



Spatiotemporal Differences and Spatial Convergence of the Water-Energy-Food-Ecology Nexus in Northwest China

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The Water-Energy-Food-Ecology (W-E-F-E) nexus is related to the realization of the goal of high-quality economic development in Northwest China. This paper analyzed the dynamic change trend, spatial evolution characteristics, and spatial convergence of identified W-E-F-E nexus in Northwest China utilizing the coupling coordination degree model, an ESDA instrument, and the spatial convergence model. The results show that: first, the W-E-F-E nexus in Northwest China presents a "V" shaped trend of decreasing first and then rising in time dimension. After a decline of 25.1% in 2002–2012, it increased by 29.7% in 2012–2017. Second, the W-E-F-E nexus in Northwest China shows positive spatial autocorrelation, and the Moran's I index of this is about 0.15. In spatial dimension, it shows a trend of high-value agglomeration around provincial capitals, and the distribution pattern is relatively stable. Thirdly, the W-E-F-E nexus in Northwest China has significant spatial convergence, that is, the W-E-F-E nexus gap between the prefectures in Northwest China is shrinking, and the convergence rate is between 2.83 and 3.16. Moreover, with the development of the economy, the rational allocation of land and labor resources, and the optimization of fiscal expenditure structure, the W-E-F-E nexus in Northwest China will converge to the same steady state level after a long period of time. In general, in the process of improving the W-E-F-E nexus in Northwest China, the heterogeneous characteristics of prefectures should be fully considered, and a trans-regional cooperative management and restriction mechanism of the W-E-F-E nexus should be explored to achieve high-quality development of the region.

Keywords: W-E-F-E nexus, spatiotemporal differences, spatial convergence, dynamic evolution, ESDA instrument

INTRODUCTION

In recent years, the most prominent non-traditional security issues have been water, energy, food, and ecological security. The W-E-F-E nexus has drawn increasing attention from the international community (Fouladi et al., 2021). As a big consumer of resources, China's water resources per capita are only 25% of the world average, and external energy dependence exceeds 20%. China feeds 20% of the world's population on 7% of its arable land, and its average

overloading rate of livestock in key natural grasslands is still higher than 10%, which indicates its contradiction between supply and demand of resources is prominent. Water resources are more abundant in the south and scarcer in the north, especially in the northwest, and energy resources are more abundant in the west and less in the east, which are obvious characteristics of the spatial distribution of resources in China. In particular, the lack of water resources and abundant energy reserves in the northwest region form a sharp contrast, and the innate ecological vulnerability also threatens food security in the northwest region. The imbalanced and unmatched spatial and temporal distribution of water, energy, food and ecological resources greatly affects the efficiency of resource flow and transformation and aggravates the imbalance between supply and demand of resources (Yuan et al., 2020). In November 2011, the German Federal Government summed up the relationship between water security, energy security, and food security as a "bond" of interdependence for the first time at the Bonn Conference. In September 2019, the Forum on Ecological Protection and High-Quality Development of the Yellow River Basin made it clear that promoting the intensive use of water resources, developing modern agriculture, and strengthening ecological and environmental protection were the current goals for ecological protection and high-quality development of the Yellow River Basin. In this context, it is of great value to incorporate ecology into the research of the coupling system. Only when water resources, energy, food, and ecology are studied as a whole, and the synergy of the four is enhanced and the overall efficiency of the system is improved, can high-quality regional development be more conducive to the realization of regional development. Therefore, how to promote the upgrading of the coupling system of water, energy, food, and ecology in Northwest China, where the contradiction between supply and demand of resources is prominent, so as to realize the intensive utilization of regional water resources, the efficient and unblocked energy channels, the security and stability of food supply, and the significant improvement of ecological environment, has become an important proposition concerning high-quality development in Northwest China and even the whole country. Moreover, it has important reference value for many countries and regions in the world with the same climate and resource distribution characteristics.

Water, energy, food, and ecology are an organic whole connected with and influencing each other (Chang et al., 2020). The exploitation of energy often causes damage to the local ecological environment. As an essential part of the ecosystem, water is an important index to measure the agricultural production potential of a region. Every link between social production and water and energy consumption will lead to environmental pollution through the global food and energy supply chain (Harris and Kennedy, 1999; Bhuiyan et al., 2010; Owen et al., 2018). However, there are very few studies that analyze it as a system, and the research on resource integration centered on a single resource not only fails to meet the demand of resource governance oriented by "multi-resource problem governance," but also fails to effectively deal with the changes

of ecological environment, economy, and population (Muller, 2015; Sun et al., 2020). Moreover, the blind emphasis on the exploitation of the potential of a single resource will inevitably have a negative impact on other resources. Threats to the security of any subsystem will trigger a chain reaction within the system, and then affect the normal operation of the system as a whole (Bryan et al., 2014; Gao and Bryan, 2017; Melo et al., 2021). Most of the existing literatures focus on the study of the water—energy—grain coupling system (Zhang et al., 2018; Niva et al., 2020), however, bringing the ecological environment into the coupling system has rarely been explored. This is mainly because modeling the water-energy-food-ecology relationship faces the challenge of how to reduce multidimensional and interdependent uncertainty (Shi et al., 2020). At present, the coupling relationship evaluation methods of composite systems mainly include the coupling coordination degree model, the PSR model, and the SD model (Yin and Wu, 2019; Liu et al., 2020; Ravar et al., 2020), but the spatial differentiation and convergence of the coupling relation of complex coefficients are seldom discussed.

