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Study on the coupling coordination and barrier factors between agroecological security and rural green development in China

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Agroecological security is an important part of ecological security. Exploring the coupled and coordinated relationship between agroecological security and rural green development is of great strategic importance for sustainable economic and social development. This study takes 31 provinces (autonomous regions and municipalities directly under the central government) in China from 2011 to 2021 as the research object and constructs an index system of agroecological security and rural green development. On this basis, the comprehensive evaluation index of agroecological security and rural green development is measured using the coefficient of variation method, the synergistic evolutionary relationship between the two is quantitatively analyzed using the coupled coordination model, the spatial distribution and evolution characteristics are analyzed using spatial autocorrelation method, and the barrier factors are diagnosed via combination with the barrier degree model. The research results show that the coupled coordination type of agroecological security and rural green development is the primarily coordinated agroecological security lag type, the spatial clustering effect is relatively weak, and the coupled coordination relationship needs to be further improved. The local financial expenditures on agriculture, forestry and water affairs per unit of GDP, the ratio of flood-removing area, and the ratio of soil erosion control have always been the greatest barriers to China's agroecological security and rural green development. The results of this study help to compensate for the lack of research on the coupling and coordination of agroecological security and rural green development, and provide a reference for exploring the benign coordination and interaction between agroecological security and rural green development.

Keywords Agroecological security, Rural green development, Coupling coordination, Barrier factors

There is an enormous ecological cost behind increasing food production and gross agricultural output value. Rough agricultural production and management modes, excessive use of chemical fertilizers and pesticides, inappropriate livestock and poultry farming manure, wastewater treatment, and a series of other activities have caused disturbances to the agroecosystem, resulting in severe agricultural surface pollution, soil toxicity, overexploitation of groundwater resources, crop pests and diseases, and a series of additional ecological problems. The negative effects of agricultural "reverse ecologization" have intensified, agricultural resources are insufficient, and the ecological environment is fragile. This illustrates the prevalence and severity of agroecological security problems. The countryside is a centralized agricultural production and development place and is the main battlefield for maintaining China's agroecological security. Therefore, agroecological security and the development of the countryside are closely related. Under the guidance of the green development concept of harmonious coexistence between man and nature, China has proposed the green development of the countryside in combination with the actual development of the countryside in the hope of realizing the sustainability of the countryside's economy and ecological environment. In the new era, with the proposal of ecological civilization construction and high-quality development, addressing the relationship between agroecological security and rural green development is particularly important. Agroecological security and rural green development are closely related, and this relationship is based on the sustainable development goals pursued by both parties together. Agroecological security aims to safeguard the production capacity of agriculture and the quality and safety of agricultural products while maintaining and restoring the health and stability of agroecosystems. Rural green development emphasizes seeking a balance between economic development and environmental

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protection and realizing the unity of economic, social, and ecological benefits through optimizing the industrial structure and promoting green production methods. The two are interdependent and complementary, together constituting an important theoretical framework for promoting the comprehensive revitalization of rural areas and the construction of ecological civilization. Agroecological security provides the necessary material foundation and ecological support for rural green development. Healthy agroecosystems can effectively supply clean water, fertile land, and rich biodiversity, which are all prerequisites for sustainable rural economic development. For example, good soil and water conservation measures can prevent soil erosion, increase the productivity of land, and reduce the waste of resources in agricultural production. In addition, the stability and diversity of ecosystems can help prevent natural disasters and reduce the occurrence of pests and diseases, thus reducing the costs and risks of agricultural production and creating favorable conditions for rural green development. Rural green development further promotes the realization of agroecological security through measures such as improving resource utilization efficiency and reducing pollutant emissions, forming a virtuous cycle. An optimized industrial structure and green production methods can reduce the excessive development and utilization of natural resources and alleviate pressure on the ecological environment. For example, the promotion of organic agriculture and ecoagriculture techniques can reduce the use of chemical fertilizers and pesticides, reduce the pollution of soil and water, and protect the health of agroecosystems. Moreover, the green development of the countryside also focuses on the establishment and improvement of the ecological compensation mechanism, which incentivizes farmers to actively participate in ecological protection and restoration activities. Furthermore, it consolidates and improves the level of agroecological security. In short, agroecological security and rural green development are causal and mutually reinforcing, and together they promote the comprehensive and sustainable development of rural areas. Therefore, exploring whether China's agricultural agroecological security and rural green development are coupled and coordinated to promote ecological environmental protection, accelerate the modernization of agriculture and rural development, and safeguard national ecological security is highly theoretical and practical.

In recent years, with the increasingly prominent contradiction between resources and the environment, agroecological problems have occurred frequently, and agroecological security and rural green development have gradually become hot spots of academic research. Scholars have conducted more in-depth studies on the connotations, evaluation methods, influencing factors, and practice paths of agroecological security and rural green development. Agroecological security is an important part of ecological security. With respect to agroecological security, Wu Guoqing (2001), Zhao Fei (2007) and other scholars, from the perspective of social and natural composite and sustainable development, believe that agroecological security refers to the fact that the natural resources and ecological environment on which agriculture relies for its development are in a nonthreatening, healthy and balanced state[1,2]. With respect to methods for evaluating agroecological security, Ling Ying (2020), Yu Fei (2011), Zhang Cuijuan (2020), He Xiaoyao (2020) and other scholars have used the entropy weight method, hierarchical analysis, the ecological footprint and the ecological carrying capacity to measure the level of agroecological security in different regions[3–6]. With respect to the practical path of agroecological security, Xiong Ying, Wang Kelin (2003) and other scholars proposed continuously strengthening and improving the legislation of agroecological environmental security, adjusting the structural adjustment of the agricultural industry, strengthening the national investment in scientific research on agro-environment, and continuously strengthening and improving national ecological and environmental cultural education and construction[7]. Zhu Meiying, Luo Yunkuo (2006) and other scholars proposed strengthening the construction and management of soil ecosystems and improving the construction of ecologically protected forest systems[8]. Luo Haiping, Li Zhuoya (2022) and other scholars proposed optimizing the spatial pattern of agricultural development and promoting the balanced development of the region to build a safe system of fertilizer, medicine and film application and to strengthen the supervision of ecological environmental protection[9]. With respect to the connotation of rural green development, Qin Lu (2023) and other scholars believe that rural green development refers to the shift from the traditional development mode to the green development mode in the process of production and life in rural areas and the realization of the sustainable development of the rural economy and environment[10]. In terms of methods for evaluating rural green development, scholars such as Gou Xingzhao (2020), Cheng Li (2020), Ma Xiaodong (2022), Zhao Wei (2023), Ji Kaiting (2023) and others have used TOPSIS, the gray correlation coefficient, the entropy weighting method, Tyrell's index, Moran's I, and principal component analysis (PCA) to measure and decompose rural green development from different perspectives and clarify its spatiotemporal characteristics and regional differences. These methods have revealed that economic development, rural human capital content, urban-rural integration and development, rural innovation and entrepreneurship, agricultural green infrastructure investment, urbanization, industrialization, and financial support for agriculture have facilitating or inhibiting effects on rural green development[11–15]. Regarding the practical path of rural green development, Yang Shiwei (2020) proposed improving the laws and policies of rural green development and the ecological compensation mechanism and coordinating the comprehensive management of outstanding rural environmental problems and the sustainable improvement of human habitat[16]. Duan Yanfeng (2020) proposed promoting rural green development from the aspects of cultural construction, ecological governance, production mode, lifestyle, and institutional innovation[17]. Moreover, Zhou Ying, He Ruhai (2020) conducted a dynamic analysis of the time series trend and spatial differentiation characteristics of the coupled coordination level of urbanization and agroecological security[18]. Jian Xiaoyu and Wei Yuan (2022) studied the coupling and coordination level of the ecological security of arable land and agricultural economic development in Guizhou Province[19]. The above studies have laid the foundation for comprehensively revealing the coupled and coordinated relationship between agroecological security and rural green development, but there is still room for further expansion. First, at the research scale, scholars have used mostly the main grain-producing areas as the main research objects, while there is a relative lack of research at the national scale. Second, in the index system, the evaluation index system is diverse and lacks a unified evaluation standard. Third, in terms of research content, it focuses mainly on the evaluation of agroecological security and rural green development and the proposal of development strategies but lacks systematic research on the relationship between the two.

