxia, Zhejiang, Jiangsu, Fujian, and Heilongjiang) were located in the first quadrant, with above-average water and food efficiency. Gansu, Guizhou, and Chongqing were located in the second quadrant, with relatively inefficient water efficiency and efficient food efficiency. Henan, Jilin, Liaoning, Anhui, Sichuan, and Shaanxi were located in the fourth quadrant, with inefficient food efficiency and efficient water efficiency. However, as one of the main grain-producing areas in China, the food efficiency of Henan was lower than the national average. The other provinces were located in the third quadrant, with poor performance in water and food efficiency.

For the extent of water-energy congruence, 12 provinces (Beijing, Tianjin, Shanghai, Shandong, Guangdong, Hainan, Qinghai, Jiangsu, Zhejiang, Fujian, Heilongjiang, and Hubei) were located in the first quadrant, with relatively efficient water and energy efficiencies. The provinces located in the second quadrant were Jiangxi, Ningxia, and Anhui, which had relatively inefficient water efficiency and efficient energy efficiency. Of these provinces, Jiangxi and Anhui were water-rich areas. The third quadrant contained 11 provinces (Guangxi, Jilin, Yunnan, Shaanxi, Sichuan, Hunan, Xinjiang, Inner Mongolia, Gansu, Guizhou, and Shanxi), with energy and water efficiencies that were lower than the average. Henan, Chongqing, Liaoning, and Hebei were located in the fourth quadrant and had relatively inefficient energy efficiency and efficient water efficiency. Among these provinces, Shanxi and Hebei represented the provinces with the most abundant energy resources

Please cite this article as: Han, D et al., Assessment on the features of coupling interaction of the food-energy-water nexus in China, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2019.119379

Table 2
Changing slopes of the FEW nexus for different provinces in China.

DMU$_S$	Regions	Abbreviation	Coupling degree	Coupling coordinated degree	Water efficiency	Food efficiency	Energy efficiency	Overall efficiency
DMU1	Beijing	BJ	0.000	0.000	0.000	0.000	0.000	0.000
DMU2	Tianjin	TJ	0.000	0.000	0.000	0.000	0.000	0.000
DMU3	Hebei	HE	−0.011	−0.005	0.006	−0.009	−0.001	−0.005
DMU4	Shanxi	SX	0.003	−0.006	0.000	−0.020	−0.004	−0.004
DMU5	Inner Mongolia	NM	0.001	−0.003	0.002	−0.010	0.001	−0.002
DMU6	Liaoning	LN	−0.027	−0.024	−0.004	−0.049	−0.011	−0.013
DMU7	Jilin	JL	−0.009	−0.002	−0.003	−0.003	0.017	0.000
DMU8	Heilongjiang	HL	−0.016	−0.008	−0.003	−0.007	0.000	−0.012
DMU9	Shanghai	SH	0.000	0.000	0.000	0.000	0.000	0.000
DMU10	Jiangsu	JS	0.000	0.000	0.000	0.000	0.000	0.000
DMU11	Zhejiang	ZJ	0.000	0.000	0.000	0.000	−0.005	−0.002
DMU12	Anhui	AH	−0.026	−0.026	−0.029	−0.046	0.001	−0.013
DMU13	Fujian	FJ	0.000	0.000	0.000	0.000	0.000	0.000
DMU14	Jiangxi	JX	0.004	−0.004	0.007	−0.017	−0.014	−0.002
DMU15	Shandong	SD	0.000	0.000	0.000	0.000	0.000	0.000
DMU16	Henan	HA	−0.010	−0.005	0.005	−0.007	0.006	0.000
DMU17	Hubei	HB	−0.023	−0.020	−0.007	−0.051	0.006	−0.005
DMU18	Hunan	HN	−0.028	−0.031	−0.029	−0.061	0.006	−0.011
DMU19	Guangdong	GD	0.000	0.000	0.000	0.000	0.000	0.000
DMU20	Guangxi	GX	−0.007	−0.010	−0.003	−0.013	−0.009	0.000
DMU21	Hainan	HI	0.000	0.000	0.000	0.000	0.000	0.000
DMU22	Chongqing	CQ	0.003	0.003	0.034	−0.023	−0.002	0.009
DMU23	Sichuan	SC	−0.022	−0.015	0.002	−0.029	−0.001	−0.003
DMU24	Guizhou	GZ	0.007	−0.004	0.002	−0.042	0.010	0.003
DMU25	Yunnan	YN	−0.001	−0.004	0.002	−0.014	−0.002	−0.004
DMU26	Shaanxi	SN	−0.003	−0.008	0.002	−0.017	−0.010	−0.002
DMU27	Gansu	GS	0.004	0.002	0.006	−0.010	0.004	−0.001
DMU28	Qinghai	QH	0.000	0.000	0.000	0.000	0.000	0.000
DMU29	Ningxia	NX	0.000	0.000	0.000	0.000	0.000	0.000
DMU30	Xinjiang	XJ	0.013	−0.009	0.000	−0.020	−0.021	−0.009

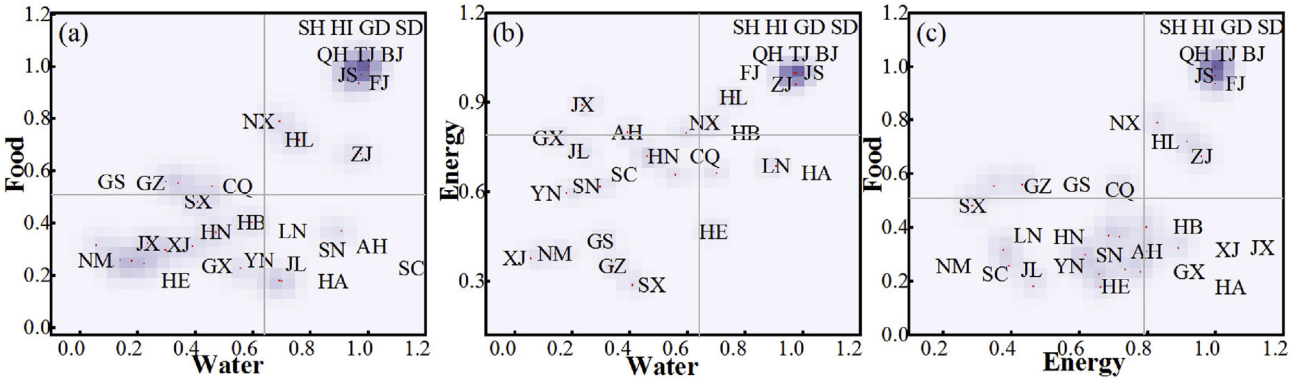


Fig. 4. Congruence of food, energy and water efficiencies during 2005–2017. Panels (a), (b), and (c) represent the extent of congruence of the energy-water, food-water, and food-energy subsystems, respectively. See Table 2 for the full province names.