Based on the prefecture-level city panel data of five provinces in Northwest China from 2002 to 2018, this paper analyzes the W-E-F-E nexus and its temporal and spatial evolution characteristics in Northwest China, and constructs a spatial convergence model to further analyze the convergence and convergence rate of the W-E-F-E nexus, aiming to provide reference for ecologically fragile areas to improve their comprehensive development advantages and achieve high-quality development. The marginal contribution of this study mainly includes two points. First, considering the importance of the ecosystem for development in Northwest China, we put the ecosystem into the analysis framework and measure the W-E-F-E nexus with the coupling coordination degree (CCD) model. Secondly, the spatial correlation is further introduced into the traditional spatial convergence model to investigate the spatial convergence of the W-E-F-E nexus in Northwest China under the condition of the spatial spillover effect and its influencing factors. Through the study of the W-E-F-E nexus in Northwest China, this paper is expected to provide important policy implications for the promotion of high-quality development in Northwest China and other ecologically fragile areas in the world.

MATERIALS AND METHODS

In this paper, the comprehensive evaluation index, coupling coordination degree, and spatial convergence rate of the W-E-F-E nexus in Northwest China are calculated and analyzed to study the spatial and temporal evolution characteristics and spatial convergence of the W-E-F-E nexus in Northwest China.

Identification of W-E-F-E Nexus

Since the units and orders of magnitude of each indicator are different, in order to eliminate the influence caused by different dimensions or orders of magnitude of different indicators, the original data is firstly processed by dimensionless processing. The

calculation formulas for positive and negative indicators are as follows:

$$x'_{it} = (x_{it} - x_{min}) / (x_{max} - x_{min}) \tag{1}$$

$$x'_{it} = (x_{max} - x_{it}) / (x_{max} - x_{min}) \tag{2}$$

where x_{it} , x'_{it} are the original value and the normalized value, respectively. After processing the original data, according to Sun and Yan (2018), a logistic curve model and coefficient of variation method are used to conduct single-factor evaluation of each subsystem in the W-E-F-E nexus. Logistic curve function is shown in **Appendix Figure A1**, and the expression is:

$$P_{it} = \frac{1}{1 + e^{a-bx'_{it}}} \tag{3}$$

where x'_{it} is the standard value after dimensionless treatment, P_{it} is development evaluation value, and a and b are constants. In this paper, the undetermined coefficient method is used to determine the parameters a and b , that is, by setting up a binary system of first order equations, when $x'_{it} = 0.01$, P_{it} is approximately 0.001, and when $x'_{it} = 0.99$, P_{it} is approximately 0.999; thus, the values of a and b are 4.595 and 9.19, respectively. Then the Logistic curve formula is adjusted as follows:

$$P_{it} = \frac{1}{1 + e^{4.595-9.19x'_{it}}} \tag{4}$$

The comprehensive evaluation index P of water resources, energy, food, and ecological subsystems is:

$$P_n = f_n(x) = \sum_{j=1}^4 (W_j P_j) \tag{5}$$

$$W_j = V_j / \sum_{j=1}^4 V_j \tag{6}$$

$$V_j = \sigma_j / \bar{x}_j \tag{7}$$

where P_j is the development evaluation value of this index, W_j is the weight of each index in the subsystem determined by the coefficient of variation method, and V_j is the coefficient of variation of the j index in the subsystem. In Equation (7), σ_j and \bar{x}_j are, respectively, the standard deviation and average value of the j index in the subsystem. Based on the comprehensive evaluation index of each subsystem, the calculation formula of the W-E-F-E nexus is finally obtained:

$$F = \alpha_1 f_1(x) + \alpha_2 f_2(x) + \alpha_3 f_3(x) + \alpha_4 f_4(x) \tag{8}$$

where F is the weighted evaluation index of water, energy, food, and the ecosystem, $F \in [0, 1]$; n is the number of subsystems, which is 4 in this paper; and $\alpha_1, \alpha_2, \alpha_3,$ and α_4 are undetermined coefficients. Considering the interconnection, mutual influence, mutual promotion and inseparable relationship characteristics among water, energy, food, and the ecology and the requirements of high-quality development, this paper believes that the target layers are equal in weight, so $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = 1/4$.

"Coordination" refers to the relationship between two or more subsystems that cooperate with each other and develop harmoniously and in a virtuous circle. According to the actual situation of 38 prefecture-level cities, regions, and county-level cities directly under the jurisdiction of autonomous regions in the five provinces of Northwest China, and based on the study of coordinated development degree model by Yang (2003), the W-E-F-E nexus evaluation model is established as follows:

$$C = \left\{ \frac{f_1(x)f_2(x)f_3(x)f_4(x)}{[(f_1(x) + f_2(x) + f_3(x) + f_4(x)) / 4]^4} \right\}^4 \tag{9}$$

where C is the coupling degree, which is determined by the magnitude of $f_n(x)$. Because $f_n(x) \in [0, 1]$, so $C \in [0, 1]$. $C = 0$ indicates that the coupling degree of the system is the minimum, and the system is in an independent state. $C = 1$ indicates that the coupling degree of the system is the maximum and the benign coupling state is reached between the systems. However, the value of the coupling degree can only represent a kind of strong and weak relationship between subsystems, but cannot reflect the level of coordinated development, so this paper introduces the CCD model in order to analyze and solve the degree of coupling coordination development of several systems. Finally, the calculation formula of the W-E-F-E nexus is obtained as follows:

$$D = \sqrt{CF} \tag{10}$$

Spatial Convergence Model

The convergence theory of neoclassical economics was originally used to investigate whether the per capita income of different countries or regions converged or diverged. In recent years, the application of this theory has been extended to the research field of resources and the environment. In this paper, the convergence analysis is helpful to examine the convergence or divergence characteristics of the W-E-F-E nexus between different cities in Northwest China, that is, whether the gap between the W-E-F-E nexus is expanding or shrinking, and analyze the W-E-F-E nexus in different prefectures and different development stages of the same prefecture in Northwest China.