Therefore, this paper calculates comprehensive evaluation indices of agroecological security and rural green development in 31 provinces in China to explore the coupling and coordination relationships between the two, as well as the key barrier factors, with the goal of providing references for promoting rural revitalization and achieving high-quality development.

Research methodology and indicator system construction

Overview of the study area

This paper refers to the National Bureau of Statistics' division of China's 31 provincial regions (autonomous regions and municipalities directly under the central government) into four major areas, namely, the eastern area, central area, western area and northeastern area, based on social development (in view of the content of the study as well as the availability of data, Taiwan Province, the Hong Kong Special Administrative Region and the Macao Special Administrative Region are not included in the study). The specific division is shown in Table 1.

Research methods

Coupled coordination model

The coupled system of agroecological security and rural green development is a composite system coupled with agroecological security and rural green development subsystems. The way and rules of interaction between the elements and variables are the keys to the coupled system, which determines the direction of the future development of the coupling and the degree of stability. The coupling mechanism of agroecological security and rural green development is reflected mainly through the impact of agroecological security on rural green development and the impact of rural green development on agroecological security. Among them, the impact of agroecological security on rural green development manifests as supportive and constraining effects. The impact of rural green development on agroecological security manifests as promotion and coercion.

The degree of coupling coordination can be used to judge the coupling relationship between agroecological security and rural green development and whether it is benign and sustainable. The relative development degree index of agroecological security and rural green development is constructed, and the calculation steps of the model are as follows[20–23]:

Coupling degree: $C = \frac{2\sqrt{(U1*U2)}}{U1+U2}$

Comprehensive coordination index: $T = \alpha\, U1 + \beta\, U2$

Coupling coordination degree: $D = \sqrt{(C*T)}$

Relative development degree: $\gamma\ = \frac{U1}{U2}$

Where U1 is agroecological security, U2 is rural green development, α and β are the parameters to be estimated for the comprehensive coordination index, and $\alpha+\beta=1$. In this paper, we believe that in the coupled system of agroecological security and rural green development, both are equally important. Therefore, let $\alpha=0.5$ and $\beta=0.5$, and their coupling coordination degrees are divided, as shown in Table 2:

Moran's I

This paper applies the Moran's I to explore whether the coupled and coordinated relationship between agroecological security and rural green development has spatial correlation and agglomeration. The index is calculated via the following formula[24]:

Global Moran's I: $I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n}w_{ij}(x_i-\bar{x})(x_j-\bar{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n}w_{ij}\sum_{i=1}^{n}(x_i-\bar{x})^2}$

Local Moran's I:

$$I_i = \frac{n(x_i-\bar{x})\sum_{j=1}^{n}w_{ij}(x_j-\bar{x})}{\sum_{i=1}^{n}(x_i-\bar{x})^2}$$

Where n is the number of regions, w_{ij} is the spatial weight matrix of regions i and j, and x is the target variable (the level of coupling and coordination of agroecological security and rural green development). When I passes the test of significance, $I>0$ indicates a positive correlation; $I<0$ indicates a negative correlation; and $I=0$ indicates that there is no spatial correlation.

Research area	Provinces
Eastern area	Beijing Tianjin Hebei Shanghai Jiangsu Zhejiang Fujian Shandong Guangdong Hainan
Central area	Shanxi Anhui Jiangxi Henan Hubei Hunan
Western area	Inner Mongolia Guangxi Chongqing Sichuan Guizhou Yunnan Tibet Shaanxi Gansu Qinghai Ningxia Xinjiang
Northeast area	Liaoning Jilin Heilongjiang

Table 1. Research area division.

Coupling coordination degree	Coordination level	Relative development degree	Coupling coordination type
$0 \leq D < 0.1$	Extremely imbalanced	$0 < \gamma \leq 0.8$	Extremely imbalanced agroecological security lag type X1
		$0.8 < \gamma \leq 1.2$	Extremely imbalanced agroecological security and rural green development co-loss type X2
		$1.2 < \gamma$	Extremely imbalanced rural green development lag type X3
$0.1 \leq D < 0.2$	Seriously imbalanced	$0 < \gamma \leq 0.8$	Seriously imbalanced agroecological security lag type X4
		$0.8 < \gamma \leq 1.2$	Seriously imbalanced agroecological security and rural green development co-loss type X5
		$1.2 < \gamma$	Seriously imbalanced rural green development lag type X6
$0.2 \leq D < 0.3$	Moderately imbalanced	$0 < \gamma \leq 0.8$	Moderately imbalanced agroecological security lag type X7
		$0.8 < \gamma \leq 1.2$	Moderately imbalanced agroecological security and rural green development co-loss type X8
		$1.2 < \gamma$	Moderately imbalanced rural green development lag type X9
$0.3 \leq D < 0.4$	Mildly imbalanced	$0 < \gamma \leq 0.8$	Mildly imbalanced agroecological security lag type X10
		$0.8 < \gamma \leq 1.2$	Mildly imbalanced agroecological security and rural green development co-loss type X11
		$1.2 < \gamma$	Mildly imbalanced rural green development lag type X12
$0.4 \leq D < 0.5$	Minimally imbalanced	$0 < \gamma \leq 0.8$	Minimally imbalanced agroecological security lag type X13
		$0.8 < \gamma \leq 1.2$	Minimally imbalanced agroecological security and rural green development co-loss type X14
		$1.2 < \gamma$	Minimally imbalanced rural green development lag type X15
$0.5 \leq D < 0.6$	Barely coordinated	$0 < \gamma \leq 0.8$	Barely coordinated agroecological security lag type X16
		$0.8 < \gamma \leq 1.2$	Barely coordinated agroecological security and rural green development synchronous type X17
		$1.2 < \gamma$	Barely coordinated rural green development lag type X18
$0.6 \leq D < 0.7$	Primarily coordinated	$0 < \gamma \leq 0.8$	Primarily coordinated agroecological security lag type X19
		$0.8 < \gamma \leq 1.2$	Primarily coordinated agroecological security and rural green development synchronous type X20
		$1.2 < \gamma$	Primarily coordinated rural green development lag type X21
$0.7 \leq D < 0.8$	Moderately coordinated	$0 < \gamma \leq 0.8$	Moderately coordinated agroecological security lag type X22
		$0.8 < \gamma \leq 1.2$	Moderately coordinated agroecological security and rural green development synchronous type X23
		$1.2 < \gamma$	Moderately coordinated rural green development lag type X24
$0.8 \leq D < 0.9$	Well- coordinated	$0 < \gamma \leq 0.8$	Well-coordinated agroecological security lag type X25
		$0.8 < \gamma \leq 1.2$	Well-coordinated agroecological security and rural green development synchronous type X26
		$1.2 < \gamma$	Well-coordinated rural green development lag type X27
$0.9 \leq D < 1$	Highly coordinated	$0 < \gamma \leq 0.8$	Highly coordinated agroecological security lag type X28
		$0.8 < \gamma \leq 1.2$	Highly coordinated agroecological security and rural green development synchronous type X29
		$1.2 < \gamma$	Highly coordinated rural green development lag type X30

Table 2. Classification criteria for the degree of coupling coordination.