(e.g., coal, oil, and natural gas).

For the extent of food-energy congruence, 12 provinces were located in the first quadrant (Beijing, Tianjin, Shanghai, Shandong, Guangdong, Hainan, Qinghai, Ningxia, Zhejiang, Jiangsu, Fujian, and Heilongjiang). Guizhou, Gansu, Chongqing, and Ningxia were located in the second quadrant, with relatively inefficient energy efficiency and efficient food efficiency. Anhui, Hubei, Guangxi, Xinjiang, Jiangxi, and Henan were located in the fourth quadrant, with poor efficiencies of food and energy. The remaining provinces (Shanxi, Liaoning, Hunan, Inner Mongolia, Sichuan, Jilin, Yunnan, Shaanxi, and Hebei) were in the third quadrant and performed poorly in terms of food and energy efficiencies.

3.1.4. Efficiency bundles of the FEW nexus

Based on cluster analysis, the efficiency of the FEW nexus was classified in space, and 5 classes were identified to represent the efficiency bundles (Fig. 5). Great differences were found in partial efficiencies among the 5 groups (bundles) (Fig. 6).

Bundle 1 was located in central and eastern China, including Liaoning, Heilongjiang, Zhejiang, and Hubei (Fig. 5). The partial efficiencies were higher than the average, except for food efficiency (Fig. 6a and f). Bundle 2 was distributed in western and central China, including Anhui, Jiangxi, Hunan, Guangxi, Chongqing, Sichuan, Yunnan, and Gansu (Fig. 5). The partial efficiencies were lower than the average (Fig. 6f), except for capital efficiency (Fig. 6b and f). Bundle 3 contained only Ningxia (Fig. 5). The partial efficiencies of bundle 3 were higher than the average (Fig. 6c and f). Economic efficiency should be further improved. Bundle 4 was mainly distributed in western and central China, including Shanxi, Inner Mongolia, Jilin, Henan, Guizhou, Shaanxi, Xinjiang and Hebei (located in eastern China) (Fig. 5). Bundle 4 had similar characteristics to bundle 2, with all partial efficiencies lower than the average

Please cite this article as: Han, D et al., Assessment on the features of coupling interaction of the food-energy-water nexus in China, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2019.119379

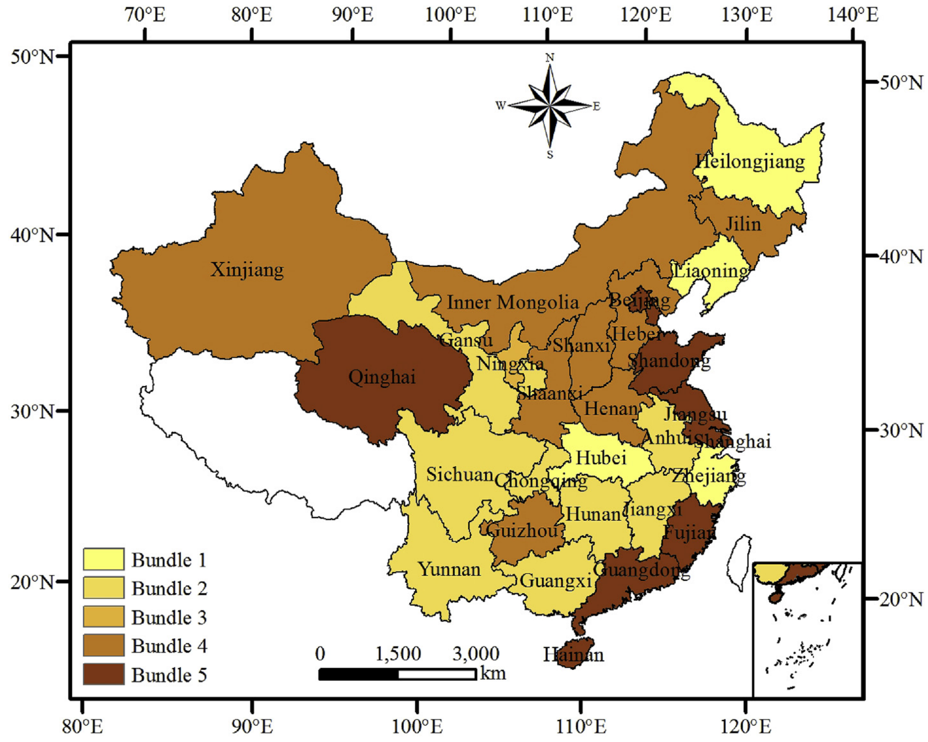


Fig. 5. Spatial patterns of efficiency bundles of the FEW nexus. The efficiency bundles were identified according to the average partial efficiency scores from 2005 to 2017 using the K-means method.

(Fig. 6d and f). In particular, the water, food and environmental efficiencies should be further improved. Bundle 5 was mainly distributed in eastern China (Fig. 5). Bundle 5 contained Beijing, Tianjin, Shanghai, Jiangsu, Fujian, Shandong, Guangdong, Hainan, and Qinghai (located in western China). This bundle had higher levels of partial efficiencies than the average (Fig. 6e, f). Notably, all partial efficiencies were achieved simultaneously.

3.2. The degree of coupling interaction of the FEW nexus

3.2.1. Spatial patterns of coupling degree and coupling coordination degree of the FEW nexus

The spatial patterns of the average coupling degree and coupling coordination degree of the FEW nexus during 2005–2017 are shown in Fig. 7. In general, the coupling degree of the FEW nexus varied from 0.5 to 1. Guangxi was in the barely coupled phase, while the other provinces were all in the superior coupled phase, with strong interactions among subsystems. The coupling coordination degree ranged from 0.25 to 1. Strong synergies (extreme coupling coordination) were mainly distributed in the eastern areas (Beijing, Tianjin, Shanghai, Shandong, Jiangsu, Zhejiang, Guangdong, Fujian, Hainan and Liaoning) and some western areas (Qinghai and Ningxia). Xinjiang and Inner Mongolia were located in moderate coupling coordination areas, with strong trade-offs among water, energy, and food. Except for the above provinces, the other provinces were in high coupling coordination status.

The coefficients of variation of the coupling degrees and coupling coordination degrees from 2005 to 2017 are shown in Fig. 8, which can measure the spatial variation among provinces. In general, there was no great variation in the coupling degree and coupling coordination degree among provinces. Compared with other provinces, Heilongjiang had the greatest variation in coupling degree and coupling coordination degree. Beijing, Tianjin, Shanghai, Shandong, Guangdong, Hainan, and Qinghai had no variation in coupling degree and coupling coordination degree.

