Heliyon 10 (2024) e31893

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Research on the spatio-temporal coupling relationship between agricultural green development efficiency and food security system in China

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A B S T R A C T

Food security and agricultural green development are fundamental issues concerning the survival of mankind. To realize the coordinated development of them is of great significance to promote the green transformation of agriculture and ensure national food security. However, few studies have analyzed the coupling relationship between agricultural green development and food security. Therefore, this study complements the research on the coupling relationship between them. First, we use the agricultural panel data of 31 provinces in China from 2010 to 2021 to measure the agricultural green development efficiency and food security level by Super-SBM model and entropy weight method. Then, the coupling relationship and spatiotemporal evolution of the two are analyzed by coupling coordination degree model. The results show that, first of all, China's agricultural green development efficiency and food security level have improved overall, but there are regional differences. Secondly, the degree of coupling and coordination between the two is significantly improved, and most provinces develop from the break-in stage to the coordination stage, and the regional differences are relatively reduced. Finally, Beijing, Shanghai and other developed areas are mostly of the lagging food security type, Liaoning, Shandong and other major grain producing areas have reached a high degree of coordination, while Tibet, Qinghai and other western regions are still in the break-in stage. According to the development situation of different regions, corresponding suggestions are put forward. For regions with lagging food security type, the government should give full play to the application of science and technology in agriculture and promote green and low-carbon planting technologies. For regions with low coupling and coordination degree, the government should improve support policies and build a collaborative operation system, adjust planting structure to improve land utilization rate and food security level. Finally, the government should work together to build agricultural industrial parks and give full play to the leading role of competitive provinces to achieve common development.

1. Introduction

Food security is related to the national economy and people's livelihood, and is the foundation of national security. China, as a major agricultural nation, places considerable emphasis on food security, a central focus of its rural revitalization strategy. In 2023, the Chinese government reaffirmed its commitment to consolidating the foundation of food security and proposed the introduction of a food security legislation. However, in recent years, with the increase of grain production in China, there have been problems including escalating demands on agricultural resources, intensified soil and water erosion, and increased pollution from nonpoint agricultural sources. These issues pose threats to agriculture and the food production process, further jeopardizing food security [1,2]. Because food security is inextricably linked to agricultural production, in order to solve the problem of food security, we must fundamentally change the agricultural production system and make it develop in a sustainable direction [3]. And in the long term, the continued growth of

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https://doi.org/10.1016/j.heliyon.2024.e31893
Received 29 January 2024; Received in revised form 21 May 2024; Accepted 23 May 2024
Available online 23 May 2024

total food consumption in China will necessitate higher standards for sustainable agricultural development [4,5]. Therefore, it is particularly important to explore a new agricultural development model.

The agricultural green development is to improve the economic efficiency of agriculture while guaranteeing the coordinated and sustainable development of human and nature and realizing resource-saving and environment-friendly green agriculture. Promoting green development in agriculture means fostering a sustainable and recyclable development model, which is conducive to ameliorating problems such as surface source pollution and increasing food production and the level of food security. Consequently, realizing the green development of agriculture is of great significance to ensuring food security [6]. To ensure the sustainable development of agriculture, the Chinese government has introduced a series of policies aimed at preserving the ecological environment and fostering green development, elevating the importance of green development and food security to a national strategic level [1,7]. At the same time, balancing agricultural sustainability and ensuring global food security stands as a critical global concern. This dual objective aligns with item 2 of the United Nation Sustainable Development Goals (SDGs) [8].

The theory of sustainable development emphasizes the coordination and balance between economic development, social progress and environmental protection. In the context of green agricultural development, this theory explains how agricultural productivity can be improved while ensuring food security through the adoption of environmentally friendly and eco-friendly agricultural technologies and methods. Green agricultural practices, such as organic farming, water-saving irrigation and soil conservation, not only help to protect the ecological environment, but also improve the yield and quality of agricultural products, thereby ensuring food security. There is an interplay between agricultural green development and food security. On the one hand, green agriculture emphasizes ecological balance and sustainable development. It favours the use of organic fertilizers and bio-pesticides to reduce pollution of the environment and protect the health of soil and water resources. This practice not only helps to maintain the ecological environment of farmland, but also improves the yield and quality of agricultural products, which is important for guaranteeing food security. On the other hand, the core of food security lies in ensuring that food is non-toxic, non-hazardous, meets nutritional requirements and does not pose any hazard to human health. The development of green agriculture is precisely aimed at achieving this goal. By reducing the use of chemical pesticides and fertilizers, green agriculture reduces the content of harmful substances in agricultural products and improves food safety. As a result, the green agricultural development efficiency is improved while ensuring food security. In order to realize agricultural green development and food security, it is of great significance to explore the coordinated development relationship between them. Therefore, this paper analyzes the coupling coordination degree between agricultural green development efficiency and food security level, which is conducive to scientific understanding of the relationship between them and provides theoretical support for promoting agricultural green development and ensuring food security.

The purpose of this study is to explore the intricate relationship between agricultural green development efficiency and food security level in China. It aims to address the following issues. Firstly, it aims to establish an indicator evaluation system to calculate the efficiency of agricultural green development and the level of food security. Secondly, it aims to analyze the evolutionary characteristics of the agricultural green development efficiency and the food security level in terms of time and space. Lastly, it aims to calculate the degree of coupling and coordination between the two, and to analyze the evolution and the type of the coupling and coordination. Our contributions can be concluded as follows: Firstly, this paper analyzes the characteristics and geospatial pattern of the coordinated development of agricultural green development efficiency and food security in China with a certain degree of innovativeness, the level of agricultural green development and food security influence each other and constrain each other, and there are few existing studies involving the spatial relationship of the degree of coordination of the coupling between the two except for Deng and Yin's research [9,10]. Secondly, this paper conducts a comprehensive analysis of the coupling coordination degree and relative development types within both the agricultural green development system and food security system. We also explore temporal and spatial variations based on dimensions and regional disparities. Lastly, by analyzing the interplay between the two, the current study proposes recommendations to enhance pertinent policies. These suggestions hold significance for both green agricultural development and food security assurance. Therefore, this paper carries practical importance for the advancement of green agricultural practices in China and offers theoretical insights for sustainable agricultural development in other developing nations.

The structure of this paper is as follows: Section 2 introduces an overview of research progress in agricultural green development efficiency and food security. Section 3 outlines the data sources and methods employed in this study. Section 4 presents the discussion. Section 5 presents the research findings, and the concluding section offers insights derived from the results.

1.1. Literature review

The integration of agricultural green development and food security is conducive to the realization of sustainable agricultural production patterns and the improvement of food security level. Under the framework of sustainable development, the green transformation of agriculture has become a prominent trend. Changing food production patterns and promoting green development in agriculture are of great significance for food security. Existing literature has examined the relationship between agricultural green development and food security, which can be summarized into the following two aspects through combing and summarizing.