Absolute β Spatial Convergence Model

The absolute β convergence of the W-E-F-E nexus means that under strict assumptions, including the same land resources, labor market, economic development, public utility security level, etc., the W-E-F-E of all cities will converge to the same level over time. The absolute β convergence model is as follows:

$$\ln D_{i,t+1} / D_{i,t} = \beta \ln D_{i,t} + \varepsilon_{i,t} \tag{11}$$

Based on the idea of the spatial convergence model of Skidmore et al. (2004) and Elhorst (2005, 2010), this paper introduces spatial factors into the basic model, and constructs the absolute β -spatial convergence model of green efficiency of water resources in Northwest China:

$$\ln(D_{i,t+1}/D_{i,t}) = \lambda W^* \ln(D_{i,t+1}/D_{i,t}) + \beta \ln D_{i,t} + \varepsilon_{i,t} \tag{12}$$

In Equation (12), $D_{i,t}$ and $D_{i,t+1}$ are the W-E-F-E nexus of the city i in the year t and $t+1$, respectively, $\ln(D_{i,t+1}/D_{i,t})$

represents the logarithmic increase of CCD in the region *i* in the year *t*; *W* is the spatial weight matrix; and λ represents the spatial autoregressive coefficient, which is used to measure the spatial spillover effect of W-E-F-E nexus growth. β is the absolute convergence coefficient. If $\beta < 0$, it means that the W-E-F-E nexus has absolute convergence, that is, the area with low W-E-F-E has a tendency to catch up with the area with high environmental efficiency; otherwise, it is the opposite. According to the principle of econometrics, the convergence coefficient has an equality relation $|\beta| = 1 - e^{-\theta T}$, where θ is the rate of convergence (or speed of convergence) and *T* is the period of sample investigation, so the rate of convergence $\theta = -\ln[(1 - |\beta|)/T]$ can be obtained.

In terms of the setting of the spatial weight matrix, considering that the economic distance weight matrix may have endogenous problems, which may lead to errors in the estimation results, this paper finally chooses the geographical contiguity weight matrix (*W_{cont}*) and the geographical distance weight matrix (*W_{dist}*) for spatial econometric analysis. Here, the queen contiguity method is used to construct the geographic contiguity weight matrix, and $W_{ii'} = 1$ is regarded as the region *i* and *i'* are adjacent, and $W_{ii'} = 0$ is regarded as non-adjacent. In addition, the geographical distance weight matrix is constructed according to the formula $W_{ii'} = 1/d_{ii'}$, and *d_{ii'}* represents the straight-line distance between two regional centers.

Conditional β Spatial Convergence Model

Different from the absolute β spatial convergence, the conditional β spatial convergence means that the urban W-E-F-E nexus converges to its own stable level over time when the characteristic differences between different prefectures are taken into account. On the basis of the absolute β spatial convergence model, the

conditional β spatial convergence model is obtained by adding some control variables:

$$\ln(D_{i,t+1}/D_{i,t}) = \lambda W^* \ln(D_{i,t+1}/D_{i,t}) + \beta \ln D_{i,t} + \alpha X_{i,t} + \varepsilon_{i,t} \tag{13}$$

In Equation (13), *X_{i,t}* represents the control variable affecting the W-E-F-E nexus and β is the conditional convergence coefficient. If β is less than zero and statistically significant, it indicates the existence of spatial conditional convergence; otherwise, there is no spatial conditional convergence. α is the estimated coefficient of the control variable, reflecting the size and direction of the influence effect of the corresponding control variable on the W-E-F-E nexus. The factors influencing the W-E-F-E nexus mainly include land resource status, labor supply, economic development level, and government fiscal expenditure. For this reason, the above factors are controlled in the estimation equation. The administrative area is used to measure land resources (area), the total population at the end of the year is used to measure labor market conditions (pop), the regional per capita GDP is used to measure economic development level (rjgdp), and the fiscal general budget expenditure is used to measure the government's control and use of social resources (fina).

Variables and Data

Evaluating the coupling coordination of water, energy, food, and the ecosystem is complicated. It is very important to select the evaluation index and grasp the structure of the index system, which should give consideration to the authenticity, systematicness, and scientificity. Based on the scientific connotation of the W-E-F-E nexus and reference to relevant literature, this paper constructs a comprehensive evaluation index system of the W-E-F-E nexus in Northwest China, which includes four subsystems and 16 specific indexes (**Table 1**).

TABLE 1 | W-E-F-E nexus evaluation index system.

The target layer	Index layer	Calculation method	Index properties
Water resources subsystem	Agricultural water consumption (billion cubic meters)	Taken from the statistics	–
	Industrial water consumption (billion cubic meters)	Taken from the statistics	–
	Domestic water consumption (billion cubic meters)	Taken from the statistics	+
	Ecological water consumption (billion cubic meters)	Taken from the statistics	+
Energy subsystem	Per capita energy consumption (tons per person)	Energy consumption/total population	–
	Energy consumption per 10,000 Yuan of industrial added value (tons/10,000 Yuan)	Total industrial energy consumption/industrial added value	–
	Total energy consumption of industries above designated size (tons of standard coal)	Taken from the statistics	–
	Investment in fixed assets in the production and supply of electricity, gas and water (10,000 Yuan)	Taken from the statistics	+
Grain subsystem	Total grain output (10,000 tons)	Taken from the statistics	+
	Oil production (10,000 tons)	Taken from the statistics	+
	Fertilizer application amount (10,000 tons)	Taken from the statistics	–
	Total sown area of crops (thousands of hectares)	Taken from the statistics	+
Ecology subsystem	Investment in landscaping (10,000 Yuan)	Taken from the statistics	+
	Park green area (ha)	Taken from the statistics	+
	Green coverage area of built-up areas (ha)	Taken from the statistics	+
	Industrial sulfur dioxide emissions (tons)	Taken from the statistics	–

