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Multi-dimensional dynamic spatio-temporal evolution of the green development efficiency of water-energy-food in China

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ABSTRACT

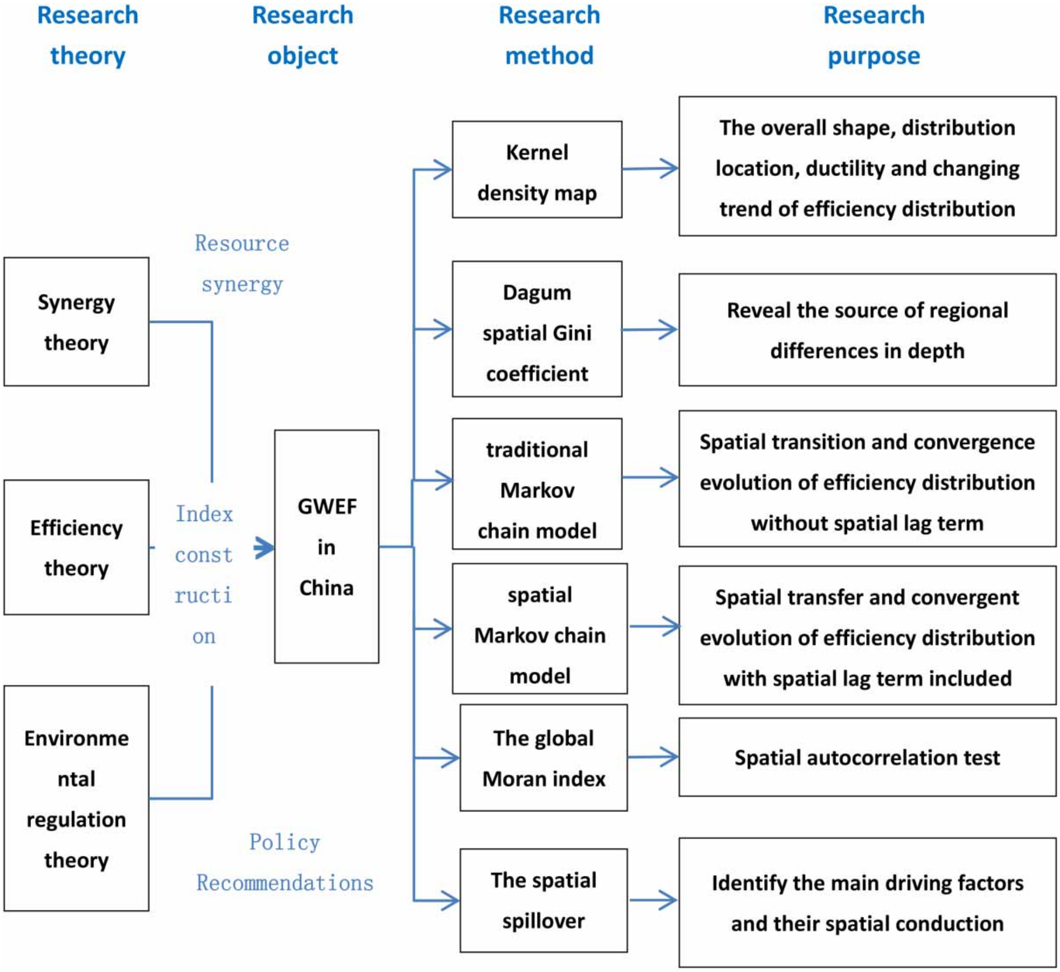
This paper constructs a green development efficiency index framework of water-energy-food in China, and uses the Super-EBM model to measure it more accurately and scientifically. The existing studies on water-energy-food efficiency lack the analysis of regional differential decomposition and spatial state transition. In this paper, two kinds of models are used for complementary analysis. One is kernel density map, Dagum spatial Gini coefficient decomposition and traditional Markov chain, which does not contain spatial factors. The other is the global Moran index, spatial Markov chain and spatial spillover effect, including spatial factors. The spatio-temporal dynamic evolution of the green development efficiency of water-energy-food (GWEF) in China is compared from the perspective of national, regional and provincial dimensions. The conclusion is more scientific and comprehensive, which is conducive to the green collaborative development among water-energy-food, economy and environment in China. The study found that GWEF had a lot of room for improvement. The overall spatial difference was mainly derived from the regional difference. GWEF had a significant positive spatial autocorrelation. The development of GWEF maintained the convergence characteristics of clubs. The spatial spillover effect of the main influencing factors was studied.

Key words: Green development efficiency, Policy drivers, Spatial effect, Super-EBM, Water-energy-food

HIGHLIGHTS

- This paper adopts two categories of models.
- One is kernel density map, Dagum spatial Gini coefficient decomposition and traditional Markov chain, which does not contain spatial factors.
- The other is global Moran index, spatial Markov chain and spatial spillover effect, including spatial factors.
- The spatio-temporal dynamic evolution of GWEF in China was compared from national, regional and provincial dimensions.

GRAPHICAL ABSTRACT



INTRODUCTION

In 2011, the World Economic Forum released the Global Risk Report, which put forward the concept of 'water-energy-food' risk for the first time and regarded it as one of the three important risk groups. In recent years, people in all regions of the world are facing more and more severe survival crises: excessive population growth, excessive consumption of resources and serious damage to the ecological environment. The interdependence and contradictions among regional water-energy-food has serious impacts on the world economy and environment. The deterioration of any resource system will have a transmission effect on other regional resources, from a region, industry or department to the whole country and even the whole world, becoming a global security problem. On the other hand, with the implementation of the concept of 'green development' in the world, people are increasingly aware of the importance of maintaining the ecological environment and ensuring the harmonious development of the environment and economy for the sustainable development of human society. From the point of view of the core values of the green development concept, green development needs to fully consider the constraints of ecological environment capacity and resource carrying capacity, and take reasonable allocation of environmental resources as an important means of harmonious coexistence between human society and nature. The coordinated development of water-energy-food is complementary to the concept of green development.

From the perspective of systematic analysis, the green development efficiency of water-energy-food (GWEF) in China includes three important resources and economic and environmental factors, which interact with each other. Based on the differences in resource endowment and economic development conditions in different regions of China, the efficiency development of each region is affected. In this paper, a green development efficiency index framework of water-energy-food in China is constructed, which considers various inputs and outputs from the perspective of green development, and the Super-EBM model is used to measure it more accurately and scientifically. Based on three basic theories, namely synergy theory, efficiency theory and environmental regulation theory, this paper focuses on the research object of 'green development efficiency of water-energy-food in China' and follows the logical thinking of 'theoretical analysis – index construction – evolution law – policy suggestions'. The main problems to be solved include: what is the overall development level of the GWEF in China, whether the regional distribution of efficiency is reasonable, what are the main sources of efficiency differences between regions, what is the spatial transfer trend of efficiency distribution and what are the main influencing factors of efficiency. The research content of this paper is of great practical significance to promote the GWEF and the coordinated spatial development of various resources in China.

At present, relevant research at home and abroad focuses on the following aspects.

One important aspect was measuring the complexity of the water-energy-food nexus. Representative ones, such as Dargin *et al.* (2019), used eight criteria to evaluate the complexity indices of the three and determine appropriate measurement tools. Li *et al.* (2019) explained the bond relationship by establishing the ISM hierarchy through factor identification and analysis. Zheng *et al.* (2019) adopted a three-stage data envelopment analysis (DEA) model evaluation method to discuss the relationship among the three from the perspective of agricultural production efficiency. Sadegh *et al.* (2020) proposed an interactive analysis toolbox to study the interdependence among the three. Mansour *et al.* (2022) used the multi-criteria approach as an assessment tool for the water-energy-food bond and conducted a case study. Hao & Sun (2022) conducted a correlation analysis on the network structure characteristics of the efficiency of the WEF bonding system in China through the social network analysis (SNA) method. Li *et al.* (2023) built a comprehensive index system from three dimensions of reliability (Ra), coordination (C) and elasticity (Rs), and used the Copula method to calculate the water-energy-food coupling security risk. Some scholars (Opejin *et al.*, 2020) summarized this kind of research. Furthermore, scholars (Schlör *et al.*, 2018; Daher *et al.*, 2019; Momblanch *et al.*, 2019; Lu *et al.*, 2021; Wu *et al.*, 2021) conducted cross-regional studies on the relationships among the three types of resources and found that there were differences in the interdependence and resource management modes of the three types of resources in different regions.