Barrier degree model

This paper introduces the barrier degree model to explore the barrier factors of agroecological security and rural green development. This is a comparative study of the barrier factors and their types that affect the coordinated development of agroecological security and rural green development in each province during the study period. The calculation steps of the method are as follows[23]:

Barrier degree: $O_{ij} = \frac{(1-x_{ij})^{*}W_j}{\sum_{i=1}^{n}(1-x_{ij})^{*}W_j}$

Where x_{ij} is the normalized value and W_j is the weight.

Indicator system construction

Agricultural ecological security and rural green development constitute a complex system that is influenced by the interaction of political, economic, ecological and social factors and involves a wide range of factors. Therefore, the construction of a comprehensive evaluation index system for China's agroecological security and rural green development is a complex systematic project that requires the use of systematic theory and a comprehensive and integrated approach to study and analyze the characteristics and movement laws of agroecological security and rural green development and to reflect the current situation and achievements of China's agroecological security and rural green development, as well as to comply with the direction of its future development. At present, the academic community has not formed a perfect comprehensive evaluation index system for agroecological security and rural green development. This paper follows the principles of scientificity, systematicity, comprehensiveness and operability when constructing an evaluation index system for agroecological security and rural green development. The objectives and scope of the study are first clarified, to comprehensively assess the current situation of agroecological security and rural green development in China. Through an in-depth literature review and theoretical analysis, key elements and influencing factors of agroecological security and rural green development are identified, and preliminary indicators that can effectively reflect these elements

Target layer	Criterion layer		Indicator layer	Serial number	Attribute
Agro-ecological security	Ecological pressure	Population pressure	Population density	Y1	Negative
			Natural rate of population growth	Y2	Negative
		Resource pressure	Urbanization level	Y3	Negative
			Electricity consumption per unit of GDP	Y4	Positive
		Environmental pressure	Service strength of agricultural plastic film	Y5	Negative
			The amount of fertilizer applied per mu	Y6	Negative
			The amount of pesticides per mu	Y7	Negative
	Ecological state	Resource state	Forest coverage rate	Y8	Positive
			Total water resources	Y9	Positive
			Arable land per capita	Y10	Positive
		Health state	Multiple cropping index	Y11	Positive
			Crop damage rate	Y12	Negative
			Natural disaster rate	Y13	Negative
			Effective irrigation area ratio	Y14	Positive
	Ecological response	Input response	Local government expenditure per unit GDP on agriculture, forestry and water conservancy affairs	Y15	Positive
			Local fiscal expenditure per unit of GDP on environmental protection	Y16	Positive
		Governance response	Area ratio of waterlogging control	Y17	Positive
			Soil erosion control ratio	Y18	Positive
		Output response	Per capita grain output	Y19	Positive
			Total power of agricultural machinery	Y20	Positive

Table 3. Comprehensive evaluation index system of agroecological security.

Target layer	Criterion layer	Indicator layer	Serial number	Attribute
Rural green development	Green economy	Growth rate of total output value of agriculture, forestry, animal husbandry and fishery	Y21	Positive
		Per capita household income of rural residents	Y22	Positive
		Agricultural labor productivity	Y23	Positive
		Industrial structure adjustment index	Y24	Positive
	Green ecology	Per capita road area	Y25	Positive
		Village green coverage rate	Y26	Positive
		Water penetration rate	Y27	Positive
		Domestic waste disposal rate	Y28	Positive
	Green society	Number of rural health technicians per 10,000 people	Y29	Positive
		Population coverage of rural TV programs	Y30	Positive
		Village culture station	Y31	Positive
		Ratio of income level of urban and rural residents	Y32	Negative

Table 4. Comprehensive evaluation index system of rural green development.

and factors are screened. Specifically, the research results of scholars such as Ji Cuimei (2019), Zhou Ziying (2021), Luo Haiping (2022), Gou Xingzhao (2021), Yan Mingtao (2022), and Ma Xiaodong (2022) were drawn upon[9,13,25–28]. On this basis, expert consultation was used to invite experts and scholars in related fields to review and discuss the preliminary indicators to ensure the scientific validity and rationality of the selected indicators. Through several expert meetings and questionnaire surveys, a set of comprehensive and systematic evaluation indicator systems was finally determined. In addition, to ensure the operability and practicability of the indicator system, this study fully considers the accessibility and reliability of the data and selects those indicators that can be obtained through existing data sources or field surveys to ensure the practicability and credibility of the evaluation results. The target layer of the indicator system reflects the overall level of China's agroecological security and rural green development; the criterion layer reflects the three aspects of agroecological security, namely, pressure, state, and response (PSR model); and the three aspects of rural green development, namely, the green economy, green ecology, and green society. The specific indicator system is shown in Tables 3, 4.

Data sources

The data in this paper come from China Statistical Yearbook, China Urban and Rural Construction Statistical Yearbook, and China Rural Statistical Yearbook. The missing values are supplemented by the interpolation method and smoothing index method.

Results

Analysis of the spatial and temporal evolution of China's agroecological security

In this work, we use the coefficient of variation method to calculate the agroecological security index of China's 31 provinces from 2011 to 2021 (Table 5) and draw a dynamic trend map of agroecological security in China and each region from 2011 to 2021 (Fig. 1) to describe the changes in China's agroecological security over different time periods. As shown in Fig. 1, the overall trend of China's agroecological security from 2011 to 2021 fluctuated and rose, and its comprehensive score rose from 0.2699 in 2011 to 0.3092 in 2021, with a rise of 14.58%. The level of China's agroecological security fluctuated from 2011 to 2017 (with an average speed of 0.17%), and from 2017 onward, the agroecological security level growth rate began to increase (average speed of 3.2%). These findings indicate that the state of agroecological security in China is not optimistic. Although, in recent years, awareness of the protection of agroecological security in China has gradually increased, the index of agroecological security has not risen substantially. How to improve the level of China's agroecological security is still an urgent problem to be solved.

As shown in Fig. 1, agroecological security in China's eastern, central, western and northeastern areas is in a fluctuating and rising state. After 11 years of development, there was a greater level of agroecological security in the eastern, central and northeastern areas than in the western area. The eastern area has a faster growth rate, increasing by 22.87%; the western area has a slower growth rate, increasing by 7.7%; and the central and northeastern areas have relatively moderate rates of increase, increasing by 15.41% and 13.48%, respectively. Although the agroecological security rankings of provinces and regions have risen or fallen during this decade and there are differences in the speed of development, generally speaking, the level of agroecological security in all regions is moving toward a relatively high level.