1.2. Agricultural green development

In recent years, the research of agricultural green development mainly focuses on three aspects: concept research, index system construction and agricultural green development efficiency measurement. Agricultural green development entails resources-efficient practices that mitigate pollution while fostering agricultural economy growth. The essence of green development lies in the shift towards sustainable production mode that harmonize economic growth with environmental protection [11,12]. Guo and Zhang proposed that a regional collaborative emission reduction mechanism should be established to achieve a long-term mechanism for agricultural carbon emission reduction and green development [13]. Scholars have constructed diverse index system to evaluate the extent of agricultural green development. For example, Bergius et al. comprehensively assessed the level of green agricultural development in Tanzania [14]. Wang formulated a multifaceted agricultural green development index system for China, compassing ecological agriculture, green production, and output benefits [15]. Liu et al. focusing on rural revitalization, developed an indicator system to measure agricultural green development across Chinese provinces [6]. Chen et al. explored the drivers of agricultural green development [16]. The notion of green development efficiency stems from Schaltegger and Sturm's ecological efficiency theory (1990) and serves as a measurement reflecting the degree of agricultural green development [17,18]. For instance, Xu et al. adopted the Super-SBM model and spatial econometric modeling to assess the agricultural green development efficiency and explore spatial spillover effects in China [19]. Ge et al. employed a SBM-DDF-Luenberger method to calculate the agricultural green development efficiency and test the heterogeneous effects of urbanization [20]. Moreover, studies on agricultural eco-efficiency, conducted in regions such as European Union [21], Italy [17], Portugal [22] and provinces of China [23], reflect agricultural green development.

1.3. Food security

Food security is a pivotal concern, universally defined by the Food and Agriculture Organization of the United Nations (FAO) as ensuring continuous access to sufficient food to meet people's dietary needs [24,25]. In recent years, research on food security has encompassed several key dimensions, including evaluating food security levels, examining the factors influencing it, and formulating strategies and recommendations. For example, studies evaluating food security levels have sought to construct comprehensive assessment frameworks. Zhang et al. developed a five-aspect index system and employed the entropy weight TOPSIS model to measure and analyze China's food security levels [26]. Similarly, Cui and Nie selected 14 evaluation indicators across five dimensions, encompassing factors such as quality safety and quantity safety, to assess China's food security levels [27]. Research has revealed that several factors impact food security, including urbanization [28], resource consumption [29] and climate change [30]. Moreover, scholars have increasingly adopted an integrated approach, considering the coupling relationships between food security and other systems. For instance, Xue and Ma evaluated the food security status of primary grain-producing regions and examined their coupled and coordinated relationship with land ecological security [31]. Yang et al. conducted an analysis of the coupled and coordinated development patterns between food security and agricultural carbon emission efficiency in Sichuan province [32].

1.4. The relationship between agricultural green development and food security

In recent years, the research on food security level assessment mainly focuses on the construction of evaluation index system [26, 28–30,33]. The existing research on the relationship between agricultural green development and food security focuses on the influence of agricultural production conditions on food security. For example, da Silva et al. calculated the ecological footprint of food production activities, emphasizing the importance of ecological sustainability for food security [34]. Bocchiola et al. explored the impact of climate change on agricultural production and food security levels [35]. Furthermore, food security promotes ecological sustainability through the human capital channel [36]. There are also scholars who look at the impact of ecological issues, such as loss of biodiversity, on food security in the context of ecological security issues [37]. Scholars have also explored the promoting mechanism of agricultural green development efficiency from the aspects of agricultural nitrogen efficiency [38] and agricultural water efficiency [39]. Wang et al. measured the agricultural eco-efficiency and the level of food security in 31 provinces in China, then they studied the coupled and coordinated relationship and spatial correlation between the two, which showed that agricultural eco-efficiency and food security were spatially positively correlated, with the positive spillover effect gradually increasing [40]. Zhang et al. used ESTDA and CCD models to analyze the coordination of agricultural green efficiency and food security in China, and found that the coupled coordination of agricultural green efficiency and food security coefficient gradually increased [41].

1.5. The significance of agricultural green development to food security

More and more studies have shown that achieving green agricultural development is of great significance to improving food security. Some scholars have pointed out that food security can be improved by building a green development model. For example, Kerr et al. identified ecological agriculture as an avenue to enhance food security based on an analysis of 56 relevant articles, and they found that agroecological transition can improve food security through synergies [42]. It has been argued that a win-win situation for both agricultural eco-efficiency and food security can be achieved through agroecological management of farmland and improvement of arable land fertility [43,44]. Zhan and Xu emphasized that green development will assume greater significance in China's food security, they found out that building a balanced system of environmental regulation was key to improving the agricultural green efficiency and guaranteeing food security [45]. Some scholars have pointed out that the green transformation of agriculture and the improvement of food security can be realized through measures such as the construction of high-standard farmland [46]. Li and Lin proposed that green technologies have made contributions to improving food production and reducing environmental pollution and studying the effects of green technologies on sustainable food production has great significance [47]. In addition, other scholars have explored the ecological problems arising from the food production process, focusing mainly on the current situation of agroecological development from an ecological perspective, and analyzing the impact of the utilization of water resources, land resources, etc., on food security [48,49].

In summary, scholars mainly study the relationship and significance between agricultural green development and food security.

However, there are few studies on the coupling coordination relationship and regional development differences between the two, and fewer studies on the evolution of coordination relationship from the perspective of space and time. In recent years, in the process of agricultural production, environmental pollution, ecological degradation and other problems have appeared. The Chinese government has attached great importance to sustainable agricultural development and food security, introduced a series of policies to improve food and agricultural production conditions, actively promoted green agricultural development and ensured food security. Therefore, it is imperative to realize the coordinated development of agricultural green development and food security.

Therefore, this study first measures the efficiency of agricultural green development and the level of food security in 31 provinces in China from 2010 to 2021 based on the indicator system. Secondly, relevant models are constructed to analyze the coupled and coordinated relationship between the two, and then we analyze the evolution from the perspective of time and space and examine the regional development differences. In addition, this study analyzes the types of coordinated development between them to provide theoretical support and suggestions for the coupled development of agricultural green development and food security.

2. Methodology and data

2.1. Methodology

2.1.1. Calculation of agricultural carbon emissions

This paper refers to Li's method [30] to measure agricultural carbon emissions, the formula is as follows:

$$C = \sum_{j=1}^{6} P_j d_j \tag{1}$$

where C denotes the total amount of agricultural carbon emissions, P_j is the amount of each emission source, and d_j is the carbon emission coefficient. The carbon emission sources are shown in Table 1.

2.1.2. Super-SBM model

Data Envelopment Analysis (DEA) mainly evaluates the efficiency of decision units containing multi-indicator inputs and multi-indicator outputs. Based on the traditional DEA model, Tone proposed the Slack-Based Measure (SBM) model [53], which eliminates the error effects of slack variables on the efficiency values of decision units. However, in practice, the results of the SBM model often show multiple efficiency values of 1, which makes it difficult to further analyze the effective decision units, so Tone proposed the Super-SBM (Super Efficiency Slack-based Measure) model [54], and in this paper, we use the non-radial, non-angle, and consider non-expected outputs of the Super-SBM model to measure and analyze agricultural green development efficiency in China. The model is defined as:

There are n Decision Making Units (DMUs), each containing m inputs, s_1 desired outputs, and s_2 undesired outputs. For the kth DMUk, its vector of inputs, desired outputs and non-desired outputs are denoted by x_{jk}、y_{jk}^g、y_{jk}^b respectively. The expression of the model is as follows [55]:

$$\min \rho = \frac{\frac{1}{m}\sum_{i=1}^{m}\frac{\overline{x}_i}{x_{ik}}}{\frac{1}{s_1+s_2}\left(\sum_{l=1}^{s_1}\frac{\overline{y}_l^g}{y_{lk}^g}+\sum_{r=1}^{s_2}\frac{\overline{y}_r^b}{y_{rk}^b}\right)} (i=1,2,...m; j=1,2,...,n; l=1,2,...,s_1; r=1,2,...,s_2)$$

$$s.t.\begin{cases} \overline{x}_i \geq \sum_{t=1}^{T}\sum_{j=1,j\neq k}^{n}\lambda_j^t x_j^t; \\ \overline{y}_l^g \leq \sum_{t=1}^{T}\sum_{j=1,j\neq k}^{n}\lambda_j^t y_j^{g,t}; \\ \overline{y}_r^b \leq \sum_{t=1}^{T}\sum_{j=1,j\neq k}^{n}\lambda_j^t y_j^{b,t}; \\ \overline{x}_i \geq x_k, \overline{y}^g \leq y_k^g, \overline{y}^b \geq y_k^b, \overline{y}^g \geq 0, \overline{y}^b \geq 0, \lambda_j^t \geq 0. \end{cases} \tag{2}$$

where λ_j^t is the weight vector and $\overline{x}_{ik}$、$\overline{y}_l^g$、$\overline{y}_r^b$ are the optimal solutions of the decision unit in the Super-SBM model.