Water, energy, food, and ecology are closely related to each other. First of all, water, as an important resource, not only ensures the orderly production activities of human society, but also maintains the ecological balance of nature. Therefore, four indexes of agricultural, industrial, domestic, and ecological water use are selected to measure the development status of the water resources subsystem. Secondly, energy systems provide power support for social production and development, and its development status can be measured through energy industry investment and construction, industrial energy consumption, and energy output efficiency. Therefore, this paper selects the per capita energy consumption, energy consumption per 10,000 Yuan of industrial added value, total energy consumption of industries above a designated size, and investment in fixed assets in the production and supply of electricity, gas, and water as the evaluation indexes. Then, food is the key factor to maintain the survival of human society. In this paper, the development of the grain subsystem is reflected by the input and output of grain; the total grain output and oil yield are taken as the output indexes, and the amount of chemical fertilizer and crop sown area are taken as the input indexes. Finally, the ecosystem provides a corresponding environment for production and life. The ecology subsystem is evaluated by investment in landscaping, park green area, green coverage area of built-up areas, and industrial sulfur dioxide emissions. The 16 indexes included in the above four subsystems jointly constitute the W-E-F-E nexus evaluation index system.

This paper selects the panel data of 38 prefecture-level cities, regions, and counties directly under the jurisdiction of autonomous regions in five provinces of Northwest China (Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang) from 2002 to 2018 for empirical analysis. The data are mainly from statistical yearbooks of provinces and cities, Bulletin of Water Resources Development, Statistical Bulletin of National Economic and Social Development, and EPS database; data that cannot be directly obtained are made up using the linear fitting method. In this paper, the panel data of 38 prefecture-level cities, regions, and counties directly under the jurisdiction of autonomous regions in Northwest China from 2002 to 2018 are selected as the analysis dataset. The data sources are as follows: (1) The data of green area of parks, green coverage area of built-up areas, industrial sulfur dioxide emissions, and fixed asset investment in the production and supply of electricity, gas, and water are mainly from the global statistical data/analysis platform of Economy Prediction System (EPS); (2) The data of agricultural water consumption, industrial water consumption, domestic water consumption, and ecological water consumption are mainly derived from Bulletin of Water Resources Development of each province and supplemented by the China Environmental Statistics Yearbook; and (3) The remaining data, such as total grain output, per capita energy consumption, and investment in landscaping, are mainly from the China Regional Economic Statistical Yearbook, and the missing data are supplemented by the Statistical Bulletin of National Economic and Social Development and the corresponding statistical Yearbook published by local governments.

RESULTS

W-E-F-E Nexus

Dynamic Evolution of the W-E-F-E Nexus

Comprehensive evaluation value is an overall quantitative evaluation of things or objects restricted by a variety of factors. The comprehensive evaluation value of each subsystem of water, energy, food, and ecology reflects its development status. As shown in **Figure 1**, the development of the four subsystems presents a dynamic evolution trend of alienation. First of all, the average comprehensive evaluation value of the energy system in Northwest China is the highest, which is about 0.7. In 2007–2008 especially, the comprehensive evaluation value of the energy system achieved rapid growth, reaching 12.9% and peaking at 0.79 in 2008. This may be related to the investment and construction of energy industry infrastructure by the Chinese government's economic stimulus plan under the background of economic crisis. The high comprehensive evaluation value of the energy system is closely related to the natural energy advantages in Northwest China and the policy support of the country. On the one hand, the northwest region has abundant energy reserves, which is suitable for the development of the energy industry. On the other hand, the national western development strategy and the "One Belt and One Road" initiative have ensured the energy industry in the northwest region received greater support in investment and construction, so the development level is also higher.

Secondly, it can be seen that the comprehensive evaluation values of water and food systems in Northwest China are relatively close, at about 0.5. Due to the drought and water shortage in Northwest China, production and living water are limited. The comprehensive evaluation value of the water resources system shows a fluctuating upward trend, with an average annual growth rate of only 1.3%. However, it still indicates that the intensive utilization of water resources in Northwest China is improving. In addition, the development of the grain system in Northwest China is relatively stable, and its comprehensive evaluation value fluctuates slightly around 0.52. Food production cannot be separated from water. The natural conditions in Northwest China determine that the

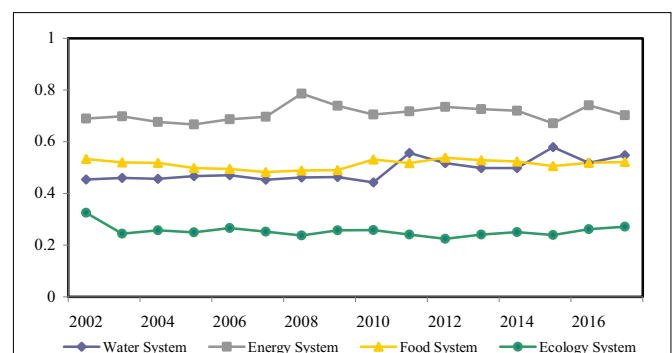


FIGURE 1 | Dynamic evolution of subsystems in Northwest China.

improvement of local agricultural production potential cannot avoid the rigid constraint of water resources. It is worth noting that in recent years, the development level of water resources system in Northwest China shows a trend of overtaking the grain system, which indicates that local awareness of water resources' protection and rational utilization has been strengthened, which is conducive to further developing the potential of food production in Northwest China and ensuring regional food security.

Finally, among the four subsystems, the development of the ecosystem in Northwest China is the worst. Except for in 2002, the comprehensive evaluation value of the ecosystem is always lower than 0.3, which is related to the local climate, terrain, and other natural conditions. However, the fragile ecological environment in Northwest China is also related to human's insufficient attention on ecological work and unreasonable development activities. Insufficient investment in ecological construction and excessive discharge of pollutants from production and living all make it impossible to effectively improve the ecological environment in Northwest China.