Analysis of the spatial and temporal evolution of China's rural green development

This paper applies the coefficient of variation method to calculate the rural green development index of China's 31 provinces from 2011 to 2021 (Table 6) and draws a dynamic trend map of China's and each region's rural green development from 2011 to 2021 (Fig. 2) to characterize the changes in China's rural green development

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Beijing	0.2720	0.2661	0.2472	0.2429	0.1987	0.1845	0.1859	0.2100	0.2712	0.2990	0.3434
Tianjin	0.2629	0.2600	0.2572	0.2597	0.2670	0.2581	0.2606	0.2712	0.3117	0.3049	0.3242
Hebei	0.2843	0.2866	0.2884	0.2885	0.2952	0.2753	0.2796	0.2921	0.2985	0.3057	0.3073
Shanxi	0.2276	0.2292	0.2276	0.2323	0.2349	0.2311	0.2204	0.2281	0.2308	0.2409	0.2309
Inner Mongolia	0.2979	0.2993	0.3031	0.3053	0.3155	0.3061	0.3036	0.3194	0.3230	0.3294	0.3238
Liaoning	0.2420	0.2515	0.2444	0.2259	0.2349	0.2388	0.2343	0.2317	0.2412	0.2430	0.2528
Jilin	0.2855	0.2918	0.2948	0.2917	0.2966	0.3087	0.3033	0.3014	0.3150	0.3156	0.3160
Heilongjiang	0.3273	0.3345	0.3445	0.3497	0.3708	0.3655	0.3806	0.3775	0.3920	0.4032	0.4014
Shanghai	0.2164	0.2201	0.2114	0.2265	0.2375	0.2275	0.2148	0.2236	0.2377	0.2383	0.2388
Jiangsu	0.2874	0.2879	0.2856	0.2920	0.3025	0.3094	0.3119	0.3261	0.3359	0.3555	0.3602
Zhejiang	0.2851	0.3042	0.2758	0.2956	0.3042	0.2951	0.2807	0.3027	0.3520	0.3574	0.3820
Anhui	0.2869	0.2918	0.2906	0.3031	0.3095	0.3123	0.3015	0.3074	0.3080	0.3323	0.3342
Fujian	0.2574	0.2735	0.2752	0.2749	0.2726	0.2871	0.2589	0.2750	0.3246	0.3268	0.3420
Jiangxi	0.3098	0.3483	0.3049	0.3155	0.3283	0.3303	0.3200	0.3138	0.3391	0.3455	0.3516
Shandong	0.2691	0.2710	0.2755	0.2705	0.2777	0.2567	0.2569	0.2822	0.2951	0.3137	0.3246
Henan	0.2810	0.2799	0.2754	0.2782	0.2874	0.2781	0.2784	0.2867	0.2882	0.2996	0.3041
Hubei	0.2489	0.2546	0.2550	0.2656	0.2741	0.2727	0.2746	0.2782	0.2793	0.3107	0.3090
Hunan	0.2858	0.3093	0.2965	0.3137	0.3187	0.3214	0.3167	0.3214	0.3488	0.3604	0.3629
Guangdong	0.2627	0.2733	0.2711	0.2618	0.2654	0.2714	0.2582	0.2820	0.3177	0.3186	0.3215
Guangxi	0.2605	0.2780	0.2755	0.2732	0.2889	0.2804	0.2811	0.2838	0.3056	0.3181	0.3123
Hainan	0.2373	0.2435	0.2502	0.2282	0.2185	0.2383	0.2404	0.2685	0.2696	0.2788	0.2931
Chongqing	0.2412	0.2434	0.2391	0.2483	0.2440	0.2467	0.2508	0.2539	0.2626	0.2820	0.2893
Sichuan	0.2494	0.2577	0.2513	0.2592	0.2585	0.2582	0.2577	0.2721	0.2843	0.2979	0.3055
Guizhou	0.2561	0.2800	0.2649	0.2855	0.2854	0.2793	0.2740	0.2752	0.2992	0.3023	0.2967
Yunnan	0.2633	0.2672	0.2671	0.2696	0.2712	0.2723	0.2733	0.2730	0.2709	0.2796	0.2826
Tibet	0.3255	0.3377	0.3173	0.3406	0.4255	0.4002	0.3319	0.3519	0.3593	0.3493	0.3151
Shaanxi	0.2448	0.2368	0.2267	0.2282	0.2323	0.2256	0.2261	0.2358	0.2549	0.2590	0.2683
Gansu	0.2488	0.2440	0.2323	0.2331	0.2473	0.2351	0.2431	0.2565	0.2564	0.2632	0.2537
Qinghai	0.3189	0.3240	0.3322	0.3238	0.3278	0.3069	0.2883	0.2981	0.3032	0.3086	0.3021
Ningxia	0.3005	0.3004	0.2911	0.2879	0.2986	0.2776	0.2861	0.2946	0.2834	0.2791	0.2689
Xinjiang	0.2292	0.2358	0.2504	0.2462	0.2634	0.2698	0.2569	0.2606	0.2669	0.2759	0.2675

Table 5. Comprehensive score of agricultural ecological security level from 2011 to 2021.

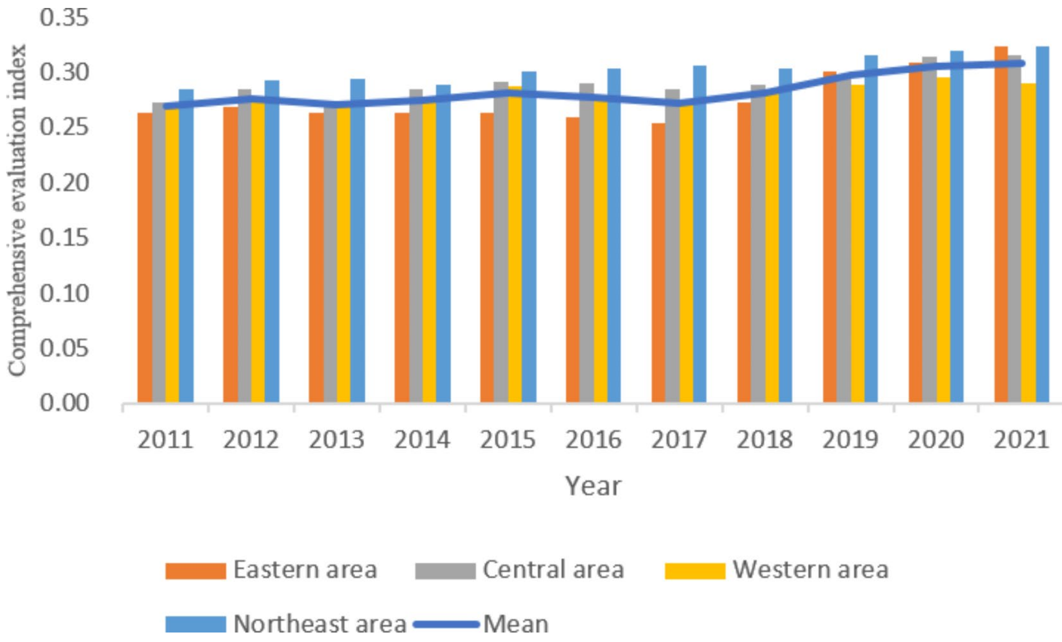

Fig. 1. Evolution trend of agroecological security in China from 2011 to 2021.

in different time periods. As shown in Fig. 2, China's rural green development as a whole shows a slow upward trend from 2011 to 2021, and its comprehensive score increases from 0.3136 in 2011 to 0.4733 in 2021, with a rise of 50.94%. From 2011 to 2017, China's level of rural green development was in a relatively slow-growing state (with an average growth rate of 2.92%), and from 2017 onward, the growth rate of the rural green development level began to increase (the average rate was 6.16%). This is inextricably linked to China's insistence on taking the path of ecological revitalization and green development in the countryside in recent years, and the introduction of the Three-Year Action Plan for the Improvement of Rural Habitat (2018–2020) in 2017 accelerated the pace of green development in the countryside.