2.1.3. Entropy weight method

The fundamental principle of the entropy weight method is to assign weights according to the degree of variability of each indicator. Before the measurement, it is first necessary to eliminate the influence of the index scale to standardize the indicators, this paper adopt the method of Liu et al. [6], non-negativity processing of the indicators, the specific practices are as follows:

Table 1
Agricultural carbon emission sources.

Carbon Emission Source	Carbon Emission Coefficients	Reference Source
pesticide	0.8956 kg·kg-1	Oak Ridge National Laboratory [50]
fertilizer	4.934 kg·kg-1	
agricultural film	5.18 kg·kg-1	Institute of Agricultural Resources and Ecological Environment, Nanjing Agricultural University [40]
diesel fuel	0.5927 kg·kg-1	IPCC [51]
ploughing	312.6 kg·km-2	College of Biology and Technology, China Agricultural University [40]
irrigation	20.476 kg·hm-2	Reference related literature [52]

$$\text{Positive indicators}: y_{ij} = \frac{x_{ij} - \min(x_{1j}, x_{2j} \cdots x_{nj})}{\max(x_{1j}, x_{2j} \cdots x_{nj}) - \min(x_{1j}, x_{2j} \cdots x_{nj})} + 0.01 \tag{3}$$

$$\text{Negative indicators}: y_{ij} = \frac{\max(x_{1j}, x_{2j} \cdots x_{nj}) - x_{ij}}{\max(x_{1j}, x_{2j} \cdots x_{nj}) - \min(x_{1j}, x_{2j} \cdots x_{nj})} + 0.01 \tag{4}$$

where x_{ij} is the value of the jth indicator in the ith province, y_{ij} is the value of the jth indicator in the ith province after standardization, and $\max(x_{1j}, x_{2j} \cdots x_{nj})$ and $\min(x_{1j}, x_{2j} \cdots x_{nj})$ denote the maximum and minimum values of each indicator, respectively, $i = 1, 2, \ldots n; j = 1, 2, \ldots, m$.

Next, the entropy weight method is utilized to determine the weights of the indica-tors [6]:

$$\begin{aligned} P_{ij} &= \frac{y_{ij}}{\sum_{i=1}^{n} y_{ij}}, \\ E_j &= -\frac{\sum_{i=1}^{n} P_{ij} \ln(P_{ij})}{\ln(n)}, \\ w_j &= \frac{1 - E_j}{\sum_{j=1}^{m} (1 - E_j)} \end{aligned} \tag{5}$$

where P_{ij} is the weight of the sample value of the ith evaluation object under the jth indicator, E_j is the information entropy, and w_j is the weight of the jth indicator.

Finally, the composite score S_i of each province's food security level is calculated:

$$S_i = \sum_{j=1}^{m} w_j \times y_{ij} \tag{6}$$

2.1.4. Coupled coordination degree model

The concept of coupled coordination is initially derived from physics, which means the interaction between two or more different systems. In this paper, the coupled coordination degree model is applied to measure the coordination between the agricultural green development efficiency and the level of food security [56]. The calculation formula is as follows:

$$\begin{aligned} C &= \frac{2\sqrt{U_1 U_2}}{U_1 + U_2}, \\ T &= \alpha U_1 + \beta U_2, \\ D &= \sqrt{C \times T} \end{aligned} \tag{7}$$

where C is the coupling degree, $C \in [0, 1]$, U_1、 U_2 respectively represents the agricultural green development efficiency and food security level. T is the green development efficiency and food security level comprehensive evaluation index, α、 β are the pending weight coefficients, this paper believes that the two are equally important, so $\alpha = \beta = 0.5$. D is the degree of coupling and coordination, $D \in [0,1]$. Referring to related literature [55,57], the coupling coordination degree of the two systems is divided into ten types, which is convenient to reflect the degree of coordination between the two systems. Table 2 shows the specific grades.

2.1.5. Relative development degree model

The relative development degree model can analyze the relative development state of two systems and further determine type of coupled development based on the relative development degree. The formula for measuring the relative development degree is [58]:

$$F = \frac{U_1}{U_2} \tag{8}$$

Table 2
Types of coupling coordination degrees in regard to agricultural green development efficiency and food security.

Coupling Coordination Degree	Type
[0.0,0.1)	Extreme imbalance
[0.1,0.2)	Serious imbalance
[0.2,0.3)	Moderate imbalance
[0.3,0.4)	Mid imbalance
[0.4,0.5)	Near imbalance
[0.5,0.6)	Reluctant coordination
[0.6,0.7)	Primary coordination
[0.7,0.8)	Intermediate coordination
[0.8,0.9)	Good coordination
[0.9,1.0)	High coordination

Based on the existing literature on the relative development degree level [58], this paper categorizes the coupled and coordinated development of the two systems into nine types, Table 3 show the features.

2.2. Data

2.2.1. Construction of the index system

By referring to relevant studies and existing literature [55,59,60], this paper selects three input indices, including land, labor and resources, and the output indicators include desirable output and undesirable output. Specifically, the land input selects the crop sown area, which represents utilization of land resources, the labor input selects the number of agricultural laborers to represent utilization of labor resources, the resource input selects the total power of agricultural machinery and the total agricultural water use as a representative. The desirable output represents the good output, which is represented by the total agricultural output value in this paper. The undesirable output is the negative impact on the environment in the process of agricultural production, which is represented by the agricultural carbon emission. Table 4 shows the details.

On the basic of the concept, this paper builds a food security index system from four aspects combined with the existing literature research [61–63], including quantity security, quality security, resource security and ecological security, which contains 13 indicators showed in Table 5. Quantity security is the basis of ensuring food security, and people's demand for food quantity must be met first. In this paper, we use the indicators that can measure the quantity of grain, such as the total grain output and the sown area of grain. Quality security is a higher requirement based on the realization of quantity safety, which means that people can obtain healthy and safe food. We use indicators such as agricultural fertilizer application and pesticide application rate to measure quality security. Resource security focuses on the food supply capacity under resource constraints, including water resources, land resources, etc., so we adopts indicators such as water resource consumption per unit of grain and land resource consumption per unit of grain. Ecological security means that food production should consider the sustainability of production methods, and the quality of ecological environment is related to food output. This paper adopts flood-removal area and soil erosion control area to measure the ecological security.

2.2.2. Data sources

Based on the principles of data availability, we select data of 31 provinces (municipalities and autonomous regions) in China in 2010–2021, and data from Hong Kong, Macao and Taiwan are not taken into account due to their serious missing data. The data are mainly from China Statistical Yearbook and China Rural Statistical Yearbook, and some of the data are from the statistical yearbooks of provinces, and the interpolation method is used to make up for individual missing data.

3. Results

In this paper, we firstly use MaxDEA Ultra 8.22 software to calculate and analyze the agricultural green development efficiency in 31 mainland Chinese provinces(considering data availability, Hong Kong, Macao and Taiwan are not included) from 2010 to 2021 using the Super-SBM model which is non-radial, non-angular, and takes into account the undesirable outputs. Secondly, we measure the food security level by using the entropy weight method. Finally, we use the coupled coordination degree model to measure the two systems' coupling coordination level.