Based on the calculation of the comprehensive evaluation value of water, energy, food, and the ecosystem, this paper investigates the coupling and coordination status of all subsystems (as shown in **Figure 2**). As can be seen from the figure, the W-E-F-E nexus in Northwest China showed a fluctuating downward trend from 0.39 in 2002 to 0.29 in 2012, with a decrease rate of 25.6%. Among them, in 2003–2008 and 2009–2012, there was a V-shaped trend of first rising and then declining. This is because during the above period, a series of policies on water resources, energy resources, agricultural production, and ecological environment were issued in Northwest China, resulting in significant fluctuations in the W-E-F-E nexus in the short term. Each time the W-E-F-E nexus experienced a relatively large decline, there would be a relatively slow recovery process, which may be related to the local concept of development of natural resources first, protection later. Since 2012, the central government has paid more attention to coordinated development and ecological and environmental protection, and put forward a series of related policies. For example, the Measures for Examining the Implementation of

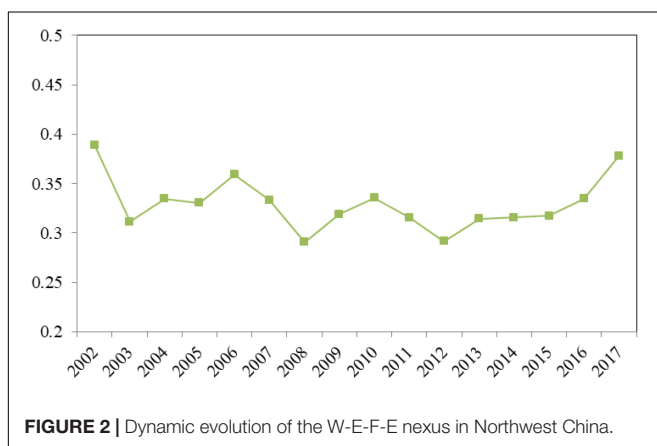
the Strictest Water Resources Management System was officially released in 2013, and the Air Pollution Prevention and Control Act was revised in 2015 and implemented in 2016. The efficient exploitation and utilization of resources, the improvement and restoration of ecology, and the coordinated development of economic development and ecological protection will be promoted to a new height. This is reflected in the fact that the W-E-F-E nexus continued to increase from 2012 to 2017, rising from 0.29 in 2012 to 0.38 in 2017, with an average annual growth rate of 5.5%, and the growth rate from 2016 to 2017 was particularly obvious, reaching 12.8%.

Regional Heterogeneity of W-E-F-E Nexus

This paper calculates the W-E-F-E nexus of prefecture-level cities, regions, and counties directly under the jurisdiction of autonomous regions in Northwest China and analyzes its spatial heterogeneity. This paper has selected an observation point of every 5 years since 2002 and visualized the W-E-F-E nexus in Northwest China in 2002, 2007, 2012, and 2017 by using GeoDA spatial data statistical software (as shown in **Figure 3**). The darker the shadow color in the figure is, the higher the CCD of the composite system in this area is, while the white color shows areas with missing data.

Through data analysis, it is found that the majority of the W-E-F-E nexus between different cities or regions in the five northwest provinces from 2002 to 2012 is lower than 0.5. It indicates that the development of the W-E-F-E nexus in Northwest China is in a state of imbalance or near imbalance, and most cities or regions have shown a decline to varying degrees, with the number of cities or regions with W-E-F-E nexus misalignment (coupling coordination score less than 0.4¹) nearly doubling from 18 in 2002 to 34 in 2012. Among these cities or regions, the W-E-F-E nexus in Yulin of Shaanxi Province, Wuwei of Gansu Province, and Zhongwei of Ningxia Province decreased most significantly, by 79.9, 58.1, and 52.2%, respectively. In many cases, economic development comes at the expense of the ecological environment, and the ecological cost of development is high. The waste of water resources, pollution, and destruction of the ecological environment restricts local food production, which in turn has a negative impact on the production of energy and gradually forms a vicious circle. In terms of spatial dimension, the W-E-F-E nexus is relatively high in other provincial capitals and nearby cities in Northwest China, except for Qinghai Province where the data is seriously missing. Such spatial agglomeration and a distribution trend are not obvious. W-E-F-E nexus is in a relatively static state in each city or region, that is, the spatial gap of W-E-F-E nexus development has not been significantly narrowed.

From 2012 to 2017, the overall trend of the W-E-F-E nexus in Northwest China was on the rise, with the nexus increasing significantly. The number of cities or regions with W-E-F-E nexus imbalance decreased from 34 in 2012 to 26 in 2017,



¹Based on the practice of Liu and Chen (2016), we use the uniform distribution function method to grade the coupling coordination value. When the coupling coordination value is less than 0.4, the W-E-F-E nexus is in a state of imbalance; when the coupling coordination value is 0.4–0.5, the W-E-F-E nexus is in a state of imbalance; when the coupling coordination value is greater than 0.5, the W-E-F-E nexus is in a state of coordination.