As shown in Fig. 2, the level of rural green development is on the rise in all areas of China. After 11 years of development, the level of rural green development is highest in eastern area, followed by the central and northeastern areas, and lagging behind in the western area. However, the western area has a faster growth rate, with a rise of 75.08%; the eastern area has a slower growth rate, with an increase of 33.05%; and the central and northeastern areas have relatively moderate rates of increase, with increases of 53.03% and 48.43%, respectively.

Analysis of coupling and coordination between agroecological security and rural green development

This paper uses the coupling coordination model to calculate the coupling coordination of agroecological security and rural green development in 31 provinces from 2011 to 2021 (Table 9).

Analysis of coupling coordination development stage

In terms of time, the coupling and coordination of agroecological security and rural green development in China shows a steady upward trend, but the increase is low (Fig. 3). During the 11 years, the degree of coupling coordination between agroecological security and rural green development in 31 provinces in China exhibited two states: fluctuating increase and relative stability. Guizhou, Tibet, Shaanxi, Gansu, and Qinghai have moved from the minimally imbalanced stage to the barely harmonized stage; the remaining provinces have entered the primary harmonization stage. Those in a relatively stable state include Beijing, Shanxi, Liaoning, Chongqing, Yunnan, and Ningxia; except for Beijing (which is in the primary coordination stage), the remaining provinces are in the barely coordinated stage. Overall, the current level of coupled coordination between agroecological security and rural green development in China has not reached an ideal state but has shown a positive development trend.

From the spatial dimension, the overall coupling and coordination of China's agroecological security and rural green development shows a spatial pattern of "high in the east and low in the west, high in the south and low in the north". The degree of coordination of the two couplings is in the following order: East > Central > Northeast > West. The eastern, central and northeastern areas have entered the primary coordination stage from the barely coordinated stage, whereas the western area is still in the barely coordinated stage. This is due mainly to the poor geographic environment, crude production methods, and dependence on resources for development in the western area, resulting in a vicious cycle. Various factors have led to low levels of agroecological security and rural green development in the region, which has not produced a good agroecological security–rural green development interaction effect.

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Beijing	0.4899	0.4551	0.4753	0.4692	0.4952	0.5076	0.4626	0.4983	0.5407	0.5540	0.5845
Tianjin	0.4017	0.4096	0.4372	0.4546	0.4571	0.4940	0.4574	0.4360	0.4481	0.4530	0.4585
Hebei	0.2734	0.2849	0.2937	0.3004	0.3064	0.3487	0.3677	0.3703	0.4010	0.4559	0.4808
Shanxi	0.2816	0.2820	0.2927	0.3103	0.3065	0.3170	0.3272	0.3378	0.3696	0.4098	0.4138
Inner Mongolia	0.2652	0.2649	0.2705	0.2775	0.2856	0.3112	0.3382	0.3326	0.3433	0.3916	0.4287
Liaoning	0.3019	0.3021	0.3203	0.3155	0.3203	0.3121	0.3585	0.3450	0.3656	0.3745	0.4168
Jilin	0.2940	0.2806	0.2731	0.2885	0.2926	0.2951	0.4622	0.3473	0.3857	0.4690	0.4789
Heilongjiang	0.2924	0.2936	0.2933	0.2825	0.2880	0.2994	0.3187	0.3131	0.3537	0.4010	0.4229
Shanghai	0.5041	0.4915	0.5344	0.5365	0.5311	0.4981	0.4423	0.5246	0.5448	0.5547	0.5770
Jiangsu	0.4418	0.4409	0.4396	0.4563	0.4760	0.4884	0.5033	0.5107	0.5462	0.5711	0.5886
Zhejiang	0.3879	0.4057	0.4085	0.4077	0.4171	0.4461	0.4734	0.4715	0.5040	0.5932	0.5770
Anhui	0.2895	0.2931	0.3198	0.3347	0.3434	0.3610	0.3679	0.3982	0.4332	0.4749	0.4939
Fujian	0.4011	0.4101	0.4296	0.4477	0.4525	0.4713	0.4541	0.4753	0.4895	0.5641	0.5852
Jiangxi	0.3230	0.3197	0.3315	0.3366	0.3391	0.3527	0.3540	0.3741	0.4113	0.4478	0.4736
Shandong	0.3848	0.3804	0.4024	0.4163	0.4258	0.4358	0.4547	0.4581	0.4610	0.4873	0.5301
Henan	0.3344	0.3341	0.3435	0.3563	0.3566	0.3654	0.3579	0.3771	0.4063	0.4541	0.4714
Hubei	0.3242	0.3162	0.3254	0.3417	0.3605	0.3792	0.4037	0.3957	0.4233	0.4460	0.4842
Hunan	0.2986	0.2793	0.2995	0.3255	0.3546	0.3697	0.4119	0.4079	0.4637	0.4990	0.4962
Guangdong	0.3740	0.3506	0.3799	0.3977	0.3871	0.4122	0.3971	0.4271	0.4545	0.5130	0.4914
Guangxi	0.2976	0.2856	0.2987	0.3175	0.3250	0.3398	0.3413	0.3625	0.3964	0.4304	0.4665
Hainan	0.3910	0.3901	0.4011	0.4175	0.4066	0.3947	0.3754	0.4291	0.4397	0.4717	0.5149
Chongqing	0.2657	0.2614	0.2683	0.2736	0.2884	0.3221	0.3089	0.3425	0.3669	0.3980	0.4478
Sichuan	0.3765	0.3729	0.3740	0.3880	0.3990	0.4018	0.4255	0.4272	0.4574	0.4836	0.4862
Guizhou	0.2253	0.2391	0.2487	0.2795	0.2924	0.2869	0.3096	0.3196	0.3339	0.3855	0.4214
Yunnan	0.2470	0.2384	0.2492	0.2613	0.2728	0.2967	0.3171	0.3359	0.3781	0.4146	0.4143
Tibet	0.1763	0.1885	0.2163	0.2336	0.2378	0.2803	0.2580	0.2872	0.3175	0.3691	0.3680
Shaanxi	0.2223	0.2120	0.2290	0.2423	0.2426	0.2788	0.3034	0.3119	0.3523	0.3964	0.4105
Gansu	0.1647	0.1886	0.2013	0.2082	0.2158	0.2311	0.2538	0.2686	0.3081	0.3334	0.3731
Qinghai	0.1691	0.1813	0.2034	0.2038	0.1941	0.2248	0.2908	0.2943	0.3269	0.3625	0.3770
Ningxia	0.2254	0.2217	0.2427	0.2573	0.2781	0.2826	0.3016	0.3363	0.3555	0.4374	0.4479
Xinjiang	0.2971	0.3033	0.3366	0.3489	0.3519	0.3609	0.3538	0.3883	0.4366	0.4602	0.4923

Table 6. Comprehensive score of rural green development level from 2011 to 2021.