3.1. Analysis of changes in spatial and temporal patterns of green development efficiency in agriculture

3.1.1. Analysis of time change of agricultural green development efficiency

Firstly, the agricultural green development efficiency in each province of China is calculated by Equation (2). In order to visualize the changes of the agricultural green development efficiency in China, we divide the eastern, central, western and northeastern regions with reference to relevant literature [41,64,65], and we draw a map of changes in agricultural green development efficiency. As we can see in Fig. 1, the average efficiency value of the whole country improves from 0.196 in 2010 to 0.636 in 2021, which indicates that the

Table 3
Types of coupling coordination degrees in regard to agricultural green development efficiency and food security.

Coupling Coordination Degree	Relative Development Degree	Type	Features	Developmental Stage
(0.0,0.3]	(0.0,0.8]	1	Green agricultural development systems lag behind food security systems, constraining their coordinated development	high antagonism
	(0.8,1.2]	2	Synchronization of greening agricultural development systems with food security systems, promoting their coordinated development	low antagonism
	(1.2,∞]	3	Food security systems lag behind agricultural green development systems, constraining their coordinated development	high antagonism
(0.3,0.7]	(0.0,0.8]	4	Green agricultural development systems lag behind food security systems, constraining their coordinated development	low break-in
	(0.8,1.2]	5	Synchronization of greening agricultural development systems with food security systems, promoting their coordinated development	high break-in
	(1.2,∞]	6	Food security systems lag behind agricultural green development systems, constraining their coordinated development	low break-in
	(0.0,0.8]	7	Green agricultural development systems lag behind food security systems, constraining their coordinated development	low level coordination
(0.7,1.0]	(0.8,1.2]	8	Synchronization of greening agricultural development systems with food security systems, promoting their coordinated development	high level coordination
	(1.2,∞]	9	Food security systems lag behind agricultural green development systems, constraining their coordinated development	low level coordination

Table 4
Agricultural green development efficiency indicator system.

Index	Category	Variable	Unit	Data Sources
Input	Land input	Crop sown area	1000 ha	China Statistical Yearbook
	Labor input	Number of agricultural laborers	Ten thousand	Statistical Yearbook of the Provinces
	Resource inputs	Total power of agricultural machinery	Ten thousand kw	China Statistical Yearbook
		Total agricultural water use	100 million m^3	
Output	Desirable output	Total agricultural output	Ten thousand yuan	
	Undesirable output	Agricultural carbon emissions	Ten thousand tons	Calculated from Equation (1)

Table 5
Food security evaluation index system.

Target	Criterion	Explanation	Attribute[a]	Weight	Data Sources
Food Security	Quantity security (C_1)	C_{11} Total grain output	+	0.0116	China Statistical Yearbook
		C_{12} Sown area of grain crops	+	0.1048	
		C_{13} Crops affected area	–	0.1045	China Rural Statistical Yearbook
		C_{14} Effective irrigated area	+	0.0616	
	Quality security (C_2)	C_{21} Agricultural fertilizer application rate	–	0.1050	China Statistical Yearbook
		C_{22} Pesticide application rate	–	0.0589	China Statistical Yearbook
		C_{23} Agricultural film application rate	–	0.0534	China Rural Statistical Yearbook
	Resource security (C_3)	C_{31} Water resource consumption per unit of grain	–	0.0588	Ratio of total agricultural water use to total grain output
		C_{32} Land resource consumption per unit of grain	–	0.0686	Ratio of area sown to total grain output
		C_{33} Total power of agricultural machinery	+	0.0647	China Statistical Yearbook
		C_{34} Number of agricultural laborers	+	0.1035	Statistical Yearbook of the Provinces
	Ecological security (C_4)	C_{41} Flood-removal area	+	0.1050	China Statistical Yearbook
		C_{42} Soil erosion control area	+	0.0996	Statistical Yearbook of the Provinces

[a] The attribute "+" means that the larger the value, the stronger the positive effect on the level of food security, and the weaker the vice versa.

agricultural green development efficiency is generally improving. It shows that Chinese agriculture has made significant progress in improving the green development efficiency in recent years. In 2010–2016, the improvement of agricultural green development efficiency in the eastern, central and western regions is slow. And there is a slight decline in the northeast region in 2015–2017 and in the eastern and central regions in 2016–2017, which may be related to changes in climate and other environmental conditions. In 2017–2021, the growth of agricultural green development efficiency in all regions has accelerated. It is worth noting that, with the implementation of the large-scale agricultural land policy, the construction of high-standard farmland has been increasing, the efficiency of agricultural input utilization has improved, and the green development of agriculture has achieved excellent results. At the end of 2017, the 19th National Congress of the Chinese government proposed the concept of " Lucid waters and lush mountains are invaluable assets", indicating that the government attaches great importance to the green development of agriculture. At the same time, a series of policy opinions have been issued, which marks the green development of agriculture has entered a new stage. People are increasingly aware of the importance of environmental protection, and green development is reflected in agricultural production [59]. These conditions have laid the foundation for the rapid improvement of China's agricultural green development efficiency.

3.1.2. Analysis of changes in the spatial distribution of agricultural green development efficiency

We select three time points of 2010, 2016 and 2021 to observe the changes of agricultural green development efficiency. According to the natural discontinuity grading method, China is divided into five regions such as low efficiency regions, low-medium efficiency regions using ArcGIS10.8 software. Fig. 2 shows the spatial distribution of the agricultural green development efficiency. In 2010–2021, the spatial distribution of agricultural green development efficiency changes significantly and has regional differences. Specifically, in the eastern region, the efficiency value maintains a high level. Compared with the other three regions, most of the eastern region belongs to provinces with vast terrain or rich ecological resources. And it has abundant agricultural resources, perfect agricultural infrastructure and good comprehensive agricultural development, so the efficiency value in this region is higher. The western region is not at a high level of economic development, but it is rich in land, forests and other natural resources, and as the country increases its support for green development in the western region, the level of financial and agricultural technology in the western region have been improved. At the same time, a number of pilot zones for green agricultural development have been set up in the western region to promote green agricultural development and accelerate the transformation of agricultural development from quantity to quality. As we can see in Fig. 2, the agricultural green development efficiency in the western region has improved more significantly, especially in Shaanxi, Chongqing and Guizhou, which are high-efficiency regions. The agricultural green development efficiency in the northeast and central regions fluctuates more than the other two regions in terms of change, mainly because although these regions have certain resource advantages, such as a wide area of land and rich resources in agricultural technology. However, there may be problems such as agricultural pollution in the process of long-term development, so the level of agricultural green development in these regions is unstable.