Notably, high coupling coordination degrees were found in the eastern plains. This result indicated that coupling interactions among subsystems matched well with the overall efficiency of the FEW nexus (Figs. 2 and 7). When water, energy and food subsystems were in an extreme coupling coordination stage, the FEW nexus tended to achieve high efficiency (e.g., Beijing, Tianjin, Shanghai, Shandong, Jiangsu, Zhejiang, Guangdong, and Hainan). When each subsystem had larger synergies or weaker trade-offs, the FEW nexus could realize higher efficiency.

3.2.2. Changing trends of coupling degree and coupling coordination degree during 2005–2017

The coupling degree of most provinces decreased from 2005 to 2017 (Fig. 9a). The provinces with significant decreases were distributed in central and eastern China, including Hebei, Liaoning, Jilin, Heilongjiang, Anhui, Henan, Hubei, Hunan, Sichuan and Shaanxi, which were located in western China. As illustrated in Table 2, the slopes of changes in the coupling degree of Hunan (−0.028), Liaoning (−0.027), Anhui (−0.026), Hubei (−0.023), and Sichuan (−0.022) were the largest. The provinces with a significant increase in coupling degree were distributed in western China, including Chongqing, Guizhou, Gansu, and Xinjiang. Xinjiang was a hotspot of coupling degree increase (0.013) (Table 2). There was no obvious changing trend in Beijing, Tianjin, Shanghai, Shandong, Guangdong, Hainan, Qinghai, and Ningxia.

As indicated by Fig. 9b, the coupling coordination degree of almost all provinces decreased from 2005 to 2017; the exceptions were Chongqing, Ningxia, Gansu, and Jiangsu. Hunan (−0.031), Liaoning (−0.024), and Anhui (−0.026) were hotspots of decreasing coupling coordination degree (Table 2). The slopes of the changes in Beijing, Tianjin, Shanghai, Shandong, Guangdong, Hainan, and Qinghai were zero (Table 2).

Please cite this article as: Han, D et al., Assessment on the features of coupling interaction of the food-energy-water nexus in China, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2019.119379

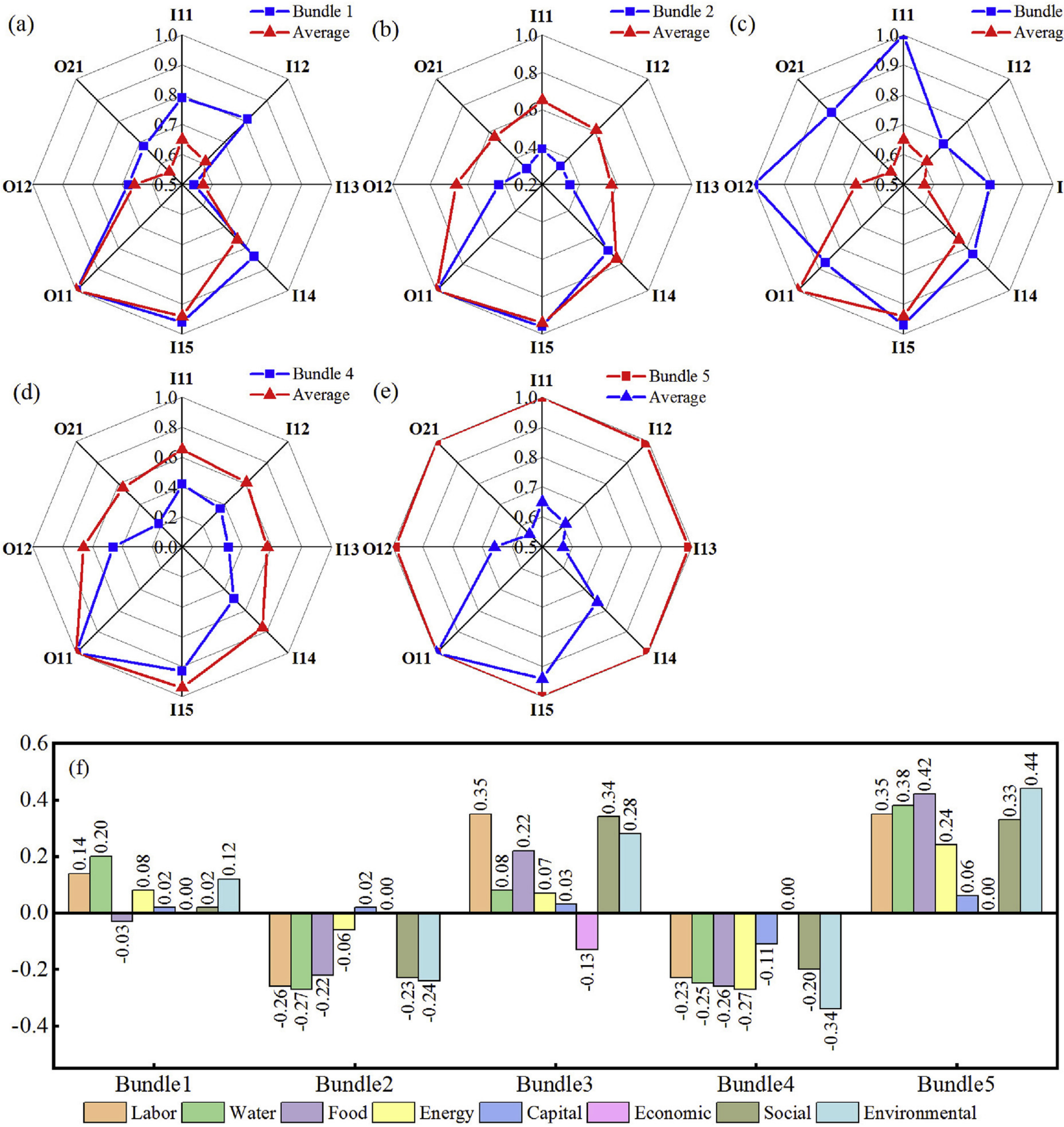


Fig. 6. Partial efficiency scores of the clusters. I11, I12, I13, and I14 represent the labor, water, food and energy efficiencies, respectively. O11 and O12 represent the economic efficiency and social efficiency, respectively. O21 is the environmental efficiency. Values in (f) depict the deviation of the specific clusters from the average. Positive values indicate above-average values, and negative values indicate below-average values.