Using the global Moran's I, the spatial correlation effect of the degree of coupling between agroecological security and rural green development in 31 provinces of China from 2011 to 2021 is examined, as shown in Tables 7, 8. The Moran's I is greater than 0 and passes the significance test. Therefore, there is a significant spatial correlation between the degree of coupling between agroecological security and rural green development. In terms of temporal trends, the intensity of the spatial autocorrelation of agroecological security and rural green development has fluctuated. The calculation of the local Moran's I to explore whether the degree of coupling and coordination between agroecological security and rural green development has a spatial clustering effect is shown in Table 8. The results of the local Moran's I show that, at the 0.1 significance level, in 2011, Tianjin, Jiangsu, Anhui, Shanghai, Zhejiang, Jiangxi, and Fujian Provinces presented "high-high" agglomeration characteristics. In 2016, Shandong, Jiangsu, Anhui, Shanghai, Zhejiang and Jiangxi presented high-high agglomeration characteristics. In 2021, Jiangsu, Anhui, Zhejiang, Jiangxi, Fujian and Guangdong exhibited high-high agglomeration characteristics. The spatial agglomeration effect of the coupled coordination of agroecological security and rural green development in China is relatively weak, and the spatial agglomeration characteristics are relatively stable.

Analysis of relative development states and types of coupled and coordinated development

China's agroecological security and rural green development can be divided into three relative development states: agroecological security lags behind rural green development, agroecological security is synchronized with rural green development, and agroecological security is ahead of rural green development. In 2011, those ahead of the state were Ningxia, Gansu, Tibet, and Qinghai; those in the synchronized state were Liaoning, Shanxi, Henan, Guangxi, Chongqing, Hunan, Jiangxi, Jilin, Anhui, Hebei, Yunnan, Shaanxi, Heilongjiang, Inner Mongolia, and Guizhou; and the other provinces were in the lagging state. Jilin, Anhui, Hebei, Yunnan, Shaanxi, Heilongjiang, Inner Mongolia, and Guizhou; other provinces lag behind. In 2016, Tibet and Qinghai were ahead of the curve; Shaanxi, Guangxi, Anhui, Hunan, Yunnan, Jiangxi, Guizhou, Ningxia, Inner Mongolia, Gansu, Jilin, and Heilongjiang were synchronized; and the other provinces lagged behind. In 2021, the following provinces were synchronized: Qinghai, Tibet, and Heilongjiang; other provinces were in lagging status. Overall, from

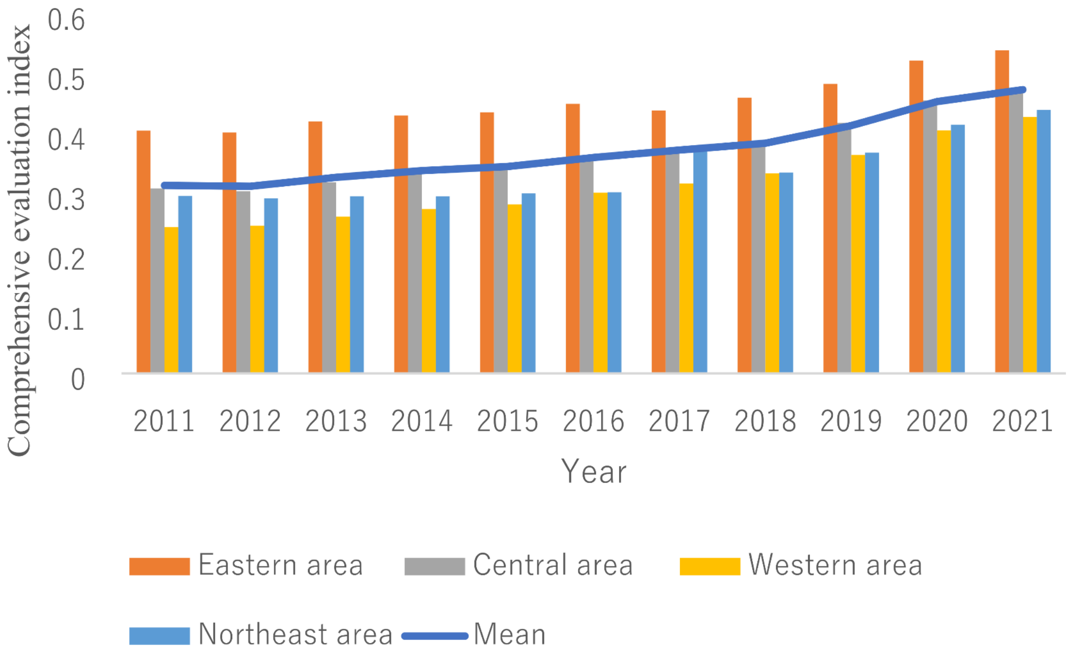

Fig. 2. Evolution trend of rural green development in China from 2011 to 2021.

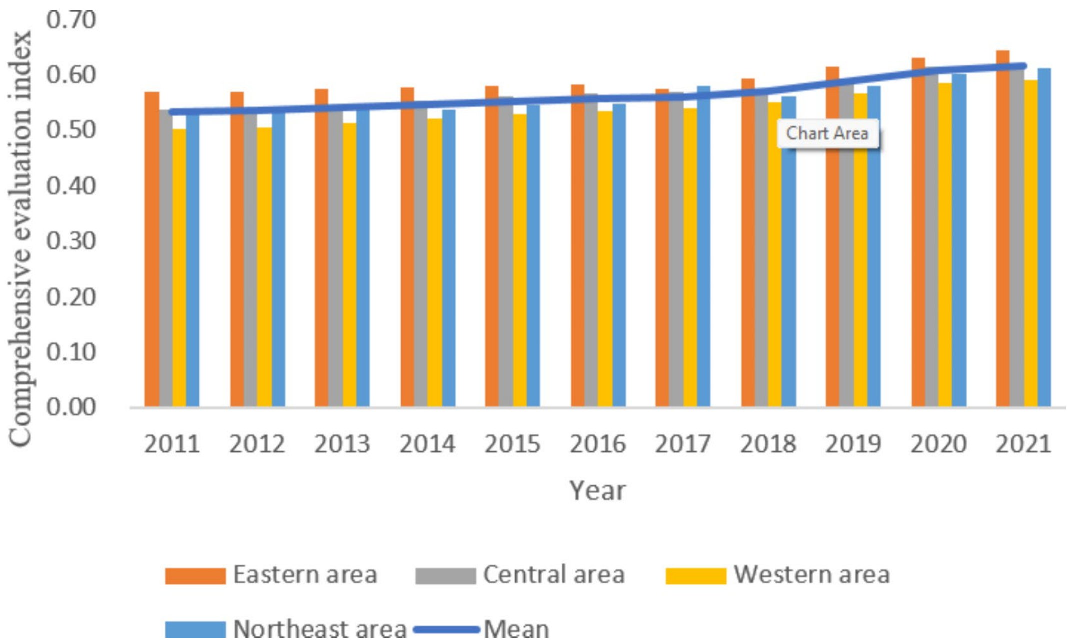

Fig. 3. Evolution trend of the coupling coordination degree between agricultural ecological security and rural green development in China from 2011 to 2021.

2011 to 2021, the relative development status of China's agroecological security and rural green development gradually changed from being in the "synchronized state" and "ahead of schedule" to the lagging state.

As shown in Table 9, the type of coupled and coordinated development of agroecological security and rural green development in China has shifted from barely coordinated agroecological security and rural green development synchronous type to primarily coordinated agroecological security lag type. The eastern area has shifted from the barely coordinated agroecological security lag type to the primarily coordinated agroecological security lag type. The central and northeastern areass have shifted from barely coordinated agroecological security and rural green development synchronous type to primarily coordinated agroecological security lag type. The western area has shifted from barely coordinated agroecological security and rural green development synchronous type to barely coordinated agroecological security lag type. Specifically, in 2011, there were six

	Global Moran's I	P
2011	0.4925	0.001
2012	0.5345	0.001
2013	0.5132	0.001
2014	0.5115	0.01
2015	0.426	0.002
2016	0.4067	0.001
2017	0.2667	0.013
2018	0.4095	0.001
2019	0.438	0.001
2020	0.36	0.003
2021	0.4096	0.001

Table 7. Global Moran's I from 2011 to 2021.