3.2. Analysis of changes in spatial and temporal patterns of food security

3.2.1. Analysis of temporal changes in food security

Before calculating the level of food security in each province of China using Equation (6), the indicators are first processed by Equations (3) and (4), and then the weights of the indicators are obtained by Equation (5). The food security level in China shows a fluctuating upward trend in 2010–2021, and in order to visualize the trend of changes in food security level in various regions, a graph of changes of food security level is drawn. As shown in Fig. 3, the food security level in the eastern, central and western regions fluctuates in 2010–2021, but there is an overall increase, indicating that the food security level is heading for the better. The food security level in the northeast region has declined slightly, but its average level during the 2010–2021 period is higher than that of the other regions as a whole. After experiencing the global food crisis in 2007–2008, the government of China issued and introduced development policies to help agriculture and increased agricultural inputs, the level of food production inputs gradually increased, and land productivity also rose, so the national food security level was in a fluctuating state of development in the period 2010–2016. This is also related to the regional development strategy formulated by China, which focuses on the development of secondary and tertiary industries, with a relatively weak capacity to undertake food production. After 2016, with the emergence of problems such as surface source pollution in agriculture, the food security level declined relatively, and the national average level was in a period of equilibrium during this period. With the introduction of concepts such as green development, food production will gradually develop in the direction of green and high quality. In 2016, the "Central No. 1″ document clarified the transformation of food security strategy, that is,

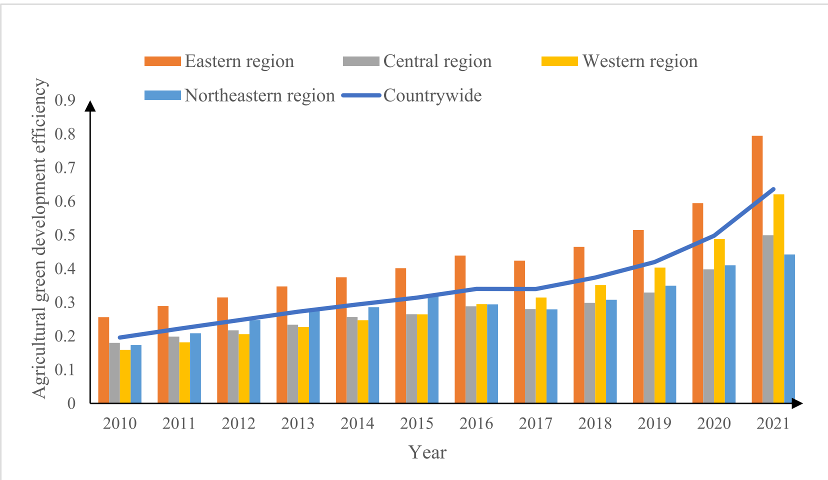

Fig. 1. Changes in the agricultural green development efficiency of China. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

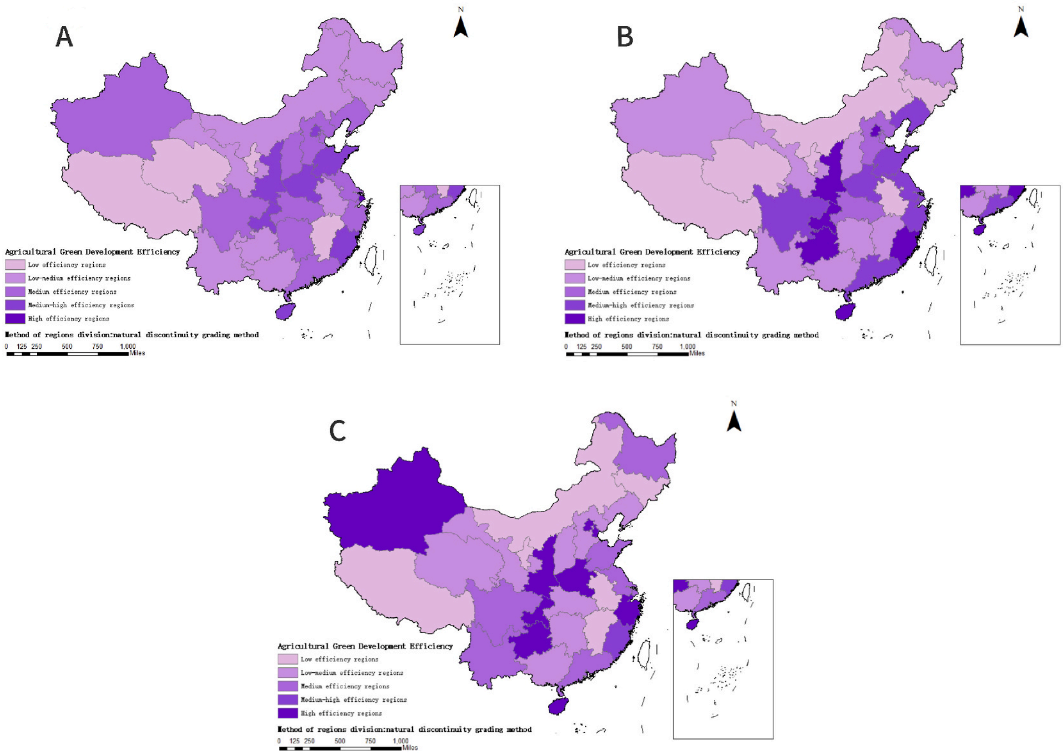

Fig. 2. Spatial distribution of agricultural green development efficiency in China. (A) Distribution map for 2010, (B) Distribution map for 2016, (C) Distribution map for 2021. Figures are drawn by the authors according to the standard map of the National Surveying and Mapping Geographic Information Bureau (Approved drawing number: GS (2016) 2921) (http://bzdt.ch.mnr.gov.cn/). All maps on this website are available for free download without copyright. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the transformation from quantity to quality. The implementation of the strategy has improved the national food security level to a certain extent, but on the whole, the extensive grain production mode still brings hidden dangers to China's food security. Problems such as agricultural non-point source pollution still existed, and the national food security level was in a balanced period during this period [66].

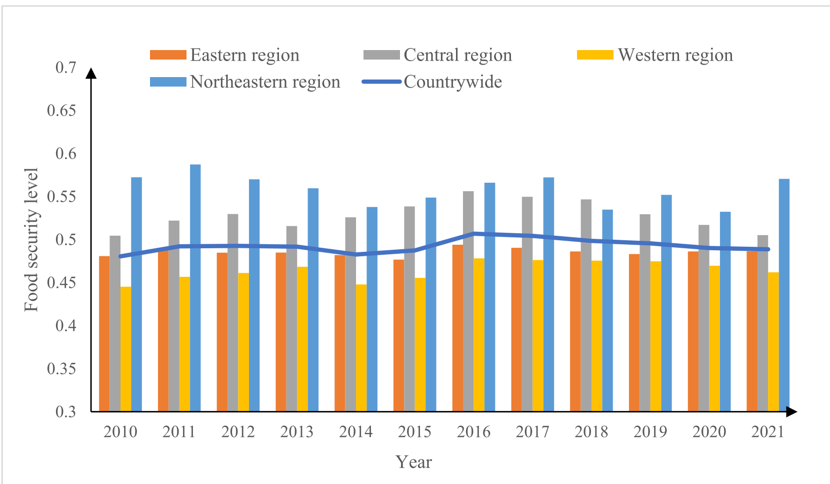

Fig. 3. Changes in the level of food security of China.

3.2.2. Analysis of changes in the spatial distribution of food security

We select three time points of 2010, 2016 and 2021 to observe the food security level. According to the natural discontinuity grading method, China was divided into five regions such as low level regions, low-medium level regions, medium level regions using ArcGIS 10.8 software. And the spatial distribution map of food security level in China is shown in Fig. 4. There are regional differences in the spatial distribution of food security in China in 2010–2021, which is specifically reflected in the food security of the northeast region to maintain a high level and Heilongjiang Province has been a high-level region. As the main grain-producing regions, the food security level of the northeast region is relatively high because of the wide area of arable land and excellent soil resource, which is suitable for the production of agricultural mechanization. However, the food security level of the western regions such as Xinjiang and Tibet has been at a low level because of lack of resources. In 2015, the Ministry of Agriculture put forward the goal of "double reduction" and carried out the zero-growth action of fertilizer and pesticide use, which can reduce pesticide residues and source pollution in grain, and effectively ensure food quality and safety. From 2018 to 2020, the government of China accelerated the implementation of the strategy of "reserving grain on the land and reserving grain on technology", implemented the system of farmland protection and ensured that all indicators of China's food security initially showed a balanced development trend, which greatly improved and enhanced food security [26]. As a whole, the food security level of China shows a decreasing trend from east to west, in which the provinces and regions with high food security in 2010 include Heilongjiang Province and Henan Province, etc. In 2016, Shandong Province, Jiangsu Province and other areas evolved into a high level of status, and the spatial pattern in 2021 is similar to that in 2016. The reason is that Heilongjiang, Henan, Shandong, Jiangsu and other provinces are the main grain producing areas, with a wide area of arable land, rich agricultural resources, and strong government support. After the implementation of farmland protection and other systems, the level of food security has improved rapidly. It can be seen that the food security level is mainly related to regional planning, and the level of food security in key areas of grain production is relatively high.