3.2.3. Trade-offs and synergies between efficiency factors

Synergies describe the situation where two factors change in the same direction, while trade-offs represent the situation where two factors change in the opposite direction (Bennett et al., 2009). Correlation analysis was usually used to determine trade-offs and synergies among multiple factors, namely that significantly positive and negative correlation indicated synergy and trade-off, respectively (e.g., Hao and Yu, 2018). In this study, trade-offs and synergies represent relationships among efficiency components, and Spearman's rank analysis was adopted to determine the correlation coefficient between two partial efficiencies. The correlation coefficients and significant levels among partial efficiencies are indicated in Table 3. These values were used to describe trade-off and synergistic relationships among the efficiency components of the FEW nexus. Significantly positive correlations represent synergies, while negative correlations demonstrate trade-offs.

Among the 28 possible pairs of partial efficiencies, 21 pairs were significantly correlated. Trade-offs were found between economic efficiency and others. The strongest trade-off existed between economic and social efficiencies, which suggested that economic and social benefits can hardly be synchronously realized in the current phrase. Strong synergies were found between all other efficiency pairs. In the FEW nexus, energy, water, and food components were highly correlated with each other. Stronger synergies were found in the water-energy pair ($r = 0.792$, $p < 0.01$). Our results revealed that labor, water, food, energy, capital, social and environmental efficiencies were characterized by a strong synergistic relationship.

Please cite this article as: Han, D et al., Assessment on the features of coupling interaction of the food-energy-water nexus in China, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2019.119379

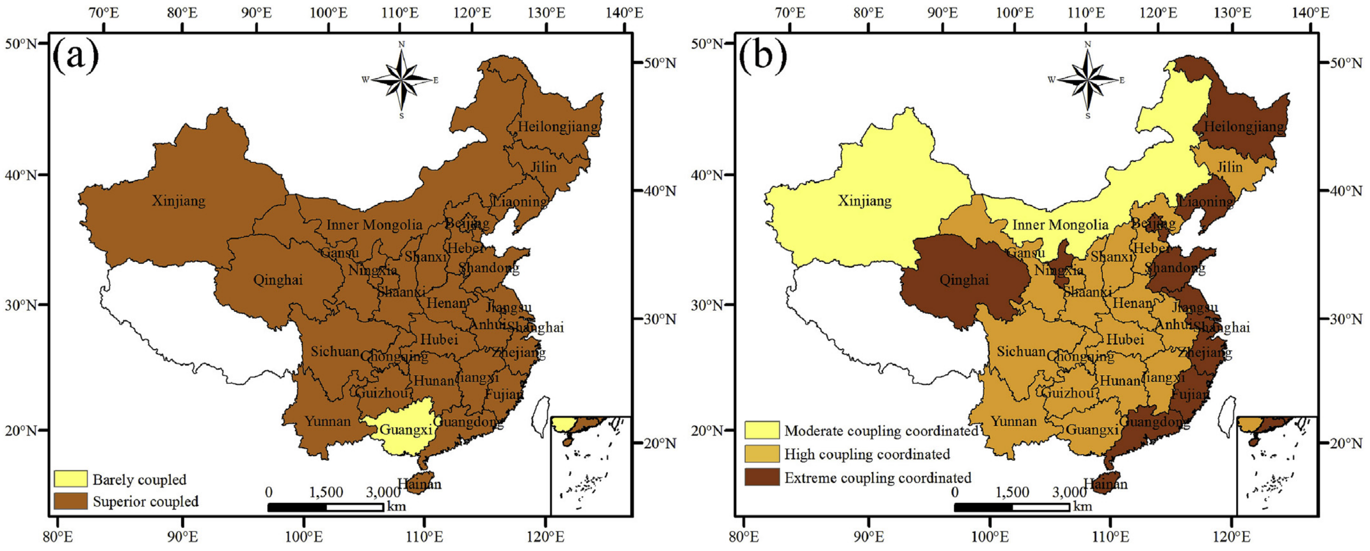


Fig. 7. Spatial patterns of the average (a) coupling degrees and (b) coupling coordination degrees of the FEW nexus during 2005–2017. Coupling degrees ranging from 0.50 to 0.75 and 0.75–1.0 were mapped to the barely coupled and superior coupled phases, respectively. Coupling coordination degrees of 0.25–0.50, 0.50–0.75 and 0.75–1.0 were mapped to the moderate, high and extreme coupling coordination phases, respectively (the coupling degree and coupling coordination degree scopes referenced Xing et al., 2019).

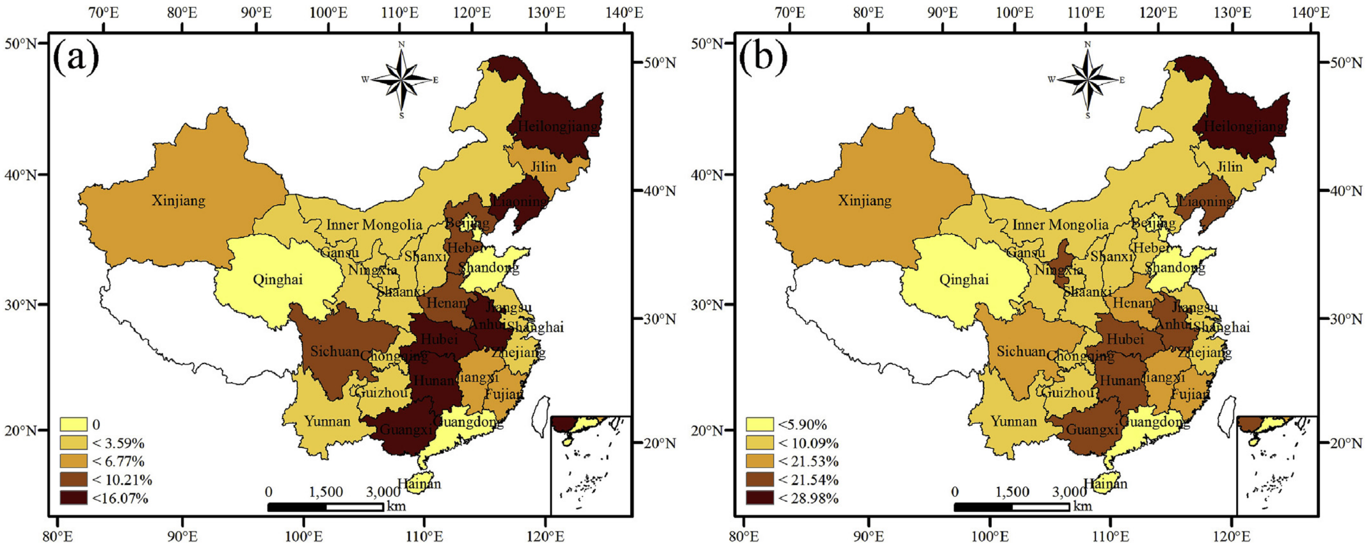


Fig. 8. Coefficients of variation of (a) coupling degrees and (b) coupling coordination degrees of the FEW nexus during 2005–2017. The natural breakpoint method was employed to classify the scope divisions.