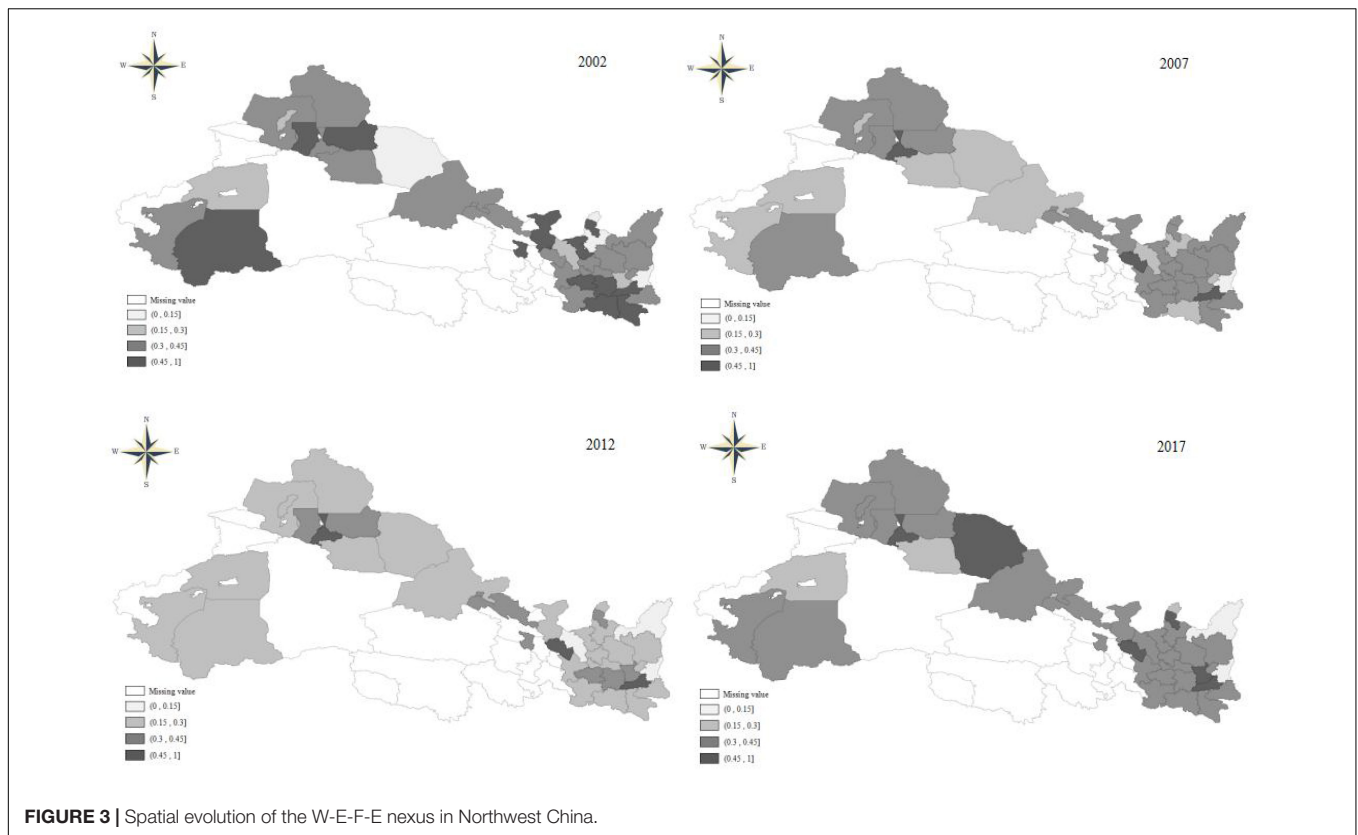


FIGURE 3 | Spatial evolution of the W-E-F-E nexus in Northwest China.

and in 32 of the 38 cities or regions covered by the data, the W-E-F-E nexus improved to varying degrees. Among these cities or regions, W-E-F-E nexus coupling coordination values of Hami of Xinjiang Province, Baiyin of Gansu Province, and Weinan of Shaanxi Province increased by 0.33, 0.29, and 0.24, respectively, and all of them got rid of the state of W-E-F-E nexus imbalance. From the perspective of spatial dimension, the W-E-F-E nexus in provincial capitals and nearby cities is still relatively high, showing an obvious trend of spatial agglomeration. Among the provincial capitals, the W-E-F-E nexus of Xi'an in Shaanxi Province reaches 0.77, realizing the moderate coordination of W-E-F-E nexus. These phenomena indicate the enhancement of the W-E-F-E nexus in Northwest China. With the strengthening of social ecological awareness and the implementation of the concept of coordinated development, the concept of development first followed by governance in the past has been gradually abandoned, replaced instead by development and governance. The concrete embodiment of the action is to strengthen the intensive use of water resources, pay attention to the development of new energy sources, develop efficient agriculture, and strengthen ecological restoration efforts. These actions have effectively improved the coordinated development of water, energy, food, and the ecosystem in Northwest China.

Spatial Correlation of the W-E-F-E Nexus

Since the W-E-F-E nexus in Northwest China shows obvious regional differences, does the coupling coordination of complex

systems in this region have a spatial correlation effect? In this paper, GeoDa is used to calculate Moran's I index of the W-E-F-E nexus in Northwest China and to test its spatial autocorrelation. Wherein, the value range of Moran's I index is [-1,1]. The closer this index is to 1, the more similar attributes are clustered together; the closer the index is to -1, the more disparate attributes are clustered together. Through calculation, it is found that the Moran's I index value of the W-E-F-E nexus in northwest China is significantly positive, indicating that there is a significant spatial autocorrelation or spatial correlation effect of the W-E-F-E nexus in Northwest China (Figure 4).

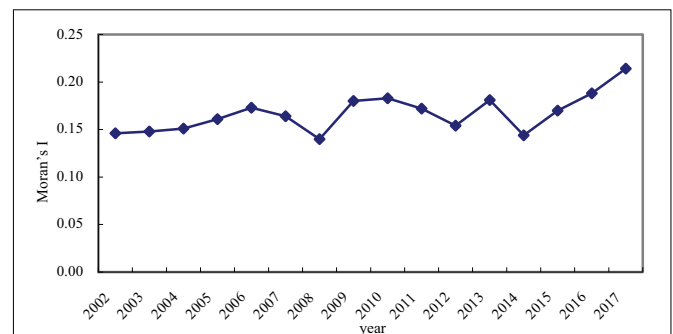


FIGURE 4 | Moran's I index of the W-E-F-E nexus in Northwest China.