3.3. Analysis of the coupled coordination degree of agricultural green development efficiency and food security

3.3.1. Spatio-temporal analysis of coupled coordination

Firstly, Equation (7) is used to calculate the coupling coordination degree between the agricultural green development efficiency and the food security level in each province in China. From the time dimension, Fig. 5 shows how the coupling coordination degree of the two systems changes from 2010 to 2021. From Fig. 5, we can see that the average value of the coupling coordination degree of the two systems increased from 0.545 to 0.730 with a growth rate of 33.8 % in 2010–2021, which further indicates that the coordinated development of the two systems is constantly improving. In 2010–2016, the average level of coordinated development was relatively low. In 2016–2017, the degree of coupled coordination in some regions declined, which was mainly related to the fluctuation of the level of agricultural green development efficiency and food security. After 2017, the level of coupled coordinated development has continued to improve, and most regions have reached the primary coordination level. The coupled coordination development of the two systems in the eastern region is relatively fast, and in the western region shows a trend of slow and then fast. This situation is

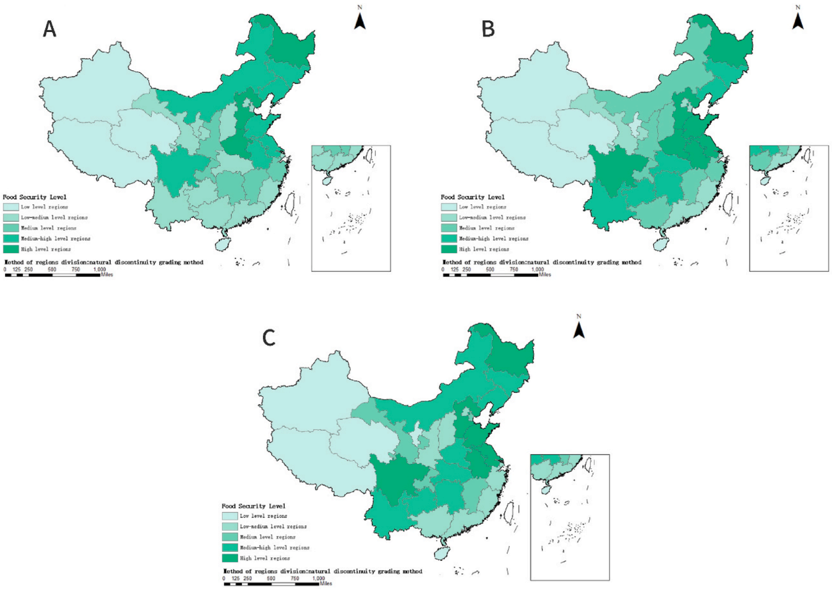

Fig. 4. Spatial distribution of the level of food security of China. (A) Distribution map for 2010, (B) Distribution map for 2016, (C) Distribution map for 2021. Figures are drawn by the authors according to the standard map of the National Surveying and Mapping Geographic Information Bureau (Approved drawing number: GS (2016) 2921) (http://bzdt.ch.mnr.gov.cn/). All maps on this website are available for free download without copyright.

broadly consistent with the changes in agricultural green development efficiency and food security level. This is mainly because in recent years, the Chinese government has focused on China's "three rural" issues (agriculture, rural areas and farmers) for many years, especially since the 19th National Congress of the Chinese government in 2017, continued to emphasize the green development of agriculture, led the rural revitalization with green development and achieved remarkable results in the transformation of the green economy and the construction of ecological civilization [66]. As agricultural technology resources continue to be enriched and various agricultural production technologies continue to be improved, the agricultural green development efficiency has improved and the level of food security has gradually stabilized, so that the level of coupled and coordinated development of them has continued to improve.

From the spatial dimension, Fig. 6 shows the spatial distribution map of the coupled coordination degree level of the two systems by using ArcGIS 10.8 software for the three time points of 2010, 2016 and 2021. Combining with the coupled coordination degree level division, China is divided into six regions including mildly dysfunctional regions, near dysfunctional regions and so on. From Fig. 6, the coupling coordination degree of the two systems in 2010 showed an overall trend of decreasing from east to west. The western region is resource-poor and backward in terms of agricultural production conditions, and both the efficiency of green agricultural development and the level of food security are low, so the coupling and coordination of the two systems is at a low level. Since the 19th National Congress of the Chinese government, with the implementation of various national strategic measures, the concept of green development has affected agricultural production, and the green development of agriculture has entered a new stage. The green and efficient development of agriculture is an important guarantee for sustainable food supply, and the coordinated development of the two is the top priority of China's "three rural" issues. As can be seen from Fig. 6, in 2016, with the improvement of agricultural production technology and the abundance of various agricultural resources, the coupling coordination level of them has been improved as a whole, and the distribution of primary coordination regions is relatively wide, covering the eastern region as well as the northeastern region except for Jilin Province, and in the central region, except for Anhui Province and Jiangxi Province, other provinces and regions have also reached the primary coordination level of the coupling coordination level. The development of the degree of coupling coordination in the western region is differentiated, with Sichuan, Guizhou and Chongqing having a relatively high degree of coupling coordination of them, belonging to the intermediate coordination level, while Tibet is still on the verge of dislocation. In 2021, with the food production mode in each province gradually taking green standards as the development direction, agricultural production pays more attention to green development and high-quality development, food production capacity continues to improve and food security is guaranteed. Therefore, the coupling coordination of agricultural green development efficiency and food security continues to improve. The spatial distribution variability of the coupled coordination level has relatively narrowed, with most provinces and regions in the eastern, central and northeastern regions reaching the intermediate coordination level. In the western region, all provinces and regions except Tibet have reached the primary level of coupling coordination, and the coupling coordination grades of Chongqing, Guizhou and Shaanxi have increased to the good coordination level. This distribution is related to the efficiency of agricultural green development and the level of food security in each province. The eastern and central regions have relatively high levels of agricultural green development efficiency and food security, agricultural production is more focused on green development, and the conditions for food production are more perfect, so the coupling and coordination between the two is also high. Overall, the provinces with a higher degree of coupling coordination are mostly located in regions with a larger scale of food production, while the degree of coupling coordination in regions such as the west is limited by agricultural resources and the scale of food production is insufficient, resulting in a low level of overall coordination between the efficiency of green development in agriculture and food security.