Another important aspect was to find the driving factors and optimization methods of the three types of resource ties. Al-Saidi & Elagib (2017) found three important drivers of bond relations: the increase in resource interconnection, resource crisis and policy failure. Helmstedt *et al.* (2018) found solutions for the systematic management of three types of resources: solving the problem of time and space separation at multiple scales, closing the resource cycle and creating actionable information. Toboso-Chavero *et al.* (2019) developed the roof Mosaic method to optimize the relationship between water resources, energy and food. Chamas *et al.* (2021) proposed an optimization model of resource management and allocation among water, energy and food at a regional scale. Almulla *et al.* (2022) found that climate change, over-extraction of groundwater and heavy use of fossil fuels had exacerbated water shortages in the Souss-Massa basin, and an integrated strategy was needed to stimulate contributions from different resource sectors. Wang & Sun (2022) found that land factors had an important impact on the water-energy-food system of the Beijing-Tianjin-Hebei city cluster in China.

With the promotion of the concept of green development, scholars began to focus on the interaction of three types of resources with the environment and economy. Yue & Guo (2021) proposed a new optimization model of the water-energy-food-environment relationship for sustainable agricultural development, balancing the trade-offs among socio-economic, resource and environmental issues. Zaman *et al.* (2017) tested the non-linear relationship between water, energy, food resources and air pollutants. Biggs *et al.* (2015) proposed the concept and framework of environmental livelihood security to test the relationship between water, energy, food and other natural resource systems and environmental security. Cansino-Loeza & Ponce-Ortega (2018) used the multi-objective analysis method to mathematically plan freshwater consumption, greenhouse gas emissions and comprehensive system costs as objective functions, so as to determine the optimal and sustainable allocation of resources.

Through literature analysis, it was found that although the international research on the relationship between water-energy-food and its driving factors was relatively mature, the research on the GWEF in China was relatively scarce. Efficiency measurement tools were also limited to traditional models. In terms of research methods, most of the existing studies tested the evolution trend of GWEF through convergence methods such as coefficient of variation and Theil index, the data processing method was relatively single, and the dynamic spatio-temporal evolution trend could not be explained from the spatial dimension.

The main innovations of this paper are as follows:

First of all, existing studies on the efficiency measurement of water-energy-food in China often only include one or several pollutants in the setting of environmental factors, but fail to fully consider the five important components of industrial pollutants. The five important industrial pollutants have a very important impact on the economic environment. Therefore, we construct a green development efficiency index framework for water, energy and food in China, which considers multiple inputs and outputs from the perspective of green development. We also consider the relationship between resources (water-energy-food), economy and environment (five important industrial pollutants). Total water consumption, energy input, intermediate consumption of agriculture, forestry, husbandry and fishery, investment in fixed assets, and employment at the end of the year are taken as input variables. Five important industrial pollutants, including carbon dioxide, sulfur dioxide, smoke (powder) dust, waste water discharge and industrial solid waste production, are also included in the adverse output. Gross regional product is taken as expected output. The GWEF in China is analyzed from three dimensions: national, regional and provincial. It can more comprehensively reflect the multi-level status of the GWEF in China.

Secondly, the traditional efficiency measurement model has obvious shortcomings. For example, the pure technical efficiency model (BCC), A. Charnes, W. W. Cooper & E. Rhodes data envelope analysis (CCR), etc., do not contain non-expected output indicators. However, other efficiency models often only reflect radial distance or non-radial distance, and cannot combine the two important types of distance. The measurement results are unscientific and biased. To solve these defects, this paper uses the hybrid distance model (EBM) proposed by Tone & Tsutsui (2010), which includes both radial and non-radial distances. The EBM model better preserves the original proportion of the front projection value and solves the problem of dimensionality difference of input–output factors, which can measure the green development efficiency of decision making units (DMUs) more scientifically and effectively. Furthermore, this paper combines the EBM model with the super-efficiency model to obtain the Super-EBM model. It can combine the advantages of the two types of models and include the non-expected output variable, which can more accurately distinguish the frontier efficiency whose efficiency value is greater than 1. In recent years, the effectiveness of this model in measuring the efficiency of green development has been proven (Sun *et al.*, 2020; Chengyu *et al.*, 2022). In this paper, the Super-EBM model is used for the first time to measure the efficiency of green development of water-energy-food in China, which effectively improves the science and accuracy of efficiency measurement.

In addition, there are obvious shortcomings in spatial Markov chain analysis in most literature. Existing research is often limited to using spatial and geographical weight matrix to reflect the spatial transfer state of research objects. Using geographical location to represent the spatial connection and intensity of the research object only reflects the spatial influence characterized by geographical location but lacks the consideration of the economic significance of the spatial connection of the research object. In this paper, the asymmetric economic and geographic spatial weight matrix is scientifically and innovatively taken as the spatial weight matrix and applied to the spatial Markov chain model containing spatial factors, which can simultaneously consider the effects of geographical location factors and economic factors on the spatial transfer of GWEF.

Finally, the quantitative analysis of the dynamic evolution of GWEF distribution in China has obvious shortcomings, and there is no application of the Dagum spatial Gini coefficient decomposition method and spatial Markov chain model. The existing research could not reflect the decomposition and spatial transfer state of the efficiency differences of the research objects in different regions. Based on the classical kernel density map and Moreland index measurement, this paper adds the Dagum spatial Gini coefficient decomposition method to decompose and analyze the overall differences and contribution rates, inter-regional differences and intra-regional differences of GWEF in China, which can further reveal the sources of regional differences. In addition, the spatial Markov chain model is used to further study the spatial transfer and convergence evolution trend of GWEF in China within and between regions, which can analyze the dynamic evolution law of efficiency distribution and make up for the lack of this research. This paper provides a multi-dimensional and comprehensive perspective to study the spatio-temporal evolution trend of GWEF in China, and puts forward multi-angle policy suggestions based on it, which is beneficial to comprehensively understand the development law of GWEF in China. It also promotes the optimization of the overall spatial pattern of GWEF in China, and achieves the cross-regional collaborative improvement of efficiency.

MATERIALS AND METHODS

Theoretical analysis

Based on three basic theories, namely synergy theory, efficiency theory and environmental regulation theory, this paper focuses on the research object of ‘green development efficiency of water-energy-food in China’ and follows the logical thinking of ‘theoretical analysis – index construction – evolution law – policy suggestions’.

The three basic theories of this paper include synergy theory, efficiency theory and environmental regulation theory, each of which is closely related to the research object.

Synergy theory

Synergy theory, also known as synergetic theory, is an important part of systems theory. In recent years, it has developed on the common basis of various cross-disciplines. Its main function is to discover the development law of the system from chaos to order of various economic research objects. The object of economic research has gradually evolved from the traditional structure to the new structure, in which all kinds of resources can play more economies of scale through the synergistic effect. It can reduce the cost and improve the efficiency of the whole system.

The GWEF includes three kinds of natural resources, economic and environmental factors, which is a comprehensive system, involving the systematic management of resources of various government departments. It is necessary for all kinds of resources and economic and environmental management departments to break the management barriers between each other, form new departments to cooperate, formulate reasonable policies and promote the synergistic effect of all kinds of resources with the economy and environment. When saving the use of various resources, we should actively improve the level of technological innovation, promote the improvement of economic benefits and the reduction of environmental pollutants, and ultimately bring about the overall improvement of the green development efficiency of the whole water-energy-food system.

Efficiency theory

Efficiency theory is a core theory in management. It was originally used to measure the labor capacity of employees in an enterprise, that is, the output in a given time. Combined with the idea of optimization, efficiency refers to the enterprise's ability to achieve the maximum output under the condition of specific time and specific input factors, or to achieve the minimum total input factors under specific output, that is, to achieve the Pareto optimal production.

The GWEF refers to the total amount of water resources, energy and food consumed relative to specific economic output and environmental negative output. The efficiency value is represented by the ratio of optimal resource input to real resource input on the front plane of the production function. Water resources, energy and food are three key material resources essential to the development of social economy. In the process of exploitation and utilization of all kinds of resources, a lot of economic and environmental problems will be involved. All the links of resource exploitation, production and processing, conversion, sales, circulation and recycling contain rich laws of economic development, and all kinds of environmental pollutants will also play an important role in people's living environment.

Environmental regulation theory

Environmental regulation is the regulation of environmental issues by relevant government departments. It is a kind of social regulation category. Environmental regulation aims to protect the environment and improve the public environmental quality through some measures, including reasonable control of various ecological resources and comprehensive treatment of various environmental pollutants produced in the production processes of enterprises. Environmental regulation is an important means to correct system failure. Its main contents include clearly defining the enterprise ownership relationship of environmental resources to make them exclusive, so as to avoid the excessive use or inefficient use of environmental resources by these productive enterprises. In the transaction of environmental rights and interests of enterprises, scientific pricing is needed to internalize the externalities of environmental pollution, awaken the green consciousness of enterprises and promote their comprehensive competitiveness. Enterprise environmental regulation can also control enterprise behavior by setting production technology standards, environmental emission standards and other indicators and corresponding reward and punishment rules. On the one hand, it increases the environmental cost burden of enterprises and requires them to 'follow the cost principle'; on the other hand, it encourages enterprises to increase research and development efforts, improve comprehensive production efficiency through technological innovation, and play the 'innovation compensation role'.