4. Discussion

4.1. Mechanisms underlying the spatiotemporal changes in the efficiency and coupling interaction of the FEW nexus

The spatial heterogeneity of efficiency was determined by common geographic conditions, climate, and human activities. High-efficiency regions were mainly concentrated in eastern coastal plains with abundant natural resources, such as adequate precipitation and fertile cropland. In addition, the non-natural resources, such as labor and capital investment, of these regions were sufficient. Low-efficiency regions were mainly located in central and western inland locations. Conversely, development in these regions was restricted by limited precipitation, insufficient investment, and excessive industrial emissions.

Mapping the overall and partial efficiencies is essential for decision-making because it can directly indicate where management policies should be focused. Among the “FEW nexus-efficient” provinces, Beijing, Tianjin, Shanghai, and Guangdong are economically developed provinces in China, with high quality labor, capital, and advanced technology. It is noted that Qinghai also achieved the overall efficiency of the nexus. With slow economic development, Qinghai is an environmentally friendly province. Under the “Twelfth Five-year Plan for Energy Conservation and Emission Reduction” policy, high values of energy efficiency were achieved in Qinghai. The electricity in Qinghai comes from clean energy, such as wind, solar and water power. Among the “FEW nexus-inefficient” provinces, lower values were found in Inner Mongolia, Shaanxi, and Shanxi. Notably, these provinces were rich in energy resources (coal, oil, and natural gas) but low in efficiency levels. According to a prior study (Li et al., 2016), the reason why these energy-intensive regions had lower efficiencies may be due to excessive industrial

Please cite this article as: Han, D et al., Assessment on the features of coupling interaction of the food-energy-water nexus in China, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2019.119379

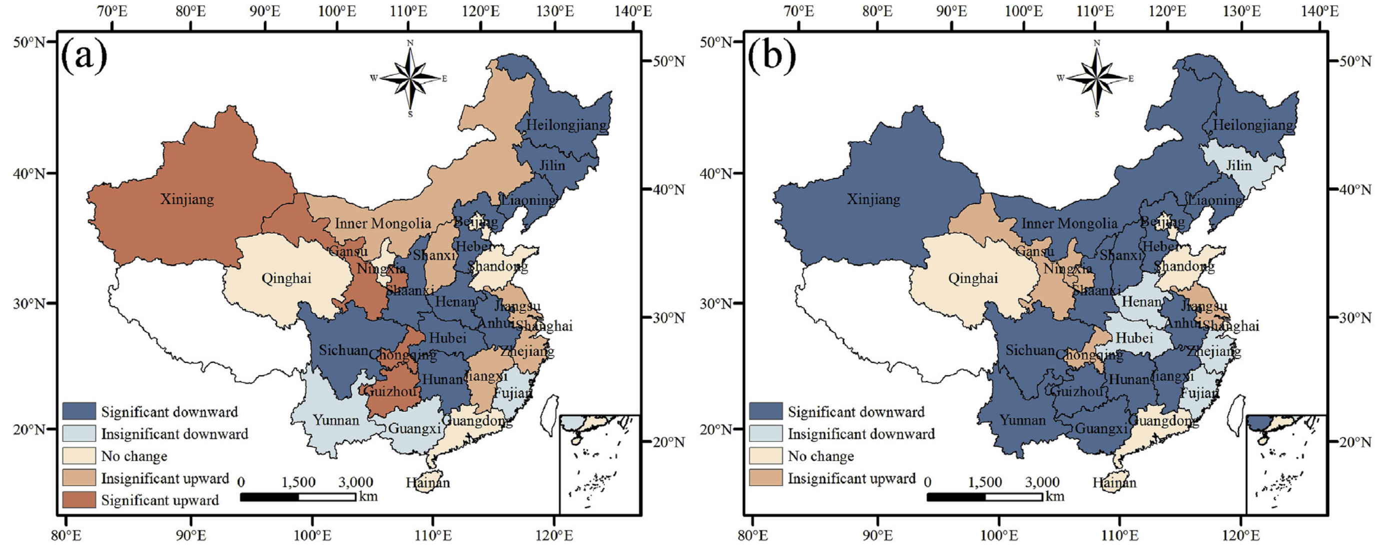


Fig. 9. Changing trends of a) coupling degree and b) coupling coordination degree. The given significance level α is 0.05.

Table 3
Spearman's rank correlation coefficients among partial efficiencies of the FEW nexus (**$p < 0.01$).

Efficiency factors	Code	I11	I12	I13	I14	I15	O11	O12	O13
Labor efficiency	I11	1							
Water efficiency	I12	0.819**	1						
Food efficiency	I13	0.804**	0.772**	1					
Energy efficiency	I14	0.791**	0.792**	0.742**	1				
Capital efficiency	I15	0.596**	0.662**	0.708**	0.822**	1			
Economic efficiency	O11	−0.228	−0.032	−0.119	−0.054	−0.011	1		
Social efficiency	O12	0.910**	0.695**	0.880**	0.777**	0.592**	−0.238	1	
Environmental efficiency	O13	0.872**	0.913**	0.732**	0.931**	0.751**	−0.097	0.758**	1

Note: Highly correlated ($|r| \geq 0.5$), moderately correlated ($0.3 \leq |r| < 0.5$), and weakly correlated ($0.1 \leq |r| < 0.3$).

emissions. The barriers for these provinces to achieve efficiency stem primarily from the difficulty in achieving balance between economic development and the resulting environmental pollution (Yang and Wei, 2019).

Effective resource management requires a deep understanding of the mechanisms underlying interactions among food, water, and energy, including trade-offs and synergies. From 2005 to 2017, the hotspots with significant increases in water, food and energy efficiencies were distributed in western China, such as in Chongqing, Yunnan, Gansu, and Guizhou (Fig. 3). The changing trends of coupling degree and coupling coordination degree exhibited similar patterns (Fig. 9). The hotspots with significant increases in coupling degree and coupling coordination degree were also distributed in western China (Xinjiang, Gansu, Guizhou and Chongqing). The spatial patterns of coupling degree and coupling coordination degree varied greatly (Fig. 7), and the levels of coupling coordination degree were much lower than those of coupling degree. According to the spatial patterns (Fig. 7), the number of the provinces having been in extreme coupling coordination status (96.7%) was less than that of the provinces having achieved superior coupling degree (43.3%). This scenario occurred because the coupling degree indicates only the interactions among the subsystems, while the coupling coordination degree represents the synergy extent among the subsystems.