3.3.2. Analysis of coupled coordination types

To further analyze the coupled and coordinated development degree of the two systems, the relative development degree model is introduced to measure and analyze the relative development degree of them, and Equation (8) is used to calculate the relative development degree. Table 6 demonstrates the coupled and coordinated development stages and development types in 2010, 2016 and 2021. It is not difficult to find that the coupled and coordinated development stage of the two systems is mainly the low break-in, high break-in, low level coordination and high level coordination stage. And the types of coupled and coordinated development are mainly

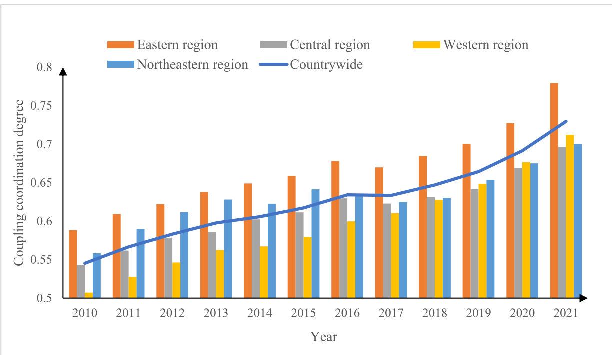

Fig. 5. Changes in the coupled harmonization of agricultural green development efficiency and food security in China. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

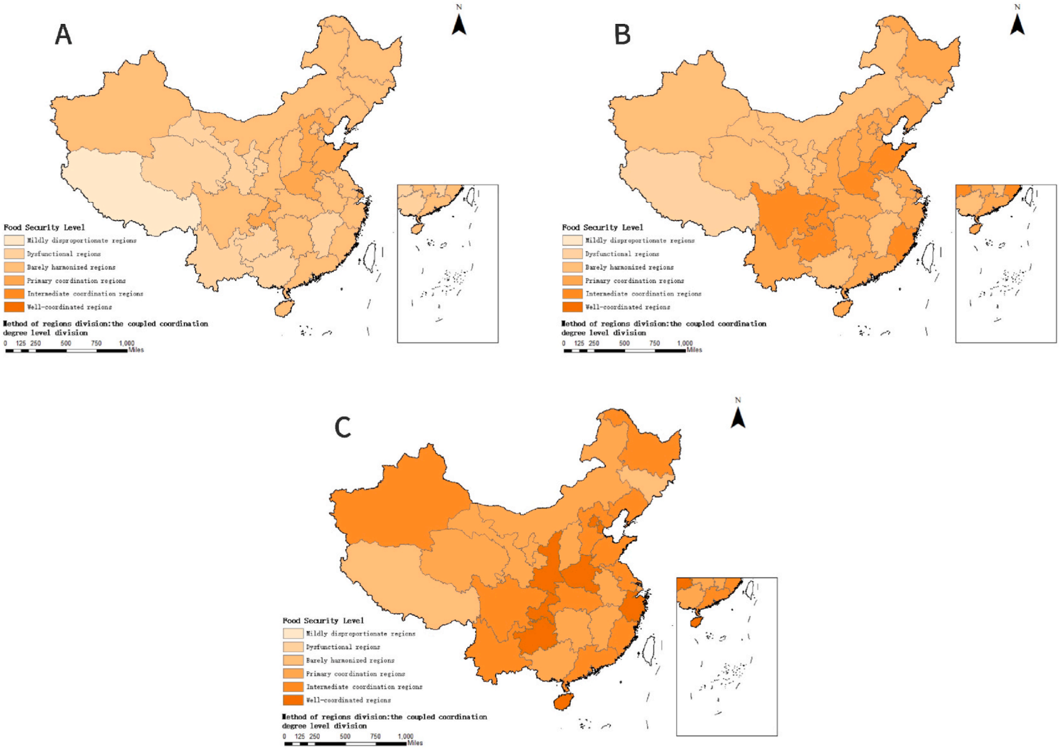

Fig. 6. Spatial distribution of coupled coordination rank of agricultural green development efficiency and food security in China. (A) Distribution map for 2010, (B) Distribution map for 2016, (C) Distribution map for 2021. Figures are drawn by the authors according to the standard map of the National Surveying and Mapping Geographic Information Bureau (Approved drawing number: GS (2016) 2921) (http://bzdt.ch.mnr.gov.cn/). All maps on this website are available for free download without copyright. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4, 5, 8 and 9. In 2010, except for Shanghai, other regions were at a low break-in stage and belonged to category 4. In 2016, the coupled coordinated development type of Beijing, Tianjin, Zhejiang, Guangdong and Shaanxi was category 5, which developed into a high break-in stage. And Shandong, Henan, Sichuan and Fujian were in the low level coordination stage while Chongqing and Guizhou were in the high level coordination stage. And other regions, such as Hebei, Shanxi and Hainan were still in the low break-in stage. In 2021, Shanxi, Guangxi, Gansu, Qinghai, and Ningxia evolved from the low break-in stage to the high break-in stage. Hebei, Liaoning, Heilongjiang, Jiangsu et al. had a coupling coordination type of 8, reaching the high coordination stage while Beijing, Tianjin, Shanghai et al. were in the low coordination stage and belonged to category 9.

To summarize, in the early stage, the coupled coordination development type of agricultural green development efficiency and food security was mostly 4 categories, which means that the agricultural green development system lagged behind the food security system. With the development of agricultural production in the direction of green and high quality, the efficiency of agricultural green development gradually improved. Therefore, the two systems began to synchronize their development and the stage of coupled and coordinated development gradually transitioned to the low level coordination stage and high level coordination stage. This shows that under the guidance of food security and green production policies, most provinces have achieved excellent results in greening agricultural production and ensuring food security, and the coupling and coordination capacity has been further strengthened. In short, only by maintaining the synchronous development of the two systems can we promote the coupling and coordinated development of agricultural green development efficiency and food security.

4. Discussion

This study first analyzes the spatio-temporal evolution of China's agricultural green development efficiency and food security level. The results show that from 2010 to 2021, China's agricultural green development efficiency showed a trend of continuous improvement, with the eastern region maintaining a high level and the western region improving significantly. The research results are consistent with Xu et al. 's research [19] on the efficiency measurement of agricultural green development in China. The eastern regions are rich in agricultural resources and have a good state of comprehensive agricultural development, so the agricultural green development efficiency remains a high level. With the implementation of various policies, agricultural production in the western regions has begun to develop from quantity to quality, and the efficiency of agricultural green development has increased significantly. The level of food security in China from 2010 to 2021 shows an overall trend of improvement, but the change rate is relatively small.

Table 6
Types of coupled and harmonized agricultural green development efficiency and food security in China, 2010, 2016 and 2021.

Region	2010		2016		2021	
	F	Type	F	Type	F	Type
Beijing	0.6791	4	1.1893	5	2.3936	9
Tianjin	0.5235	4	0.8421	5	2.2272	9
Hebei	0.3425	4	0.5968	4	0.8750	8
Shanxi	0.4037	4	0.5619	4	0.9934	5
Inner Mongolia	0.2325	4	0.3924	4	0.5605	4
Liaoning	0.4110	4	0.7238	4	0.9623	8
Jilin	0.3132	4	0.3933	4	0.4519	4
Heilongjiang	0.2087	4	0.4547	4	0.8846	8
Shanghai	0.9490	5	0.8923	5	1.2865	9
Jiangsu	0.3658	4	0.6306	4	1.0617	8
Zhejiang	0.4654	4	0.9375	5	2.3030	9
Anhui	0.2425	4	0.3239	4	0.5578	4
Fujian	0.5959	4	1.2331	9	1.7807	9
Jiangxi	0.2137	4	0.4777	4	0.7185	4
Shandong	0.4615	4	0.5986	7	0.9505	8
Henan	0.4231	4	0.6074	7	2.0073	9
Hubei	0.4634	4	0.6306	4	0.8965	8
Hunan	0.3896	4	0.5218	4	0.7902	4
Guangdong	0.4685	4	0.9778	5	1.4997	9
Guangxi	0.3258	4	0.5291	4	1.0808	5
Hainan	0.6582	4	1.4301	6	2.9008	9
Chongqing	0.6213	4	1.0588	8	2.1747	9
Sichuan	0.4337	4	0.6254	7	1.0256	8
Guizhou	0.3066	4	0.8851	8	2.1488	9
Yunnan	0.3075	4	0.4532	4	1.0552	8
Tibet	0.1567	4	0.1596	4	0.5056	4
Shannxi	0.4963	4	0.9513	5	2.3817	9
Gansu	0.3167	4	0.5625	4	0.8310	5
Qinghai	0.2450	4	0.5062	4	1.0914	5
Ningxia	0.2319	4	0.4865	4	0.8082	5
Xinjiang	0.5623	4	0.6831	4	2.6791	9