During production and processing, enterprises use all kinds of natural resources including water, energy and food, and bring considerable economic benefits. However, a large number of environmental pollutants are produced in the production process, mainly including industrial wastewater discharge, air pollutant discharge, toxic and harmful industrial waste and noise pollution, etc., which has a strong negative economic externality. If not regulated, the emission of these environmental pollutants will have a bad impact on the whole social environment and can hardly be converted into private costs of enterprises. By studying the spatio-temporal dynamic evolution of the GWEF in China, this paper provides policy suggestions for the government to set an example to drive the surrounding areas, coordinate the governance of various competent departments, and coordinate the development between regions in making environmental regulation policies.

Study design

This paper constructs a green development efficiency index framework of water-energy-food in China, which considers various inputs and outputs from the perspective of green development, and uses the Super-EBM model to measure it more accurately and scientifically.

The existing studies on water-energy-food efficiency lack the analysis of regional difference decomposition and spatial state transition. In this paper, two kinds of models are used for complementary analysis. One is kernel density map, Dagum spatial Gini coefficient decomposition and traditional Markov chain, which does not include spatial factors. The other is global Moran index, spatial Markov chain and spatial spillover effect, which includes spatial factors. By comparing the spatio-temporal dynamic evolution law of the GWEF in China from a nationwide-region-province multi-dimension, the conclusions and suggestions are more scientific and comprehensive, which is conducive to the green coordinated development of water, energy, food, economy and environment in China.

Various research methods have different functions, among which:

The kernel density map is a non-parametric estimation method. Kernel density estimation can describe the distribution state of the research object by using a continuous density function curve, and analyze the overall form, distribution position, ductility and change trend of the distribution of GWEF in China.

The Dagum spatial Gini coefficient decomposition method is used to decompose and analyze the overall differences and contribution rates, inter-regional differences and intra-regional differences of GWEF in China, which can reveal the sources of regional differences more deeply.

The traditional Markov chain model and spatial Markov chain model analyze the spatial transfer and convergence evolution trend of the distribution of GWEF within and between regions by constructing the Markov transfer probability matrix. The difference between the two is that traditional Markov chains do not contain spatial lag terms, while spatial Markov chains do contain spatial lag terms.

The global Moran index is a spatial autocorrelation test for GWEF.

The spatial spillover effect is helpful to identify the main driving factors of GWEF and its spatial conduction.

The research design framework of this paper is shown in Figure 1.

Super-EBM model

The DEA model is a mainstream non-parametric method used to analyze unit efficiency (or performance) evaluation. Its basic principle is to determine the input or output variables of DMU, determine the relatively effective production frontier with the help of linear programming and statistical data, and then judge the effectiveness of efficiency by comparing the degree of DMU deviating from the production frontier. Traditional DEA models include BCC, CCR (radial model), SBM (non-radial model), etc. The defects of these models are very obvious. When reporting efficiency scores, the radial DEA model only considers the proportional changes of input or output variables, but ignores the non-radial relaxation variables, and lacks consideration of the non-expected output indexes. Although the non-radial DEA model adds non-expected output indexes and non-radial relaxation variables, it ignores the radial proportional relationship between the original input or output values and the target values.

In order to overcome such obvious defects, Tone & Tsutsui (2010) proposed a comprehensive DEA model combining radial and non-radial distances, called epsilon-based measure (EBM), using epsilon parameters. The

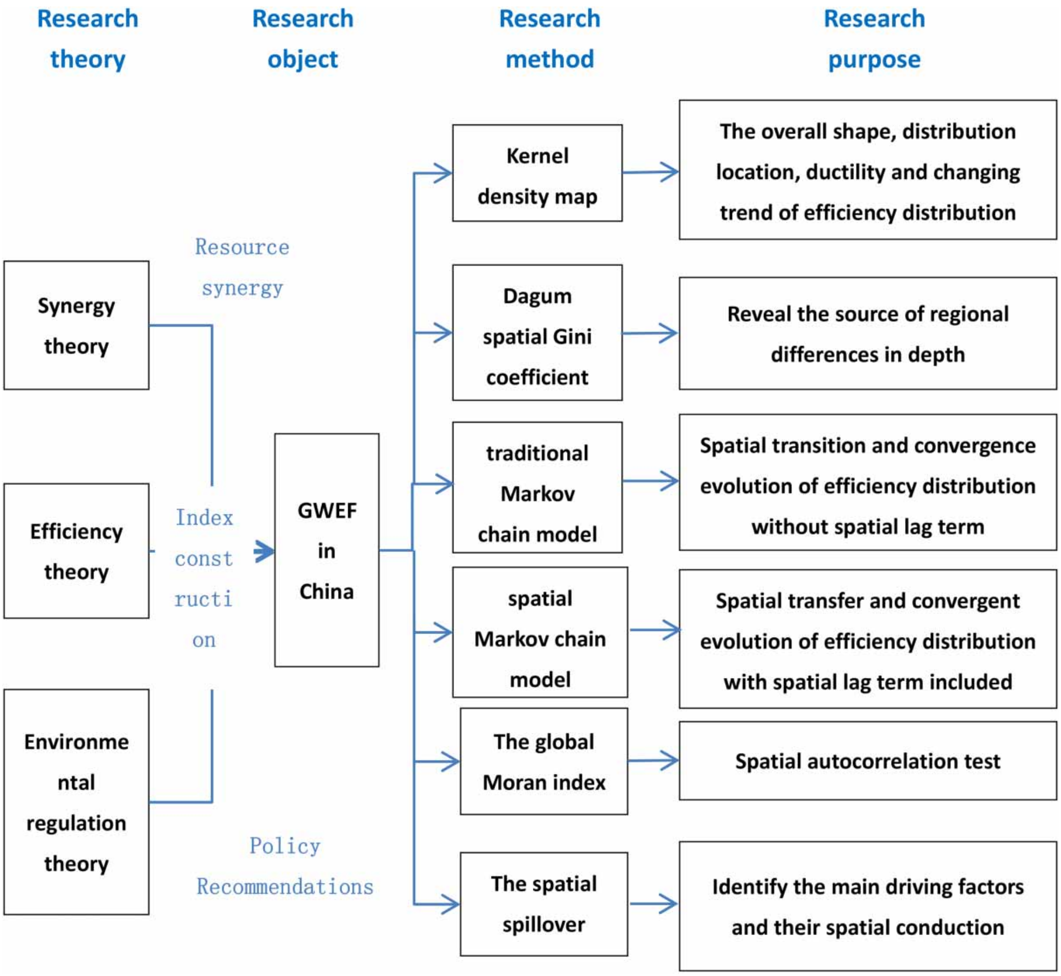


Fig. 1 | Research design framework of this paper.

EBM model not only considers the radial variation relationship of the original variables but also considers the non-radial relaxation variables, and brings the unexpected output variables into the design of the model.

Assuming that there are N DMU, the EBM model defined from the input orientation is generally defined as follows:

$$\gamma^{*} = \min \theta - \varepsilon \sum_{i=1}^{m} \frac{\omega_i^{-} s_i^{-}}{x_0} \tag{1}$$

$$\text{s.t.} \quad \begin{array}{c} X\lambda - \theta x_k + s^{-} = 0 \\ Y\lambda \geq y_k \\ \lambda \geq 0,\ s^{-} \geq 0 \end{array}$$

In Formula (1), γ^* is the optimal solution of the green development efficiency value of water-energy-food to be measured, θ is the radial efficiency value, X, Y, λ and s^- respectively, represent the input, output, weight coefficient and input relaxation vector. The model has $m+1$ parameters. ω_i^- represents the relative importance of each input index, and ε is the key parameter determining the importance of the non-radial part of the calculation of γ^* efficiency value. The value range is [0,1]. 0 is equivalent to the radial model, and 1 is equivalent to the SBM model. At this time, the efficiency value obtained by the EBM model is at most 1, and multiple DMUs will be rated as effective. The efficiency of these effective DMUs cannot be further distinguished. To solve this problem, Andersen *et al.* proposed a super-efficiency model to further distinguish effective DMUs. The key of the super-efficiency model is to remove the evaluated DMU from the reference set, so that the efficiency value of the evaluated DMU is obtained by referring to the frontier formed by other DMU. In this way, the efficiency value obtained will generally exceed 1, which is called the super-efficiency value, and effective DMU can be further compared.