Spatial Convergence Tests

Absolute and Conditional Spatial Convergence

Table 2 reports the absolute β -spatial convergence of the W-E-F-E nexus in Northwest China. From the perspective of its spatial convergence, the absolute convergence coefficient is significantly negative at the 1% level regardless of the spatial correlation effect of the W-E-F-E nexus, which means that the W-E-F-E nexus in Northwest China shows obvious absolute convergence. In other words, with the passage of time, the W-E-F-E nexus of the prefectures in Northwest China will gradually converge to a steady state level and increase along the steady state path, but the convergence is faster in developed regions than in less developed regions. In addition, after the introduction of spatial factors, it is found that the spatial spillover effect of W-E-F-E nexus growth rate is significant, and the spatial autoregression coefficients are 0.11 and 0.48, indicating that the improvement of the W-E-F-E nexus in a northwest region will also be affected by the positive spatial spillover effect from neighboring areas. After considering the spatial factors, both the absolute convergence coefficient and the convergence rate of the W-E-F-E nexus decreased slightly. Although the influence effect was not obvious, the existence of spatial spillover effect of the W-E-F-E nexus in Northwest China could not be ruled out.

The conditional β -spatial convergence estimation results of the W-E-F-E nexus in Northwest China are shown in **Table 2**. From the conditional β convergence, in the control of the administrative area, total population at year-end, per capita GDP, and general budgetary expenditures, the conditional β convergence coefficient of the W-E-F-E nexus is significantly negative at the 1% level, which indicates that the W-E-F-E nexus in Northwest China has obvious conditional convergence, that is, the growth rate of the W-E-F-E nexus in the low development stage is faster than that in the high development stage. It is worth mentioning that the existence of spatial spillover effect makes the relative convergence coefficient and convergence rate of the W-E-F-E nexus in Northwest China increase significantly, the absolute convergence coefficient rises from 0.09 to 0.31~0.32, and the convergence rate rises from 2.87

to 3.14~3.16. This also further confirms the inference that the failure to consider spatial factors in the traditional convergence studies of the W-E-F-E nexus will lead to errors in the final estimation results.

According to the estimated results of control variables, the increase of regional land area, population, and regional economic development can significantly promote the convergence of the W-E-F-E nexus in Northwest China. Among them, the regional land area and economic development status have a greater promoting effect on the overall W-E-F-E nexus convergence, while the promoting effect of population size is relatively small. Specifically, the regions with large administrative areas can take into account the development of water, energy, food, and the ecosystem, and the allocation of land use types is more flexible and reasonable, which is conducive to reducing the W-E-F-E nexus difference between regions. The regions with a higher degree of economic development provide a good economic environment for the coordinated development of social W-E-F-E nexus, which means that improving the level of economic development in Northwest China is still an important direction to promote the convergence of the W-E-F-E nexus. The reason why the convergence of the W-E-F-E nexus is less promoted in Northwest China may be due to the unreasonable structure of relevant practitioners in water, energy, food, and the ecosystem in Northwest China, which impeded the convergence of the W-E-F-E nexus. Therefore, to promote the convergence of the W-E-F-E nexus in Northwest China, we need to not only improve the population size in Northwest China, but also optimize the skill structure of the labor force.

In addition, the increase of general budget expenditure in regional finance will significantly lead to the divergence of the W-E-F-E nexus in Northwest China, but the effect is weak. This may be associated with the government's fiscal expenditure structure of the northwest region. Based on the analysis of the fiscal expenditure structure of local government in Northwest China, it was found that different local governments have different emphases in the financial expenditure on agriculture, forestry and water conservancy,

TABLE 2 | Spatial convergence estimation of W-E-F-E nexus.

	Absolute β convergence			Conditional β convergence		
	None	W_{cont}	W_{dist}	None	W_{cont}	W_{dist}
β	-0.0523*** (0.0102)	-0.0515*** (0.0101)	-0.0508*** (0.0010)	-0.0917*** (0.1030)	-0.3178*** (0.0400)	-0.3059*** (0.0409)
area				-0.0031* (0.0017)	-0.0112** (0.0049)	-0.0107** (0.0048)
pop				-0.0003*** (0.0001)	-0.0008*** (0.0002)	-0.0008*** (0.0002)
rjgdp				-0.0096** (0.0194)	-0.0168** (0.0070)	-0.0173** (0.0069)
fina				0.0002* (0.0001)	0.0003** (0.0001)	0.0003** (0.0001)
_cons	-0.0459*** (0.0120)	-0.0449*** (0.0119)	-0.0436*** (0.0117)	-0.0206 (0.0132)	-0.1008** (0.0404)	-0.0938** (0.0390)
λ		0.1131*** (0.0439)	0.4826*** (0.0869)		0.1160*** (0.0418)	0.4535*** (0.0852)
Convergence rate	2.8263	2.8255	2.8247	2.8688	3.1550	3.1377
Time	Yes	Yes	Yes	Yes	Yes	Yes
Region	Yes	Yes	Yes	Yes	Yes	Yes
R2	0.2501	0.2499	0.2555	0.2223	0.2451	0.2498

*, ** and *** indicate significant at 10%, 5% and 1% levels, respectively.

infrastructure construction, and ecological and environmental protection; as a result, the development status of water, energy, food, and the ecosystem in different regions is uneven, thus the W-E-F-E nexus presents a divergent trend. It can be seen that further optimization of the fiscal expenditure structure in Northwest China is an important problem to be solved by the current government departments.

Spatial Convergence Evolution

A longer time span can better reflect the long-term evolutionary trend of the W-E-F-E nexus in Northwest China, but the variation trend in the sample period is ignored. Although the time effect is controlled in this paper, the time period of the sample is changed to further examine the spatial convergence characteristics of the W-E-F-E nexus in Northwest China in different time periods, in order to eliminate the lasting impact of economic cycles or external impacts in the sample period. To be specific, the year 2002 is still taken as the base period T, and then the final year is re-selected according to T+4 years (to 2006), T+8 years (to 2010), and T+12 years (to 2014) in a period of 4 years. In addition, in order to reflect the coordinated development of the W-E-F-E nexus in Northwest China more objectively and accurately, the influence of related control variables should be considered to conduct the spatial convergence evolution analysis of conditional β .