The changing trends of water, food and energy efficiencies matched well with the coupling relationships of the FEW nexus. When these three subsystems were positively coupled, their hotspots of changing trends in partial efficiencies, coupling degree and coupling coordination degree tended to have similar patterns. In total, the coupling coordination degree matched well with the efficiency of the FEW nexus. When the water, energy and food subsystems were synergistic, the FEW nexus tended to achieve high efficiency. In other words, the coupling relationships among the subsystems affected the performance of the FEW nexus. Our results indicated that an FEW nexus with a high coupling coordination degree can improve the overall efficiency and reduce the negative environmental impacts, which is helpful for mitigating climate change. From this perspective, our study can affirmatively answer the question raised by current studies concerning whether an optimized strategy through the balance of the FEW nexus as a whole can achieve the goals of optimizing the efficiency of resource utilization and environmentally friendly effects (e.g., Tian et al., 2018; Karan et al., 2018; Wang et al., 2018).

4.2. Implications of coupling interaction of the FEW nexus for resource management strategy

According to the efficiency bundle classification, each bundle specialized in partial efficiencies. Therefore, the targeted resource management strategies should be developed according to the division of the bundles.

For bundle 1 (including Liaoning, Heilongjiang, Zhejiang, and Hubei), the values of partial efficiencies were close to the national average, while the labor, water and food efficiencies were higher than the national average. The results can be attributed to the amount of resources possessed by these provinces. It is notable that these 4 provinces are rich in water and food resources, and the population size is large. Therefore, these provinces performed well

Please cite this article as: Han, D et al., Assessment on the features of coupling interaction of the food-energy-water nexus in China, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2019.119379

in the water, food and labor dimensions. To balance the FEW nexus, it is recommended that the energy policies be adjusted in these provinces, such as improving the energy price and structure.

Bundle 2 (including Anhui, Jiangxi, Hunan, Guangxi, Chongqing, Sichuan, Yunnan, and Gansu) had the lowest values of partial efficiencies compared to the other bundles (Zhou et al., 2018). These provinces showed inefficiency in all partial efficiencies, particularly for labor and social efficiencies. Thus, it is recommended that the government increase employment opportunities and improve the household living conditions.

Bundle 3 (Ningxia) provided higher values of partial efficiencies than the average (Zhou et al., 2018), except for economic efficiency. This result may be because of the backward production capacity. Therefore, it is of vital importance for the government to provide policy and funding support, such as introducing advanced equipment and technology (Wu et al., 2019) and promoting industrial innovation.

Bundle 4 (including Hebei, Shanxi, Inner Mongolia, Jilin, Henan, Guizhou, Shaanxi, and Xinjiang) had lower values of partial efficiencies than the average, particularly for energy and environmental efficiencies (Deng et al., 2016). Shanxi, Shaanxi, and Inner Mongolia are three coal-rich regions in China. This result may be because of the excessive industrial emissions and energy production. Therefore, it is of vital importance for these provinces to adopt appropriate emission reduction measures. The government should pay more attention to pollution treatment. Only in this way can these central and western provinces bridge the gap between eliminating air pollution emissions and improving overall efficiency (Wang et al., 2019b). For these provinces with abundant resources, enterprises should improve clean production levels and enhance the management and dynamic monitoring ability of energy consumption and emissions (Xiong et al., 2019). The establishment of cross-sectoral policies should be advanced, and these policies should pay more attention to achieving the comprehensive benefits and synergies of the FEW nexus instead of maximizing the benefits of one or two of the subsystems.

Bundle 5 was characterized by the highest partial efficiency values, which demonstrated typical synergies across the FEW nexus. The provinces (including Beijing, Tianjin, Shanghai, Jiangsu, Fujian, Shandong, Guangdong, Hainan, and Qinghai) were mainly concentrated in eastern coastal regions (Cucchiella et al., 2018), with excellent performance in all aspects. These provinces can be the typical cases to enhance the FEW nexus in China. Current development strategies should be adhered. It is likely that this efficient bundle can provide some management references for other provinces.

Economic efficiency had trade-off relationships with others, indicating that provinces with higher economic benefits cannot simultaneously provide higher social and environmental benefits in the current phase. Additionally, an implicit trade-off existed between environmental protection and economic growth. As the major sectors with the largest industrial waste gas emissions in China (Yang and Li, 2018), the electric power and heating power production sectors had poor waste gas control. For China's energy sectors, reductions in resource depletion and environmental degradation should be given high priority, rather than blindly pursuing economic growth (Wang et al., 2019c). Therefore, we must focus on these key sectors and effectively improve their waste gas control efficiency to solve the severe air pollution issue that has been haunting China for several decades. To simultaneously achieve environmental benefits and resource efficiencies, policies should be focused on more investments in technological innovations towards energy conservation and emission reduction. For example, to boost the level of environmental regulation, China's current sewage charging system and regulations on cleaner production should be redesigned to be stricter (Wang et al., 2019b).

In summary, the FEW nexus can achieve high efficiency only when water, energy and food subsystems are in coupling coordination status. Only considering a single aspect but ignoring the interlinkages among these three subsystems may result in adverse consequences (Ghani et al., 2019). Therefore, policy makers should pay specific attention to managing the interaction among the subsystems and the efficiency components of the FEW nexus synergistically.

4.3. Limitations and future research

Considering the FEW nexus as a coupled system, our study focused on evaluating the performance of the whole system, while the interaction mechanism and drivers of the FEW nexus on the sectoral and regional scales were not evaluated. The external environment, the impacts of climate events and other global/local risks, and the system boundary of the FEW nexus should be further ascertained in future work. An alternative approach, such as system dynamics modeling, is recommended to clarify the above aspects of the FEW nexus. For example, system dynamics modeling can be utilized to understand the inter- and intra-interaction mechanisms among the subsystems of the FEW nexus, as it allows a comprehensive analysis of multi-sectoral and -regional systems by establishing causal feedback loops among the elements of the FEW nexus.

5. Conclusions

Assessing the spatiotemporal changes in the efficiency and coupling relationships was essential for promoting the sustainability of the FEW nexus and establishing a robust basis for synergistic development among different subsystems. Among the sub-high and high efficiency regions, 78% of the provinces were distributed in eastern and central China. Conversely, among the low efficiency regions, 86% of the provinces were distributed in western China. The coupling coordination degree of the FEW nexus in China showed downward trends during 2005–2017, with 14 provinces significantly decreasing and 5 provinces insignificantly decreasing, which accounted for approximately 63% of all provinces. These results revealed irreconcilable trade-offs among subsystems, and at the same time, these trade-offs were increasing.