	2011		2016		2021	
	Local Moran's I	P	Local Moran's I	P	Local Moran's I	P
Beijing	0.7588	0.2230	−0.0964	0.2110	0.1662	0.3750
Tianjin	0.8456	0.1000	−0.1398	0.4410	0.0990	0.1340
Hebei	−0.0768	0.1250	0.0052	0.4390	−0.0126	0.4130
Shanxi	0.2633	0.2580	0.5283	0.1630	0.6015	0.2010
Inner Mongolia	0.0808	0.0220	0.0875	0.0030	0.1420	0.0050
Liaoning	0.0284	0.4630	0.1672	0.3730	−0.0499	0.4930
Jilin	0.0021	0.4880	0.0676	0.3490	−0.0568	0.3340
Heilongjiang	−0.0074	0.4820	−0.0985	0.3910	0.0051	0.4710
Shanghai	1.5864	0.0130	1.1302	0.0090	−0.4298	0.0010
Jiangsu	1.3823	0.0270	1.6562	0.0110	1.4591	0.0240
Zhejiang	1.0500	0.0080	1.5254	0.0010	1.7698	0.0050
Anhui	0.0490	0.0080	0.5640	0.0100	0.5461	0.0040
Fujian	0.7750	0.0470	1.3706	0.0340	1.5693	0.0200
Jiangxi	0.3715	0.0880	0.6967	0.0110	0.6200	0.0080
Shandong	0.4756	0.1360	0.4263	0.0690	0.4984	0.1060
Henan	−0.1372	0.3180	−0.0473	0.3050	0.0099	0.3360
Hubei	0.0062	0.3790	−0.0063	0.4970	0.0134	0.3710
Hunan	−0.0235	0.4050	−0.0163	0.4720	0.0136	0.4230
Guangdong	0.2911	0.1630	0.3574	0.0760	0.2754	0.0500
Guangxi	−0.6995	0.0010	−0.2926	0.0010	-0.1202	0.0010
Hainan	0.0578	0.2840	0.0028	0.4880	−0.0013	0.4840
Chongqing	0.3300	0.3080	−0.0916	0.3520	0.0768	0.3360
Sichuan	0.3520	0.1460	0.2064	0.2480	0.0565	0.4080
Guizhou	0.2956	0.3040	0.0966	0.3920	0.0355	0.4690
Yunnan	0.4408	0.1430	0.0040	0.4710	0.3501	0.2220
Tibet	0.7538	0.1180	−0.3040	0.1800	0.5661	0.1110
Shaanxi	0.6921	0.0500	1.0550	0.0140	0.7372	0.0140
Gansu	1.4893	0.0250	1.5572	0.0130	1.0927	0.0420
Qinghai	1.3567	0.0190	0.5222	0.1960	0.8265	0.0350
Ningxia	0.8766	0.0140	1.2938	0.0080	0.8790	0.0300
Xinjiang	1.1073	0.0020	0.0001	0.0410	0.5496	0.0050

Table 8. Local Moran's I from 2011 to 2021.

types of coupled and coordinated development of agroecological security and rural green development. There were two regions (Guizhou and Shaanxi) in the minimally imbalanced agroecological security and rural green development co-loss type. Three regions (Gansu, Qinghai and Tibet) have a minimally imbalanced rural green development lag type, and one region (Ningxia) has a barely coordinated rural green development lag type. There is 1 region (Beijing) in the primarily coordinated agroecological security lag type. The barely coordinated

	2011			2016			2021		
	Coupling coordination degree	Relative development degree	Coupling coordination type	Coupling coordination degree	Relative development degree	Coupling coordination type	Coupling coordination degree	Relative development degree	Coupling coordination type
Beijing	0.6042	0.5553	X19	0.5532	0.3635	X16	0.6694	0.5875	X19
Tianjin	0.5700	0.6545	X16	0.5976	0.5225	X16	0.6209	0.7071	X19
Hebei	0.5280	1.0396	X17	0.5566	0.7895	X16	0.6200	0.6392	X19
Shanxi	0.5032	0.8082	X17	0.5202	0.7289	X16	0.5560	0.5580	X16
Inner Mongolia	0.5302	1.1233	X17	0.5555	0.9836	X17	0.6104	0.7552	X19
Liaoning	0.5199	0.8016	X17	0.5225	0.7653	X16	0.5697	0.6066	X16
Jilin	0.5383	0.9712	X17	0.5494	1.0460	X17	0.6237	0.6599	X19
Heilongjiang	0.5562	1.1195	X17	0.5751	1.2207	X18	0.6419	0.9490	X20
Shanghai	0.5747	0.4292	X16	0.5802	0.4568	X16	0.6092	0.4138	X19
Jiangsu	0.5969	0.6507	X16	0.6235	0.6334	X19	0.6786	0.6120	X19
Zhejiang	0.5767	0.7349	X16	0.6024	0.6615	X19	0.6852	0.6620	X19
Anhui	0.5368	0.9910	X17	0.5795	0.8649	X17	0.6374	0.6767	X19
Fujian	0.5669	0.6418	X16	0.6065	0.6091	X19	0.6688	0.5843	X19
Jiangxi	0.5624	0.9592	X17	0.5843	0.9366	X17	0.6388	0.7425	X19
Shandong	0.5673	0.6995	X16	0.5783	0.5890	X16	0.6441	0.6124	X19
Henan	0.5537	0.8404	X17	0.5646	0.7609	X16	0.6153	0.6452	X19
Hubei	0.5330	0.7676	X16	0.5671	0.7193	X16	0.6220	0.6383	X19
Hunan	0.5405	0.9571	X17	0.5871	0.8693	X17	0.6514	0.7313	X19
Guangdong	0.5599	0.7025	X16	0.5783	0.6584	X16	0.6305	0.6542	X19
Guangxi	0.5277	0.8751	X17	0.5556	0.8252	X17	0.6178	0.6696	X19
Hainan	0.5519	0.6068	X16	0.5538	0.6037	X16	0.6233	0.5693	X19
Chongqing	0.5032	0.9077	X17	0.5309	0.7659	X16	0.5999	0.6459	X16
Sichuan	0.5536	0.6625	X16	0.5675	0.6426	X16	0.6208	0.6282	X19
Guizhou	0.4901	1.1366	X14	0.5321	0.9734	X17	0.5946	0.7042	X16
Yunnan	0.5050	1.0656	X17	0.5332	0.9178	X17	0.5849	0.6820	X16
Tibet	0.4894	1.8462	X15	0.5787	1.4280	X18	0.5835	0.8561	X17
Shaanxi	0.4830	1.1015	X14	0.5008	0.8092	X17	0.5761	0.6535	X16
Gansu	0.4499	1.5108	X15	0.4828	1.0172	X17	0.5547	0.6799	X16
Qinghai	0.4819	1.8863	X15	0.5125	1.3652	X18	0.5809	0.8012	X17
Ningxia	0.5102	1.3330	X18	0.5293	0.9822	X17	0.5891	0.6003	X16
Xinjiang	0.5108	0.4267	X16	0.5586	0.7476	X16	0.6024	0.5433	X19
Mean	0.5347	0.9292	X17	0.5586	0.7720	X16	0.6168	0.6533	X19
Eastern area	0.5696	0.6715	X16	0.5830	0.5789	X16	0.6450	0.6008	X19
Central area	0.5383	0.8872	X17	0.5671	0.8139	X17	0.6201	0.6681	X19
Western area	0.5029	1.1563	X17	0.5365	0.9284	X17	0.5929	0.6789	X16
Northeast area	0.5381	0.9641	X17	0.5490	1.0070	X17	0.6118	0.7358	X19