Table 3 reports the convergence characteristics of the W-E-F-E nexus in Northwest China at different time periods and under different spatial weight matrices, and it is found that the long-term evolution of the W-E-F-E nexus in Northwest China is consistent with the short-term variation trend in the sample period. Among them, the W-E-F-E nexus at different time periods all showed a significant trend of spatial convergence, but the convergence rate was different. In general, the convergence rate of the W-E-F-E nexus shows a trend of increasing with the passage of time, and the convergence rate rises from 1.72~1.73 to 2.65~2.66, with an increase rate of 53.8~54.1%. The results of conditional β spatial convergence evolution analysis further confirm that there is spatial convergence of the W-E-F-E nexus in Northwest China, that is, the gap between different provinces and cities of the W-E-F-E nexus is shrinking, and shows a trend of accelerating reduction, and the concept of coordinated and sustainable development is constantly implemented and strengthened.

CONCLUSION AND DISCUSSION

In this paper, the prefectures from five provinces in Northwest China were selected as the study samples, and the CCD model was used to measure the W-E-F-E nexus. Moreover, the absolute β spatial convergence model and the conditional β spatial convergence model were established to further analyze the spatial convergence of the W-E-F-E nexus. The following findings were obtained through the study. First, the W-E-F-E nexus in Northwest China showed a V-shaped trend of decreasing first and then rising over time. From 2002 to 2012,

TABLE 3 | Spatial convergence evolution of the W-E-F-E nexus.

	T + 4		T + 8		T + 12		Full time	
	W_{cont}	W_{dist}	W_{cont}	W_{dist}	W_{cont}	W_{dist}	W_{cont}	W_{dist}
β	-0.1125*** (0.0223)	-0.1018** (0.0195)	-0.0736*** (0.0186)	-0.0674*** (0.0171)	-0.0864*** (0.0179)	-0.0847*** (0.0177)	-0.3178*** (0.0400)	-0.3059*** (0.0409)
λ	0.2878*** (0.0664)	0.7149*** (0.0896)	0.2671*** (0.0514)	0.6234*** (0.0839)	0.1383*** (0.0491)	0.4839*** (0.0970)	0.1160*** (0.0418)	0.4555*** (0.0852)
Convergence rate	1.7288	1.7168	2.2737	2.2670	2.6553	2.6535	3.1550	3.1377
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.3389	0.2975	0.1613	0.1221	0.1535	0.1612	0.2451	0.2498

*** indicates significant at 1% levels.

the overall decrease was 25.1%, and after 2012, there was an obvious rebound with an increase of 29.7%. Second, the W-E-F-E nexus in Northwest China shows positive spatial autocorrelation, and the Moran's I index of this is about 0.15. In spatial dimension, it shows a trend of high-value agglomeration around provincial capitals, and the distribution pattern is relatively stable. Thirdly, the W-E-F-E nexus in Northwest China has significant spatial convergence, that is, the W-E-F-E nexus gap between the prefectures in Northwest China is shrinking, and the convergence rate is in the level of 2.83~3.16. With the development of the economy, the rational allocation of land and labor resources, and the optimization of fiscal expenditure structure, the W-E-F-E nexus of prefectures in Northwest China will converge to the same steady state level after a long period of time.

In view of the fact that the overall level of the W-E-F-E nexus in five provinces of Northwest China is low and there is spatial convergence, we should improve the W-E-F-E nexus in ecologically fragile and underdeveloped areas from multiple aspects. First of all, in the top-level design of regional development, the central government should consider the coordinated development relationship between water, energy, food, and the ecosystem by comprehensively promoting the coordination of regional water resources protection, energy efficient utilization, food security, and ecological restoration, rather than focusing on a single issue. Secondly, we should give full credit to the leading role of the provincial capitals in the comprehensive development of Northwest China. On the premise of considering the natural conditions and the heterogeneity of industrial structure in different regions, we should extend the experience of the comprehensive development of provincial capital cities to other regions with low coupling coordination degree of the W-E-F-E nexus, so as to achieve a qualitative breakthrough in the overall comprehensive development level of Northwest China. Thirdly, according to the actual situation of different prefectures in Northwest China, we should formulate targeted measures to make up for the shortcomings in water, energy, food, and ecology, and promote the coordinated development of the W-E-F-E nexus. For prefectures with a high level of coordinated development, we should optimize their industrial layout according to their own resource endowment, carry out technological transformation and upgrading of high-energy

consumption and high-pollution enterprises, and strengthen the development of green and environmental protection industries. For prefectures with a low level of coordinated development, the research and development of agricultural water-saving technologies should be strengthened, efficient water-saving irrigation and wastewater recycling should be promoted, and the development of new energy projects with low energy consumption and low pollution should be encouraged. Finally, we should pay attention to the optimization of labor force, land use, and government financial expenditure structure in Northwest China, promote the coordinated development of the local W-E-F-E nexus, and improve the quality of economic development.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

MW: conceptualization, writing—original draft. Y-FZ: methodology, data curation. S-WG: software, visualization. C-YN: supervision, writing—review and editing. All authors contributed to the article and approved the submitted version.

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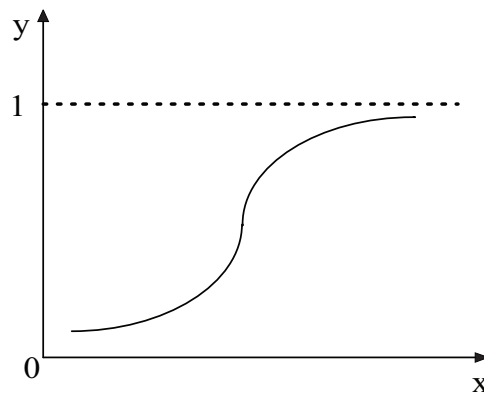
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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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APPENDIX**FIGURE A1** | Logistic curve.