To propose valuable suggestions for the sustainable use of resources, the spatial distribution and characteristics of 5 efficiency bundles were evaluated in this study. The results can provide essential information for supporting win-win or minimal trade-off solutions of the FEW nexus. (1) Bundle 1 performed well in the water, food and labor dimensions. To balance the FEW nexus, it is recommended to adjust energy-related policies in these provinces. (2) Bundle 2 was inefficient in all dimensions, particularly for labor and social efficiency. It is recommended that the government provide more employment opportunities and improve the social benefits for households. (3) A gap in economic efficiency was found in bundle 3. Policies and funding support are recommended. (4) Bundle 4 had lower values than the average, particularly in energy and environmental aspects. The government should pay more attention to pollution treatment. Finally, (5) synergies were found in bundle 5, and thus, the current development strategies should be kept.

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.

Please cite this article as: Han, D et al., Assessment on the features of coupling interaction of the food-energy-water nexus in China, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2019.119379

Acknowledgements

This study was supported by the Key Project of Science and Technology Department of Qinghai Province (Grant No. 2019-SF-A12), the Second Tibetan Plateau Scientific Expedition and Research Program (STEP) (Grant No. 2019QZKK1001), the National Natural Science Foundation of China (41971269), Fund for Creative Research Groups of the National Natural Science Foundation of China (41621061).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.119379.

References

Bennett, E.M., Peterson, G.D., Gordon, L.J., 2009. Understanding relationships among multiple ecosystem services. Ecol. Lett. 12 (12), 1394–1404.

Biggs, E.M., Bruce, E., Boruff, B., Duncan, J.M., Horsley, J., Pauli, N., McNeill, K., Neef, A., Van Ogtrop, F., Curnow, J., 2015. Sustainable development and the water–energy–food nexus: a perspective on livelihoods. Environ. Sci. Policy 54, 389–397.

Bosseboeuf, D., Chateau, B., Lapillonne, B., 1997. Cross-country comparison on energy efficiency indicators: the on-going European effort towards a common methodology. Energy Policy 25, 673–682.

Charnes, A., Cooper, W.W., Rhodes, E., 1978. Measuring the efficiency of decision making units. Eur. J. Oper. Res. 2, 429–444.

CNA, 2014. National Security and the Accelerating Risks of Climate Change. CNA Corporation, Alexandria, VA.

Conway, D., Van Garderen, E.A., Deryng, D., Dorling, S., Krueger, T., Landman, W., Lankford, B., Lebek, K., Osborn, T., Ringler, C., 2015. Climate and southern Africa's water-energy-food nexus. Nat. Clim. Chang. 5 (9), 837.

Cucchiella, F., D'Adamo, I., Gastaldi, M., Miliacca, M., 2018. Efficiency and allocation of emission allowances and energy consumption over more sustainable European economies. J. Clean. Prod. 182, 805–817.

Deng, G., Li, L., Song, Y., 2016. Provincial water use efficiency measurement and factor analysis in China: based on SBM-DEA model. Ecol. Indicat. 69, 12–18.

Deng, P., Chen, J., Chen, D., Shi, H., 2017. The evolutionary characteristics analysis of the coupling and coordination among water, energy and food: take Jiangsu Province as an example. J. Water Resour. Water Eng. 28 (6), 232–238.

Endo, A., Burnett, K., Orencio, P.M., Kumazawa, T., Wada, C.A., Ishii, A., Tsurita, I., Taniguchi, M., 2015. Methods of the water-energy-food nexus. Water 7 (10), 5806–5830.

Esir, 2013. ArcGIS 10.2 User's Guide. Esir.

Forman, R.T.T., Wu, J., 2016. Where to put the next billion people. Nat. Clim. Chang. 537, 608–611.

Forum, W.E., 2011. Water Security: the Water-Food-Energy-Climate Nexus. Island Press, Washington, DC.

Ghani, H.U., Silalertruksa, T., Gheewala, S.H., 2019. Water-energy-food nexus of bioethanol in Pakistan: a life cycle approach evaluating footprint indicators and energy performance. Sci. Total Environ. 687, 867–876.

Gilbert, R.O., 1987. Statistical Methods for Environmental Pollution Monitoring. Van Nostrand Reinhold, New York.

Gu, A., Teng, F., Lv, Z., 2016. Exploring the nexus between water saving and energy conservation: insights from industry sectorsubsystem during the 12th Five-Year Plan period in China. Renew. Sustain. Energy Rev. 59, 28–38.

Guan, W., Xu, S., 2014. Spatial patterns and coupling relations between energy efficiency and industrial structure in Liaoning Province. Acta Geograph. Sin. 69 (4), 520–530.

Hao, R.F., Yu, D.Y., 2018. Optimization schemes for grassland ecosystem services under climate change. Ecol. Indicat. 85, 1158–1169.

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

Howells, M., Hermann, S., Welsch, M., Bazilian, M., Segerström, R., Alfstad, T., Gielen, D., Rogner, H., Fischer, G., Van Velthuizen, H., 2013. Integrated analysis of climate change, land-use, energy and water strategies. Nat. Clim. Chang. 3 (7), 621.

Hussien, W.e.A., Memon, F.A., Savic, D.A., 2018. A risk-based assessment of the household water-energy-food nexus under the impact of seasonal variability. J. Clean. Prod. 171, 1275–1289.

Jiang, Y., 2015. China's water security: current status, emerging challenges and future prospects. Environ. Sci. Policy 54, 106–125.

Jiang, X., Niu, G.-Y., Yang, Z.-L., 2009. Impacts of vegetation and groundwater dynamics on warm season precipitation over the Central United States. J. Geophys. Res. Atmos. 114, D06109.

Karan, E., Asadi, S., 2018. Quantitative modeling of interconnections associated with sustainable food, energy and water (FEW) systems. J. Clean. Prod. 200, 86–99.

Karan, E., Asadi, S., Mohtar, R., Baawain, M., 2018. Towards the optimization of sustainable food-energy-water systems: a stochastic approach. J. Clean. Prod. 171, 662–674.

Khan, S., Hanjra, M.A., et al., 2009. Footprints of water and energy inputs in food production–Global perspectives. Food Policy 34 (2), 130–140.

Kuosmanen, T., Podinovski, V., 2009. Weak disposability in nonparametric production analysis: reply to Färe and Grosskopf. Am. J. Agric. Econ. 91 (2), 539–545.