The Super-EBM model with non-expected variables is defined as follows:

$$r^* = \min \frac{\theta - \varepsilon^- \sum_{i=1}^{m} \frac{\omega_i^- s_i^-}{x_{i0}}}{\varphi + \varepsilon^+ \left(\sum_{r=1}^{s} \frac{\omega_r^+ s_r^+}{y_{r0}} + \sum_{p=1}^{q} \frac{\omega_p^{u-} s_p^{u-}}{u_{p0}} \right)} \tag{2}$$

$$\text{s.t.} \ \sum_{j=1}^{n} x_{ij}\lambda_j + s_i^- = \theta x_{i0}$$

$$\sum_{j=1}^{n} y_{rj}\lambda_j - s_r^+ = \phi y_{r0}$$

$$\sum_{j=1}^{n} u_{pj}\lambda_j + s_p^- = \phi u_{p0}$$

$$\lambda_j \geq 0, s_i^-, s_r^+, s_p^- \geq 0$$

In formula (2), $i = 1, 2, \ldots, m; r = 1, 2, \ldots, s; p = 1, 2, \ldots, q$. x_{i0}, y_{r0}, u_{p0} represent the input, expected output and unexpected output of DMU0, respectively. s_i^-, s_r^+, s_p^{u-} represent input relaxation, expected output relaxation and undesirable output relaxation, respectively. ω_i^-, ω_r^+, ω_p^{u-} represent the relative importance of each input index, expected output and non-expected output, respectively. Other symbols have the same meanings as formula (1).

In this paper, the advantages of the EBM model and the super-efficiency model are combined and integrated into the Super-EBM model. In the process of measuring the GWEF, each province is regarded as a DMU unit. For input indicators (total water, energy, the intermediate consumption of agriculture, forestry, animal husbandry and fishery, investment in fixed assets, year-end employment), the unexpected output (a composite pollution index measured by five environmental pollutants) and the expected output index (economic development level) are equally weighted. Further differentiation of frontier efficiency with an efficiency value greater than 1 can more scientifically and accurately evaluate GWEF.

Spatial Markov chains

The Markov chain method mainly analyzes the dynamic transition trend of the GWEF distribution over time by constructing the Markov transition probability matrix.

Markov chain divides the distribution of the GWEF into N types, and the transfer of elements in the transfer matrix is only related to the state of the previous phase. Markov chain can reveal the probability P_{ij} that the GWEF in a certain region belongs to type i in t year, but shifts to another type j in $t+1$ year.

The spatial Markov chain is a method combining 'spatial lag term' with the traditional Markov chain. The spatial Markov transfer probability matrix is to first set the spatial lag type of each space element in t years as n, and transform the traditional $n \times n$ Order Markov transfer probability matrix into $n \times n \times n$ conditional transfer probability matrix $A_1, A_2, \ldots A_n$.

For the NTH conditional matrix, $P_{ij}(n)$ refers to the one-step spatial transfer probability that the spatial unit belongs to type i in the year t and shifts to the new type j in the year $t+1$ under the background of n-type spatial lag term. The main diagonal of the spatial Markov transfer probability matrix reflects the probability that the GWEF will remain unchanged to a certain extent under the influence of adjacent regions. The larger the value is, the higher its stability will be. Elements on non-diagonal lines reflect the probability of transfer between different levels in the local area under the influence of adjacent areas. It represents the probability of an 'up shift' or 'down shift' between different types. Thus, the influence of the distribution of water-energy-food green development efficiency on the transition probability of water-energy-food green development efficiency in neighboring areas can be analyzed.

The matrix expression of the spatial Markov chain is as follows:

$$\begin{bmatrix} A_{1,1|1} & \cdots & A_{1,n|1} \\ \vdots & \ddots & \vdots \\ A_{n,1|1} & \cdots & A_{n,n|11} \end{bmatrix}_{n\times n} \cdots \begin{bmatrix} A_{1,1|\mathrm{n}} & \cdots & A_{1,n|n} \\ \vdots & \ddots & \vdots \\ A_{n,1|n} & \cdots & A_{n,n|n} \end{bmatrix}_{n\times n} \tag{3}$$

Spatial-driven analysis model

Consider that the driving mechanism of the GWEF is based on the overall consideration of economic development, social activities and ecological environment. Referring to relevant literature (Yuan *et al.*, 2019), seven factors were selected as explanatory variables: industrial structure (IS), population density (PD), urbanization rate (UR), level of opening to the outside world (OP), forest coverage rate (FC), the innovation input level (II) and energy consumption per unit GDP (GE) to construct spatial driving analysis model of the GWEF.

Firstly, Moran's I test is used to measure the spatial correlation of GWEF. After Moran's I test is passed, the spatial econometric model can be used to study the spatial effect of GWEF. The spatial econometric models mainly include the spatial Dubin model, spatial error model and spatial lag model. In this paper, the LM test, LR test and Hausman test are used to find the suitable model to be the fixed-effect spatial lag model. After adjustment, the spatial lag model is set as follows:

$$\begin{aligned} \mathrm{GWEF}_{it} = a + \rho W_{it}\mathrm{GWEF}_{it} + \beta_1 \ln(IS_{it}) + \beta_2 \ln(PD_{it}) + \beta_3 \ln(UR_{it}) + \\ \beta_4 \ln(OP_{it}) + \beta_5 \ln(FC_{it}) + \beta_6 \ln(II_{it}) + \beta_7 \ln(GE_{it}) + \mu_i + \lambda_t + \varepsilon_{it} \end{aligned} \tag{4}$$

In the formula, subscript i represents province and t represents the year. W_{it} is the geo-economic weight matrix. β_1, β_2, β_3, β_4, β_5, β_6, β_7 are the parameter vectors to be estimated. $W_{it}\,\mathrm{GWEF}_{it}$ represents the spatial lag term of the coupling coordination degree of the explained variable, and represents the spatial interaction between the explained variable GWEF and the explained variable GWEF in the adjacent area. a is the constant term, ρ is the spatial autoregressive coefficient. μ_i and λ_t are individual and period fixed-effect capture terms, respectively. ε_{it} is the random disturbance term.

Data sources

Based on the availability of samples and the reliability of data quality, 30 provinces in China from 2005 to 2019 were selected as research samples, taking into account the sample situation at three levels (national level, regional level and provincial level). Due to the lack of data in Tibet, Hong Kong, Macao and Taiwan, the four regions are not included in the sample.

The explained variable is the GWEF, which is measured by the Super-EBM model. Both expected and unexpected outputs are considered. Its components refer to the research of Han *et al.* (2020). The specific settings are shown in Table 1. The input–output indicators and explanatory variables (Table 2) of the GWEF mainly come from *China Statistical Yearbook*, *China Urban Statistical Yearbook*, *China Energy Statistical Yearbook*, *Statistical Yearbook of Chinese Urban Construction* and national data website from 2006 to 2020. A small number of missing parts were supplemented by the interpolation method, and all data involving amount were subtracted with the GDP deflator of each province in 2000.

EMPIRICAL ANALYSIS

Change trend at the national level

The Super-EBM model was used to measure the GWEF at three levels (national level, regional level and provincial level) in China from 2005 to 2019. At the same time, R software and STATA software were used to draw the spatial distribution diagram (Figure 2) of EBM values of GWEF in the main years, respectively.

Table 1 | Input–output index construction of the green development efficiency of water-energy-food.

Category	Level 1 indicators	Level 2 indicators	Unit	Data source
Input indicators	Water consumption	The total water	Billion cubic meters	*China Statistical Yearbook*
	Energy consumption	The energy input	Tons of standard coal	*China Energy Statistical Yearbook*
	Food consumption	Intermediate consumption of agriculture, forestry, husbandry and fishery	One hundred million yuan	*China Statistical Yearbook*
	Capital input	Investment in fixed assets	One hundred million yuan	*China Statistical Yearbook*
	Labor input	Year-end employment	Ten thousand people	*China Statistical Yearbook*
Output indicators	Composite pollution index (Undesired output)	Carbon dioxide emissions	Ten thousand tons of	The IPCC method to calculate
		Sulfur dioxide emissions	Tons of	*Statistical Yearbook of Chinese Cities*
		Smoke (powder) dust emission	Tons of	*Statistical Yearbook of Chinese Cities*
		Waste water discharge	Ten thousand tons of	*Statistical Yearbook of Chinese Cities*
		Production of industrial solid waste	Ten thousand tons of	*China Statistical Yearbook*
	Level of economic development (Expected output)	Gross regional product	One hundred million yuan	*Statistical Yearbook of Chinese Cities*

Table 2 | Description of main variables.