And the level of food security in the eastern region is higher than that in the western region, which is consistent with the research results of Wang et al. [40]. The level of food security is maintained at a high level in the eastern regions, where most of the provinces in the eastern region are major food-producing areas with advanced food and agricultural production conditions. And the level of food security is lower in the western regions, owing mainly to the scarcity of resources and insufficient food production capacity, etc. Although the issue of agricultural green development and food security is the focus of academic attention, there are few studies on the coupling and coordination relationship between agricultural green development and food security. The coordinated development of agricultural green development and food security is crucial, and a scientific understanding of the relationship between the two is conducive to promoting the joint improvement of agricultural green development and food security. Therefore, the analysis of the coupling degree between the two is helpful to understand the agricultural green development and food security of China and provides theoretical support for promoting the coordinated development of the two. It also has guiding significance for relevant research in other countries or regions.

5. Conclusions and suggestions

By establishing agricultural green development efficiency index system and food security evaluation index system, this paper uses Super-SBM model, entropy weight method and comprehensive evaluation method to estimate the agricultural green development efficiency and food security level of 31 mainland Chinese provinces from 2010 to 2021, and analyzes their spatial-temporal Coupling Relationship between them. The main conclusions are as follows.

First, the agricultural green development efficiency of China shows an overall trend of improvement from the perspective of time. From 2010 to 2021, the national agricultural green development efficiency increases from 0.196 to 0.636. With the implementation of various national strategic measures, the green development of agriculture has achieved certain results, but the overall development is insufficient and still needs to be further improved. From the perspective of space, the overall trend is high in the east and low in the west, and the difference between the regions of agricultural green development is significant and the development is unbalanced. The agricultural green development efficiency in the eastern region has been maintained at a high level, whereas the western region's situation shows a trend of slow and then fast development, and the central and northeast regions' efficiency of agricultural green development experiences some fluctuation.

Second, the level of food security in China shows an overall upward trend from the perspective of time, but it has a certain volatility, showing that the development of food security is unstable. Although the high input grain production mode in China can guarantee the output, it poses a threat to the ecological environment and food quality and safety. In addition, the spatial pattern shows a decreasing trend from east to west, which is reflected in the overall high level of food security in northeast China and the relatively poor situation of food security in western China, which still needs to be further improved. The level of food security increases overall, but the rate of change is relatively small and the development is more stable. From a spatial perspective, the food security situation in the western region has developed poorly, while the overall level in the eastern region is higher.

Third, the coupling coordination between the two systems has continually increased, with the average coupling coordination degree rising from 0.545 in 2010 to 0.730 in 2021. The coupling coordination type has transitioned from reluctant coordination to intermediate coordination. The country's efforts in promoting ecological civilization have improved agricultural development and higher-quality food production and enhanced the coupling and coordination between agricultural green development efficiency and food security. The eastern, central, and north-east regions predominantly exhibit an intermediate coordination level, whereas the western region primarily remains at a primary coordination level due to eco-nomic and environmental constraints. However, with various support policies in place, the western region has improved its agricultural production conditions and ensured food security, thus narrowing regional disparities.

Fourth, in 2010–2021, the coupling coordination level shifted from the break-in stage to the coordination stage. The main coupling types are: low break-in with lagging agricultural green development, high break-in with synchronous development, and others. In 2010, most regions were in the low break-in stage, indicating relatively low coupling and coordination between agricultural green development and food security in China. In 2021, many provinces had achieved significant progress in agricultural green development and improved food security levels, resulting in an overall improvement in coupling and coordination. Most regions had reached the coordination stage.

Based on the above conclusions, differentiated measures and suggestions were put forward for different coupling coordination types of the two systems.

First, for regions in low-break-in - lagging agricultural green development, such as Inner Mongolia, Jilin and Anhui provinces, the agricultural green development system lags behind the food security system and the food security level in these regions is relatively high, but the agricultural green development efficiency needs to be improved. In view of these areas, the suggestions are as follows. First of all, the government should attach importance to the theoretical and practical value of green agricultural development, formulate a scientific green and low-carbon agricultural development model and find a green agricultural development path according to local conditions to improve the efficiency of agricultural green development. Second, it is necessary to build an agricultural green coordination mechanism to promote the flow of resources, form the green agglomeration effect of interprovincial agricultural industry and narrow the differences between regions. Third, the government should strengthen pollution control efforts in rural areas and promote green production technologies such as water and energy conservation. And reducing the use of chemical fertilizers and pesticides is an effective measure to prevent and control pollution from non-point sources and promote green agricultural development.

Second, for regions in the highly break-in - synchronous development, such as Shanxi, Guangxi, Gansu and Hebei, although the level of agricultural green development and food security development is similar, the degree of coupling and coordination between the two systems needs to be further improved. The government should establish a mechanism for connecting food security with agricultural green development, on the premise of ensuring food security, clarify the direction of agricultural green development, increase capital and manpower investment in green ecological agriculture, constantly improve the level of agricultural modernization, narrow the gap between provinces, and achieve a win-win situation for food security and agricultural green development. For regions in highly coordinated - synchronous development, such as Liaoning and Shandong provinces, the government should continue to maintain the coordinated development of the two systems and establish a long-term and effective development concept to achieve both agricultural green development and food security.

Third, for regions in low-break-in - lagging food security, such as Beijing, Tianjin and Shanghai, the food security system lags behind the green agricultural development system. The agricultural green development efficiency in these regions is relatively high, but the food security level needs to be improved. In view of these regions, the suggestions are as follows. First, the government should strengthen the protection of cultivated land resources and reduce the pollution of cultivated land. For example, increasing the construction and investment of high-standard farmland in major grain-producing areas, reducing the use of fertilizers and pesticides, improving the farmland protection system and farmland water conservancy facilities are all effective measures. Second, it is inevitable to improve the organization of grain production. On the one hand, it is necessary to cultivate new business entities and develop large-scale operations. On the other hand, the government should improve the support policy for farmers, encourage farmers to participate in large-scale and industrial management and improve the service system for farmers to introduce farmers into the development track of modern agriculture. The third is to give full play to the role of science and technology, achieve "grain storage in the ground, grain storage in technology" and enhance the ability of agricultural science and technology innovation. The government should increase investment in agricultural science and technology, develop grain breeding technologies and promote the application of high and new technologies in the grain industry to raise the level of grain production and ensure food security.

Although this study is significant in both theory and practice, there are also limitations. First of all, due to the limitation of data availability, this study only analyzed 31 provinces in China, and future studies can expand the scope of research objects to include urban and rural areas. Secondly, the evaluation index system may have limitations, and more evaluation indicators can be selected from multiple perspectives in the future to obtain more comprehensive research results.

Data availability statement

Data will be made available on request.

Ethics statement

All participants provided informed consent to participate in the study.

CRediT authorship contribution statement

Kecheng Zhang: Visualization, Validation, Conceptualization. **Yuan Tian:** Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work is supported by the Project No. 23BJY010 of National Social Science Foundation of China.

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