Li, Y., Li, Y., Zhou, Y., Zhu, X., 2012. Investigation of a coupling model of coordination between urbanization and the environment. J. Environ. Manag. 98 (1), 127–133.

Li, G., Huang, D., Li, Y., 2016. China's input-output efficiency of water-energy-food nexus based on the data envelopment analysis (DEA) model. Sustainability 8 (9), 927.

Liao, C., 1999. Quantitaitve judgement and classification system for coordinated development of environment amd economy——a case study of the city group in the Pearl river delta. Trop. Geogr. 19 (2), 171–177.

Machell, J., Prior, K., Allan, R., Andresen, J.M., 2015. The water energy food nexus–challenges and emerging solutions. Environ. Sci.: Water Res. Technol. 1 (1), 15–16.

Mann, H.B., 1945. Nonparametric test against trend. Econometrica 13 (3), 245–259.

Namany, S., Al-Ansari, T., Govindan, R., 2019. Optimisation of the energy, water, and food nexus for food security scenarios. Comput. Chem. Eng. 129, 106513.

Obersteiner, M., Walsh, B., Frank, S., Havlík, P., Cantele, M., Liu, J., Palazzo, A., Herrero, M., Lu, Y., Mosnier, A., 2016. Assessing the land resource–food price nexus of the sustainable development goals. Sci. Adv. 2 (9) e1501499-e1501499.

Proskuryakova, L.N., Saritas, O., Sivaev, S., 2018. Global water trends and future scenarios for sustainable development: the case of Russia. J. Clean. Prod. 170, 867–879.

Scott, C.A., Kurian, M., Wescoat Jr., J.L., 2015. The Water-Energy-Food Nexus: Enhancing Adaptive Capacity to Complex Global Challenges, Governing the Nexus. Springer, pp. 15–38.

Shephard, R.W., 1970. Theory of Cost and Production Functions. Princeton University Press, Princeton.

Tian, H., Lu, C., Pan, S., Yang, J., Miao, R., 2018. Optimizing resource use efficiencies in the food–energy–water nexus for sustainable agriculture: from conceptual model to decision support system. Curr. Opin. Environ. Sustain. 33, 104–113.

Valadkhani, A., Roshdi, I., Smyth, R., 2016. A multiplicative environmental DEA approach to measure efficiency changes in the world's major polluters. Energy Econ. 54, 363–375.

Wang, J., Huang, J., Yan, T., 2013. Impacts of climate change on water and agricultural production in ten large river basins in China. J. Integr. Agric. 12 (7), 1267–1278.

Wang, Q., Li, S., He, G., Li, R., Wang, X., 2018. Evaluating sustainability of water-energy-food (WEF) nexus using an improved matter-element extension model: a case study of China. J. Clean. Prod. 202, 1097–1106.

Wang, S., Yang, K., Yuan, D., Yu, K., Su, Y., 2019a. Temporal-spatial changes about the landscape pattern of water system and their relationship with food and energy in a mega city in China. Ecol. Model. 401, 75–84.

Wang, K.-L., Miao, Z., Zhao, M.-S., Miao, C.-L., Wang, Q.-W., 2019b. China's provincial total-factor air pollution emission efficiency evaluation, dynamic evolution and influencing factors. Ecol. Indicat. 107, 105578.

Wang, X., Ding, H., Liu, L., 2019c. Eco-efficiency measurement of industrial sectors in China: a hybrid super-efficiency DEA analysis. J. Clean. Prod. 229, 53–64.

Wu, J., 2013. Landscape sustainability science: ecosystem services and human well-being in changing landscapes. Landsc. Ecol. 28, 999–1023.

Wu, K., Lu, B., Yuan, Z., 2006. The recent developments and the contribution of farmland irrigation to national grain safeness in China. J. Irrig. Drain. 25 (4), 7–10.

Wu, X., Wang, L., Zheng, H., 2019. A network effect on the decoupling of industrial waste gas emissions and industrial added value: a case study of China. J. Clean. Prod. 234, 1338–1350.

Xie, X., Zhang, T., Gu, J., Huang, Z., 2018. Water footprint assessment of coal-based fuels in China: exploring the impact of coal-based fuels development on water resources. J. Clean. Prod. 196, 604–614.

Xing, L., Xue, M., Hu, M., 2019. Dynamic simulation and assessment of the coupling coordinated degree of the economy–resource–environment system: case of Wuhan City in China. J. Environ. Manag. 230, 474–487.

Xiong, J., Chen, D., Peng, B., Deng, S., Xie, X., 2014. Spatio-temporal difference of coupling coordinated degree of ecological carrying capacity in the Dongting lake region. Sci. Geogr. Sin. 34 (9), 1108–1116.

Xiong, S., Ma, X., Ji, J., 2019. The impact of industrial structure efficiency on provincial industrial energy efficiency in China. J. Clean. Prod. 215, 952–962.

Yang, W., Li, L., 2018. Efficiency evaluation of industrial waste gas control in China: a study based on data envelopment analysis (DEA) model. J. Clean. Prod. 179, 1–11.

Yang, Z., Wei, X., 2019. The measurement and influences of China's urban total factor energy efficiency under environmental pollution: based on the game cross-efficiency DEA. J. Clean. Prod. 209, 439–450.

Zhang, Y.-H.P., 2013. Next generation biorefineries will solve the food, biofuels, and environmental trilemma in the energy–food–water nexus. Energy Sci. Eng. 1

Please cite this article as: Han, D et al., Assessment on the features of coupling interaction of the food-energy-water nexus in China, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2019.119379

(1), 27–41.

Zhang, C., Chen, X., Li, Y., Ding, W., Fu, G., 2018. Water-energy-food nexus: concepts, questions and methodologies. J. Clean. Prod. 195, 625–639.

Zhao, J., Jia, G., Tian, Y., 2018. Environmental vulnerability assessment for mainland China based on entropy method☆. Ecol. Indicat. 91, 410–422.

Zheng, X., Wang, C., Cai, W., Kummu, M., Varis, O., 2016. The vulnerability of thermoelectric power generation to water scarcity in China: current status and future scenarios for power planning and climate change. Appl. Energy 171, 444–455.

Zhou, X., Luo, R., Yao, L., Cao, S., Wang, S., Lev, B., 2018. Assessing integrated water use and wastewater treatment systems in China: a mixed network structure two-stage SBM DEA model. J. Clean. Prod. 185, 533–546.

Please cite this article as: Han, D et al., Assessment on the features of coupling interaction of the food-energy-water nexus in China, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2019.119379