Variable types	Variable name	Code	Instructions	Data source
Explained variable	Industry single factor energy efficiency	GWEF	Table 1	*China Statistical Yearbook*
Explanatory variables	Industrial structure	IS	GDP of secondary industry/Total GDP	*Statistical Yearbook of Chinese cities*
	Population density	PD	Population/Land area	*China Statistical Yearbook*
	Urbanization rate	UR	Urban population/Total population	*China Statistical Yearbook*
	Level of opening up	OP	Foreign direct investment/Total investment	*China Statistical Yearbook*
	Forest coverage	FC	Forest area/Land area	*Statistical Yearbook of Chinese Urban Construction*
	Innovation input level	II	RD internal expenditure/Total GDP	*China Statistical Yearbook*
	Energy consumption per unit of GDP	GE	Energy consumption/Total GDP	*China Energy Statistical Yearbook*

First, from the overall perspective of the whole region, the efficiency of GWEF in China was not high, with an average of 0.72. There was still a lot of room for improvement from the efficiency frontier. During the reporting period, the EBM value of each province was distributed between 0.4 and 1.1, showing obvious regional differences. In the spatial distribution diagram (Figure 2), the distribution of EBM values in major years was compared. Between 2005 and 2009, the dark green areas ($\text{EBM} > 1$) representing the efficiency frontier decreased. The dark red area [0.4–0.5] and the orange area [0.5–0.6], which represented lower efficiency, showed a trend from increasing to decreasing again. The dark yellow region [0.6–0.7] had a significant increase. The development of efficiency values in different regions was not stable.

Changes at the regional and provincial levels

Furthermore, the evolution of inter-regional efficiency values was studied through the statistics and ranking changes of efficiency values in eastern, central, western and provincial regions (Table 3).

(1) From the 15-year mean value of GWEF of all provinces, Shanghai, Tianjin, Beijing, Guangdong and Jiangsu were the top five among the 30 provinces, mainly concentrated in the eastern region. The last five were Ningxia, Qinghai, Guizhou, Gansu and Yunnan, mainly concentrated in the western region. (2) From the 15-year mean value comparison of GWEF in the eastern, central and western regions, eastern region $0.859 >$ central region $0.690 >$ western region 0.590, with a large gap among economic regions. The efficiency value of the eastern region was significantly better than that of other regions, far exceeding the national average, while the efficiency values of the central and western regions were lower than the national average. (3) By comparing the changes of efficiency values between 2005 and 2019, Sichuan, Hunan and Ningxia had seen a great improvement, while Shandong, Heilongjiang and Hainan had seen a great decline. By the end of 2019, Tianjin, Beijing, Shanghai and Guangdong were the only four provinces whose green development efficiency had reached the effective frontier, i.e. the efficiency value ≥ 1, while Jilin and Shandong all had an efficiency value below 0.5, which was considered to be low-efficiency.

Temporal evolution law

The time-series evolution of efficiency values was observed through the kernel density diagram of GWEF (Figure 3). Kernel density estimation is a non-parametric estimation method which does not reflect the real

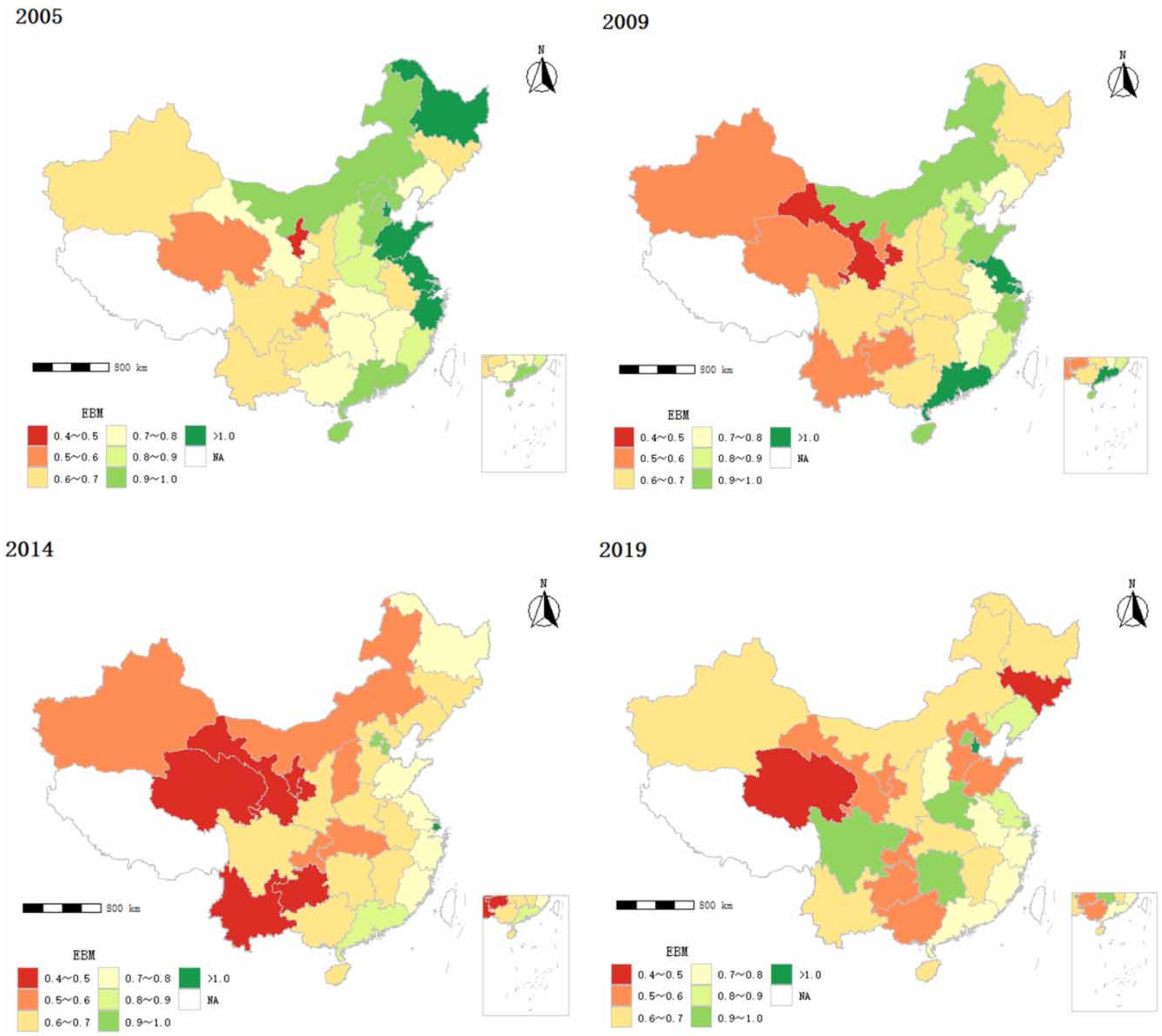


Fig. 2 | Spatial distribution of the green development efficiency of water-energy-food in main years. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/wp.2023.145.

distribution function. However, kernel density estimation can use a continuous density function curve to describe the distribution state of the research object and can analyze the overall form, distribution location, ductility and change trend of the green development efficiency distribution of water-energy-food in China. This method is a classic model of efficiency measure analysis, and its effectiveness has been widely recognized by scholars (Huang, 2018; Shen *et al.*, 2019; Lin & Chen, 2021).

(1) According to the change of the barycenter position of the kernel density curve, the barycenter of the kernel density curve shifted slightly from right to left from 2005 to 2019, and then remained relatively stable. It showed that the overall efficiency value of GWEF in 30 provinces keeps stable year by year after a slight decrease. The average efficiency value remained relatively stable after falling slightly from 0.802 in 2005. It reflected that at the beginning of the research period, the coordination between the use of various resources and the economic

Table 3 | Statistics and ranking of the green development efficiency of water-energy-food by region from 2005 to 2019.

Economic zone	Province	2005	2019	Change	15-year average	The mean rank
Eastern region	Beijing	1.000	1.000	0.000	1.000	3
	Fujian	0.874	0.783	−0.091	0.791	8
	Guangdong	1.000	0.700	−0.300	0.917	4
	Hainan	1.000	0.653	−0.347	0.780	10
	Hebei	0.902	0.581	−0.321	0.712	15
	Jiangsu	1.001	0.846	−0.154	0.864	5
	Liaoning	0.708	0.832	0.124	0.749	11
	Shandong	1.005	0.538	−0.467	0.798	7
	Shanghai	1.021	1.000	−0.021	1.016	1
	Tianjin	1.004	1.006	0.002	1.010	2
	Zhejiang	1.000	0.702	−0.298	0.807	6
Central region	Anhui	0.658	0.716	0.058	0.670	18
	Henan	0.829	0.938	0.109	0.736	13
	Heilongjiang	1.002	0.618	−0.384	0.744	12
	Hubei	0.746	0.653	−0.094	0.638	22
	Hunan	0.758	0.947	0.189	0.725	14
	Jilin	0.669	0.436	−0.233	0.616	23
	Jiangxi	0.739	0.684	−0.055	0.703	16
	Shanxi	0.835	0.779	−0.055	0.686	17
Western region	Gansu	0.716	0.506	−0.210	0.537	27
	Guangxi	0.749	0.584	−0.165	0.657	20
	Guizhou	0.607	0.548	−0.058	0.526	28
	Inner Mongolia	1.000	0.659	−0.341	0.790	9
	Ningxia	0.420	0.579	0.159	0.481	30
	Qinghai	0.564	0.493	−0.071	0.494	29
	Shaanxi	0.683	0.666	−0.016	0.669	19
	Sichuan	0.655	0.920	0.264	0.642	21
	Xinjiang	0.620	0.642	0.022	0.562	25
	Yunnan	0.694	0.670	−0.024	0.547	26
	Chongqing	0.596	0.566	−0.030	0.587	24

environment was ignored in the process of economic and social development in China, which led to the decline of the overall green development efficiency of the country. However, after the government put forward the green development strategy and issued a series of policies related to green development, all provinces actively introduced green technology, improved the scientific allocation of resources and made efforts to improve production efficiency and reduce environmental pollution. This downward trend had been reversed and gradually stabilized. (2) From the height of the main peak of the kernel density curve, the height of the main peak increased at first and then decreased from 2005 to 2019. It showed that the GWEF among provinces was concentrated at first, then flat and then concentrated. The efficiency gap showed a trend of change from small to large and then to small. The gap between regions was obvious. (3) From the number of peaks in the kernel density curve, the GWEF only showed a peak in 2014. It showed that the GWEF in different provinces of China had not yet reached the situation of multi-pole differentiation. The efficiency interval was relatively concentrated. (4) From the left and right tails of the kernel density curve, only the left tail of the kernel density curve decreased in 2009, and remained basically the same in other years, indicating that the overall range of green development efficiency of each province remained stable.

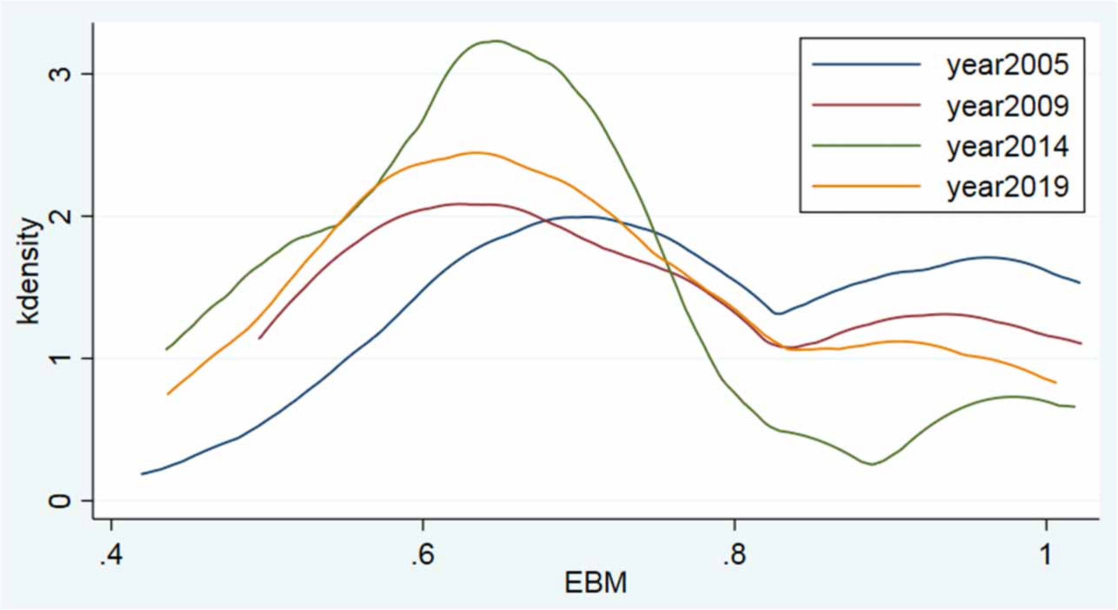


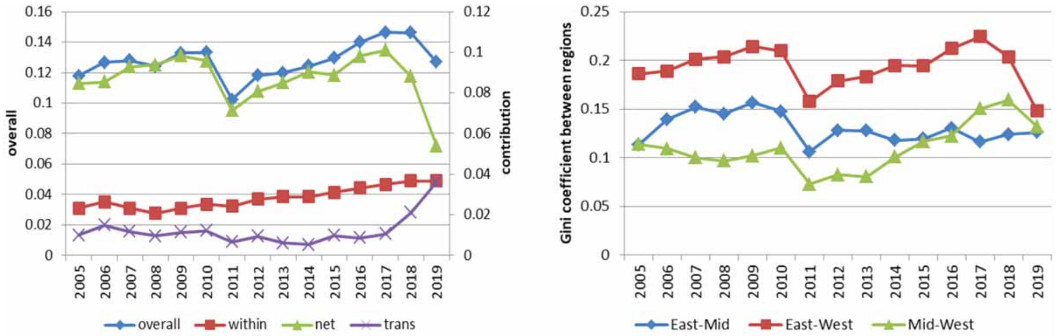
Fig. 3 | Kernel density diagram of the green development efficiency of water-energy-food in main years.

Spatial difference and decomposition

The variation trend of efficiency and kernel density map described the evolution law of absolute change of GWEF distribution on the whole, but could not obtain the relative change and source of spatial difference of GWEF. The Dagum spatial Gini coefficient decomposition described and explained the spatial disequilibrium characteristics of GWEF in a more detailed way from the perspective of relative differences, and solved the problem of the source of regional differences. In this paper, regional differences in GWEF were divided into three parts, namely, overall differences and contribution rate, inter-regional differences and intra-regional differences, according to eastern, central and western regions, as shown in Figure 4.

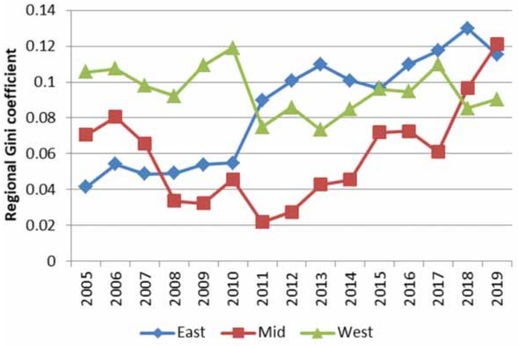
Overall spatial difference

During the study period, the overall Gini coefficient of GWEF in the province was 0.128, showing a trend of band rising, indicating that the difference in regional efficiency level was gradually increasing. Specifically, the variation trend of the overall spatial difference in the study period could be divided into four stages: the overall Gini coefficient showed an upward trend from 2005 to 2010, followed by a sharp decline from 2010 to 2011, continued to maintain an upward trend from 2011 to 2018 and then declined again from 2018 to 2019. The results showed that the GWEF difference of provinces was in the trend of ‘divergence-convergence-convergence-convergence’. Combined with the variation of contribution rate, the contribution rate of intra-regional differences fluctuated between 2.06% and 3.67% and the contribution rate of inter-regional differences fluctuated between 5.39% and 10.10%. The contribution rate of super-variable density increased from 1.00% in 2005 to 3.63% in 2019. The results showed that the contribution rate of super-variable density $<$ regional contribution rate $<$ the contribution rate between regions. It could be seen that the overall spatial differences were mainly derived from regional differences.



Overall difference and contribution rate

Interregional difference



Intraregional variation

Fig. 4 | Regional differences and their decomposition.

Regional differences

During the study period, regional differences were mainly manifested in three stages: From 2005 to 2010, the Gini coefficient of the east-central, east-west and central-west basically maintained a trend of rising after a small fluctuation. From 2010 to 2011, the Gini coefficient of the three regions decreased significantly. After 2011, the variation trends of the three regions showed great differences. Among them, the east-central regional difference increased slightly and remained stable at about 0.120. The east-west regional difference decreased slightly to 0.158 in 2011 and increased to 0.224 in 2017, and then decreased significantly to 0.148 in 2019. The central-west regional difference maintained a fluctuating upward trend, rising to 0.159 in 2018 and then decreased again. On the whole, the east-west difference was the main factor causing the regional difference of GWEF in provinces. Before 2016, the east-central difference was larger than the central-west difference, and after 2016, the central-west difference was larger than the east-central difference.

Regional differences

During the study period, the intra-group difference analysis of the eastern, central and western regions provided a basis for the horizontal comparison of the degree of disequilibrium in each region. In general, the differences in the eastern region showed a trend of wave-like rise, the differences in the central region showed a trend of wave-like decline and then a trend of wave-like rise, and the differences in the western region fluctuated around 0.10. The intra-group differences between the three regions were at different levels, and their rank was constantly changing. It could be divided into four stages: from 2005 to 2007, the order of difference value was west > central > east. From 2008 to 2010, the order of difference value was west > east > central. From 2011 to 2017, the order of difference value was east > west > central. From 2018 to 2019, the order of difference value was east > central > west.

Selection of spatial weight matrix and Global Moran's I test

It is necessary to select the spatial weight matrix scientifically before the model analysis involving spatial factors. Four spatial weight matrices (spatial adjacency weight matrix, inverse geographical distance weight matrix, economic distance weight matrix and asymmetric economic-geographical space weight matrix) were considered comprehensively. Moran's I was used to test the spatial correlation. The results are shown in Table 4. The results of the four spatial weight matrices showed that the global Moran's I of GWEF was most significant under the asymmetric economic-geographic spatial weight matrix. The spatial weight matrix of asymmetric economic-geography was set as the spatial weight matrix in the model of spatial transfer effect and a spatial spillover effect in the further test.

As shown in Figure 5, Moran's I value and Z value were both positive during the study period and passed the significance level test, indicating that there was a significant positive spatial autocorrelation, and the agglomeration effect was obvious. Overall, from 2005 to 2019, the global Moran's I value showed an inverted U pattern of 'rising-stability-decline', indicating that GWEF had a significant spatial trend of 'agglomeration-steady-diffusion'.

Analysis of spatial convergence evolution

Next, we used Markov chain to analyze the spatial transfer effect of the GWEF, and could examine the mobility and convergence evolution trend within and between regions.

Table 4 | Global Moran's I values based on different spatial weight matrices.

	GWEF			
Type/Year	**Spatial adjacency**	**Inverse geographical**	**Economic**	**Asymmetric economic-geographical**
2005	−0.092	0.100***	0.183*	0.263***
2006	−0.097	0.070***	0.183*	0.214**
2007	−0.082	0.101***	0.249**	0.276***
2008	−0.088	0.143***	0.368***	0.363***
2009	−0.109	0.141***	0.409***	0.361***
2010	−0.086	0.138***	0.377***	0.357***
2011	−0.019	0.130***	0.389***	0.381***
2012	−0.048	0.125***	0.434***	0.375***
2013	−0.095	0.120***	0.396***	0.360***
2014	−0.090	0.133***	0.338***	0.380***
2015	−0.147	0.135***	0.392***	0.348***
2016	−0.134	0.129***	0.353***	0.332***
2017	0.045	0.107***	0.264**	0.293***
2018	0.024	0.080***	0.209**	0.243***
2019	−0.015	0.028*	0.177*	0.161**

***$p < 0.01$, **$p < 0.05$,*$p < 0.1$.

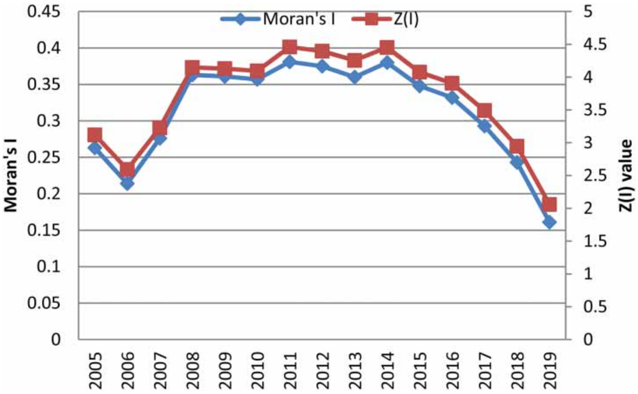


Fig. 5 | Global Moran's I and Z values.

The traditional Markov chain analysis method investigated the efficiency of the green development of water-energy-food by taking each region as an independent unit. The results were concise and intuitive, and the analysis results are shown in Table 5. Traditional Markov chains only focused on the variation between different types, but lacked spatial perspective. With the gradual strengthening of social, economic, environmental and other links among regions, the transfer of GWEF in each region began to be affected by obvious spatial interaction. Therefore, it was necessary to bring the spatial factors of GWEF into the research scope. Therefore, this paper further used the spatial Markov chain analysis method to investigate the spatial dependence of efficiency transfer of GWEF in a certain region. The spatial weight matrix of asymmetric economic-geography was used in spatial Markov chain analysis. According to the efficiency value, the distribution of GWEF in neighboring provinces was divided into four types: low level (L), medium low level (ML), medium high level (MH) and high level (H). If it is 33% lower than the national average of GWEF in the year, it belonged to the low level; if it is 33–66%, it belonged to the low level; if it is 66–100%, it belonged to the high level; if it is higher than 100%, it belonged to the high level. The value on the diagonal in the table represented the probability that the GWEF will maintain its original state, while the value on the non-diagonal represented the probability that the green development efficiency of GWEF would transfer among different types. The results are shown in Table 6.

The characteristics of GWEF type transfer under non-constraint:

(1) The probability values on the main diagonal were significantly greater than those on the non-diagonal, indicating that GWEF was greatly affected by the original GWEF level. The minimum value on the diagonal was 0.634, and the maximum value was 0.830. This indicated that at any given time, the probability of maintaining the original GWEF efficiency level in these provinces was at least 63.4% (ML level type) and at most 83.0% (L level type). Among them, the low level type and the high level type maintained a strong steady state,

Table 5 | Markov transition probability matrix of GWEF.

***t*/*t* + 1**	**L**	**ML**	**MH**	**H**
L	0.830	0.143	0.018	0.009
ML	0.188	0.634	0.161	0.018
MH	0.036	0.179	0.661	0.125
H	0.000	0.012	0.202	0.786

Table 6 | Space Markov transfer probability matrix.

ISE

Spatial lag	***t*/*t* + 1**	**L**	**ML**	**MH**	**H**
L	L	0.883	0.104	0.013	0.000
	ML	0.360	0.480	0.160	0.000
	MH	0.000	0.375	0.500	0.125
	H	0.000	0.000	0.500	0.500
ML	L	0.762	0.238	0.000	0.000
	ML	0.128	0.744	0.103	0.026
	MH	0.063	0.156	0.625	0.156
	H	0.000	0.000	0.200	0.800
MH	L	0.636	0.182	0.091	0.091
	ML	0.088	0.618	0.294	0.000
	MH	0.050	0.225	0.600	0.125
	H	0.000	0.000	0.259	0.741
H	L	0.667	0.333	0.000	0.000
	ML	0.286	0.643	0.000	0.071
	MH	0.000	0.094	0.813	0.094
	H	0.000	0.029	0.143	0.829

indicating that GWEF had a phenomenon of agglomeration to low level and high level. It showed that there was obvious club convergence in the GWEF (referring to the convergence of economic growth in a group of regions with similar initial conditions and structural characteristics of economic growth to the same steady state) (Teng *et al.*, 2019).

(2) GWEF showed a certain decline. Except for the L level provinces, the other provinces showed a certain decreasing trend in the initial stage. Numerically, the overall probability of a lower type of province moving down was greater than the overall probability of moving up. Among them, the total probability of downward transfer of ML type provinces was 0.188, while the total probability of upward transfer was 0.179. The overall probability of downward shift in MH type provinces was 0.215 and upward shift was 0.125. The probability of downward transfer of H-type provinces was 0.214. During the study period, provinces did not attach enough importance to GWEF, resulting in insufficient growth of GWEF.

(3) GWEF showed a certain 'leap-forward' change. According to the probability distribution in the matrix, most transfer types had certain probability. At the same time, the proximity effect was still significant, that is, the GWEF transition probability of most provinces was still high between adjacent types. The efficiency transfer was gradual and the probability of 'cross-level transfer' was small, indicating that different types of GWEF were susceptible to the influence of adjacent areas.

The characteristics of GWEF type transfer under the neighborhood environment constraint:

The promotion of GWEF in the region was not only affected by its own resource endowment and technical level, but also the influence of various policies of the neighboring provinces, the innovation communication and the flow of resources. In this paper, we could further study the role of different economic-geographic neighborhood types on the convergence of GWEF.

(1) When considering spatial factors, on the whole, the probability value on the main diagonal was still significantly greater than that on the non-diagonal. This indicated that after considering the influence of spatial factors, the development of GWEF still maintained the characteristics of club convergence and had a certain

degree of space-time inertia, which was mainly manifested as low level and high level (the probability value remains at a high level).

(2) The influence of the adjacent effect on GWEF's spatial evolution was greater, the state transfer was mainly occurring in the adjacent types, and the probability of 'cross-level transfer' was smaller. Compared with Tables 5 and 6, the results of the spatial Markov transition probability matrix were significantly different from those of the traditional Markov transition probability matrix in the same period, indicating that the type of neighboring provinces had a significant driving or inhibiting effect on GWEF transfer. For example, for the L-level type province, if it was adjacent to the L-level province, the neighboring province would block the upward transfer of its probability. Such as P14 | 1 = 0, P14 = 0.009.

(3) With the increase of neighborhood type, the stable type of the L level region decreased, and the probability of upward shift to the ML level became larger and larger. When it approached the MH level, the probability of maintaining at the original level was 0.636, which was significantly lower than the probability in the traditional Markov transfer matrix. The stability of the ML level region increased with the increase of neighborhood type, and the probability of downward transfer showed an overall upward trend, while the probability of upward transfer gradually decreased. When the ML level was near the MH level, the probability of maintaining the original level was 0.744, which was much higher than the probability of the traditional Markov transfer matrix. The stability of the MH level region also increased with the increase of neighborhood type, and the probability of upward transfer decreased, while the probability of downward transfer gradually decreased. When the MH level was near, the probability of maintaining the original level was 0.813, which was much higher than the probability of the traditional Markov transfer matrix. The probability of downward transition of the L level region decreased with the increase of neighborhood type, and the stability became higher and higher. When the L level was near, the probability of maintaining at the original level was 0.829, which was higher than the probability in the traditional Markov transition matrix. In general, the increase in spatial proximity types had a certain promoting effect on the development of each region. Provinces with different GWEF levels were in different horizontal stages, and the spatial spillover effects of their neighborhoods were different.

Space overflow effect

According to the previous study, the spatial and temporal difference between China's GWEF was significant, and the regional gap showed a certain divergence. With all kinds of resource flowing accelerated by the market process, various factors could also produce spatial spillover effects. In order to determine the appropriate spatial measurement model, we did a series of relevant tests. Firstly, according to the Anselin criterion, the *p*-value of the spatial error model was not significant, the space lag model was significant in the 1% level, and the spatial lag model was required for further testing. The suitability of the spatial lag model was further verified by the LR test, and the Hausman test rejected the null hypothesis at the 1% confidence level, indicating that the spatial lag model (SAR) with fixed effects should be selected. In order to accurately analyze the dynamic effects of various explanatory variables on GWEF, the SAR partial differential matrix was used to decompose the spatial effects into direct effects and indirect effects, and the results of decomposition effects are shown in Table 7.

The direct effect and indirect effect coefficients of IS on GWEF were both negative, indicating that IS had an inhibitory effect on GWEF in local and adjacent areas, but it did not pass the significance level test.

The direct effect coefficient of PD on GWEF was positive, and it was significant at the 5% level, indicating that the PD had a significant effect on the promotion of GWEF. With the absorption capacity of the provinces and the increase of urban vitality, the PD was increasing. The increase in PD means the concentration of labor resources. With the continuous improvement of the population quality of each province, the labor input efficiency of GWEF

Table 7 | Spatial effect decomposition based on the geo-economic weight matrix.

Type	IS	PD	UR	OP	FC	II	GE
Direct effect	−0.0138	0.0257	0.3071	0.0110	0.0144	0.0159	−0.0707
p-value	0.622	0.015	0.000	0.001	0.051	0.003	0.000
Indirect effect	−0.0020	0.0040	0.0456	0.0016	0.0022	0.0023	−0.0107
p-value	0.677	0.177	0.053	0.065	0.191	0.085	0.066
Total effect	−0.0158	0.0298	0.3526	0.0126	0.0166	0.0183	−0.0814
p-value	0.624	0.019	0.000	0.001	0.053	0.003	0.000

in this region could be improved, and the development of the regional economy could be promoted to improve the overall level of GWEF in this region. The indirect effect coefficient of PD on GWEF was positive, which did not pass the significance level test, indicating that the positive spillover effect was not significant.

The direct effect coefficient of UR on GWEF was positive, which was significant at the 1% level, indicating that UR played a significant role in promoting the improvement of GWEF in this region. The indirect effect coefficient was positive and significant at the level of 10%, indicating that it had produced a certain positive spillover effect. China had experienced a long period of rapid growth in the UR of the permanent population. At present, the UR of the permanent population in the Yangtze River Delta and the Pearl River Delta in China had been very high. The increase in UR means an increase in regional population mobility, which could bring new vitality and higher productivity to the region and neighboring regions.

The direct effect coefficient of the opening level (OP) on GWEF was positive and significant at the 1% level, indicating that it had a significant promoting effect on the GWEF in this region. The indirect effect coefficient was positive and significant at the level of 10%, indicating that it had produced a certain positive spillover effect. The Chinese government promoted exchanges and cooperation between regions, complemented each other's advantages, and brought about more scientific and reasonable resource allocation by improving inter-regional resource mobility.

The direct effect coefficient of the FC for GWEF was positive, and it was significant at the 1% level, indicating that its promotion of GWEF in the region had been significantly enhanced. The indirect effect coefficient was positive, and it did not pass the significant level test, which indicated that the positive overflow effect was not significant. With the advance of the idea of green development in China, the integration and optimization measures of natural protection had been steadily promoted, the Chinese provinces had been actively implementing the measures to reduce the soil, the pace of afforestation had been accelerating, and the total amount of forest resources had been greatly improved by the development of natural forests and natural grasslands. But the environmental ascension effect of FC was generally limited to the area, and had failed to have a significant impact on the GWEF of the neighborhood.

The direct effect coefficient of innovation input level (II) on GWEF was positive and significant at the 1% level, indicating that the innovation input level had a significant promoting effect on the GWEF in this region. The indirect effect coefficient was positive and significant at the level of 10%, indicating that it had produced a certain positive spillover effect. In the course of its modernization drive, China adopted a strategy of innovation-driven development, increased investment in education and scientific research, increased regional innovation capacity and level, and accelerated the release of innovation drivers, providing important support for maintaining steady and rapid economic growth and promoting high-quality economic development. This positive effect had a positive promoting effect on both local and neighborhood GWEF.

The direct effect coefficient of energy consumption per unit GDP (GE) on GWEF was negative, which was significant at the 1% level, indicating that energy consumption had a significant inhibitory effect on the GWEF in this region. The indirect effect coefficient was negative and significant at the level of 10%, indicating that it had produced a certain negative spillover effect. As GE gets higher and higher, the energy efficiency gets lower and lower. Energy efficiency also reflected the energy structure, and the development of green renewable energy could improve energy safety and reduce environmental pollution, which was the fundamental way to solve the energy problem. In recent years, China had issued a series of energy policies, which had achieved remarkable results and improved the efficiency of green development. In the future, regional governments need to break through the technological bottleneck of new energy development, strengthen the development of green industries such as energy conservation and environmental protection, and promote the innovation of green renewable energy supply mechanisms, so as to further improve the efficiency of regional green development.

CONCLUSIONS AND POLICY RECOMMENDATIONS

This paper studies the spatio-temporal dynamic evolution law of the GWEF in China from national, regional and provincial dimensions, which is conducive to comprehensively improving China's GWEF from multiple perspectives, and realizing the coordinated development of three important natural resources, economy and environment. The main conclusions are as follows: The overall mean level of GWEF in China still has large room for improvement from the efficiency frontier, and the eastern region is better than the western region, showing obvious regional differences. The overall spatial differences of GWEF in provinces are mainly due to the differences between regions, and the east-west differences are the main factors causing the differences between regions. The transfer process of GWEF distribution shows the characteristics of club convergence, which is easily affected by neighboring regions. The global Moran's I index shows significant spatial autocorrelation, and various influencing factors also show the role of travel alienation and spatial spillover effect. Based on the above conclusions, the following policy recommendations are put forward:

(1) Differentiated policies should be formulated according to resource endowment and GWEF development status in different regions. Provinces and economic regions with a high level of GWEF can set an example and drive the development of neighboring regions. It is necessary to consider the optimal allocation of resources from both input and output, and the relationship between the use of three important resources and the economy and environment. By means of technological innovation, we can improve the efficiency of resource use and at the same time improve the level of economic output and reduce the emission of various major environmental pollutants.

(2) The competent departments of water resources, energy and food need to fulfill the function of collaborative governance with the competent departments of economy and environment to break the management barriers and bring into play the economies of scale in the utilization of resources. It is necessary to enhance the correlation between different industries, formulate a reasonable industrial layout, reduce transaction costs and obtain new growth points. It is necessary to take full account of time and space factors, and actively use capital, technology, market and other potential factors to promote the overall efficiency of the whole resource, economic and environmental system.

(3) It is necessary to attach importance to the spatial proximity role of GWEF and give play to the spatial guidance role of advantageous areas. Under the efficiency distribution pattern of high level monopoly and low level trap, we should cultivate new growth points in provinces with a medium level of efficiency. At the same time, an economic network of the east, central and western regions promoting each other will be formed to give play to the synergistic effect between regions. It is necessary to guide the regions with relatively

backward GWEF to carry out technological innovation and opening-up, reduce the development imbalance between regions, and promote the overall high-quality development of the economy and environment of each region.

(4) It is necessary to give full play to the government's function of supervision, management and regulation of the market. Differentiated policies should be formulated for all kinds of important influencing factors. Efforts should be made to promote all kinds of influencing factors to play a positive role in GWEF, and gradually expand their spatial influence scope. We need to encourage urbanization and opening-up, improve the overall quality of the urban population, and guide trans-regional cooperation in resources and technology. We need to rationally arrange fiscal expenditure to guide the development of green industry and increase urban FC. Efforts should be made to increase investment in innovation and optimize the energy consumption structure.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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