Table 9. Coupling coordination types of agricultural ecological security and rural green development.

agroecological security lag type has 11 regions (Tianjin, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Hubei, Guangdong, Hainan, Sichuan, Xinjiang). The rest of the regions belong to the barely coordinated agroecological security and rural green development synchronous type. In 2016, there were four types of coupled and coordinated development of agroecological security and rural green development. The barely coordinated agroecological security lagtype in 14 regions (Beijing, Tianjin, Hebei, Shanxi, Liaoning, Shanghai, Shandong, Henan, Hubei, Guangdong, Hainan, Chongqing, Sichuan, Xinjiang). The barely coordinated rural green development lag type has 3 regions (Heilongjiang, Tibet, and Qinghai). The primarily coordination agroecological security lag type has 3 regions (Jiangsu, Zhejiang, Fujian). All others belong to the barely coordinated agroecological security and rural green development synchronous type. In 2021, there were four types of coupled and coordinated development of agroecological security and rural green development. Heilongjiang belongs to the primarily coordinated agroecological security and rural green development synchronous type. Tibet and Qinghai belong to the barely coordinated agroecological security and rural green development synchronous type. Shanxi, Liaoning, Chongqing, Guizhou, Yunnan, Shaanxi, Gansu, and Ningxia belong to the barely coordinated agroecological security lag type. All other types constitute the primarily coordinated agroecological security lag type.

The results of the above empirical analysis reveal that the overall degree of coupling and coordination between agroecological security and rural green development in China is low, and most of the provinces and regions are in the primarily coordinated agroecological security lag type. This is because China's agroecological

	Economic vitality	Structural optimization	Green ecology	Open innovation	Harmonious sharing	Ecological level
2011	7.4304	19.6426	57.6402	7.0768	3.8162	4.3939
2012	7.6470	19.8555	59.5017	7.4807	3.9516	4.4344
2013	7.7042	19.5433	57.6181	7.2437	3.7005	4.1902
2014	7.8931	19.3386	57.7585	7.3175	3.6454	4.0469
2015	8.0598	19.4278	57.4125	7.4352	3.6092	4.0554
2016	8.2239	19.0660	58.0073	7.2485	3.5027	3.9516
2017	8.2823	19.2507	58.0945	7.1709	3.3514	3.8501
2018	8.2376	19.2822	58.1546	7.2433	3.3093	3.7730
2019	8.4176	19.1824	58.4084	7.0723	3.1777	3.7415
2020	8.2555	19.1465	59.3799	6.4802	3.0584	3.6795
2021	8.0429	18.9613	60.1685	6.4855	2.9521	3.3897

Table 10. Barrier degree of coordinated development criteria of agricultural ecological security and rural green development in China from 2011 to 2021.

	First barrier factor	Second barrier factor	Third barrier factor	Fourth barrier factor	Fifth barrier factor	Sixth barrier factor	Seventh barrier factor	Eighth barrier factor	Ninth barrier factor	Tenth barrier factor
2011	Y15	Y17	Y18	Y16	Y19	Y10	Y9	Y20	Y4	Y14
	12.0533	11.5009	10.7772	9.9753	8.5673	5.4170	4.9089	4.7662	3.8407	3.7344
2012	Y15	Y17	Y18	Y16	Y19	Y10	Y20	Y9	Y4	Y14
	12.4735	11.7771	11.1547	10.3888	8.9017	5.6934	4.8058	4.7014	4.1011	3.8391
2013	Y15	Y17	Y18	Y16	Y19	Y10	Y9	Y20	Y4	Y14
	12.0506	11.5730	10.7695	10.0608	8.4670	5.4551	4.6991	4.6972	3.9481	3.7786
2014	Y15	Y17	Y18	Y16	Y19	Y10	Y9	Y20	Y4	Y14
	12.1246	11.6120	10.7947	10.1310	8.5032	5.4979	4.6993	4.5931	4.0153	3.7807
2015	Y15	Y17	Y18	Y16	Y19	Y10	Y9	Y20	Y4	Y14
	12.0051	11.6774	10.9403	9.7015	8.5486	5.5664	4.6737	4.5394	4.1330	3.8057
2016	Y15	Y17	Y18	Y16	Y19	Y10	Y20	Y9	Y4	Y14
	11.9019	11.6261	10.8799	10.1093	8.5352	5.5563	4.9548	4.2779	4.1796	3.7674
2017	Y15	Y17	Y18	Y16	Y19	Y10	Y20	Y9	Y4	Y14
	12.0735	11.8066	10.7924	9.9809	8.4856	5.5297	4.9555	4.7071	4.2023	3.7479
2018	Y15	Y17	Y18	Y16	Y19	Y10	Y9	Y20	Y4	Y14
	12.1031	11.7584	10.7717	10.1450	8.6234	5.6209	4.8730	4.7530	4.2736	3.6157
2019	Y15	Y17	Y18	Y16	Y19	Y10	Y9	Y4	Y20	Y14
	12.3349	11.7931	10.7600	10.3060	8.8408	5.7920	4.8790	4.4328	4.3737	3.4210
2020	Y15	Y17	Y18	Y16	Y19	Y10	Y9	Y4	Y20	Y14
	12.6352	11.9439	10.8161	10.7773	8.9692	5.8883	4.7834	4.5118	4.2383	3.4032
2021	Y15	Y17	Y16	Y18	Y19	Y10	Y9	Y4	Y20	Y14
	13.2296	11.8902	11.3536	10.6989	8.9497	5.9220	4.8266	4.5809	4.0464	3.3269

Table 11. Barrier level of coordinated development indicators of agricultural ecological security and rural green development in China from 2011 to 2021.

security is still at a low level. Although regions are actively transforming the mode of agricultural development and improving the quality of the agroecological environment, the improvement effect is not obvious. Moreover, it is necessary to continue promoting the green development of the countryside to achieve the synchronization and high-quality coordination between agroecological security and the green development of the countryside.

Diagnosis of barriers to the coordinated development of China's agroecological security and rural green development

Although China's agro-ecological security and rural green development coupling and coordination degree shows a positive development trend, but the provincial areas are still dominated by "no agglomeration" and low- low agglomeration. This indicates that the coupling and coordination of agroecological security and rural green development in China still need to be improved. In this context, this paper takes the goal of high-quality coordinated development of agroecological security and rural green development, and applies the barrier degree model to explore the barrier factors hindering the coordinated development of agroecological security and rural green development in China, as shown in Tables 10, 11.

Barrier factors at the guideline level
With respect to time, the degree of the barrier to the ecological response tends to increase, the degree of the barrier to green society decreases, and the degrees of the barrier to the ecological state, ecological pressure, green economy and green ecology are relatively stable. In terms of intensity, the ecological response and ecological status are always the main barriers to the coordinated development of China's agroecological security and rural green development. In addition, the degree of barriers associated with green ecology and green society is low, which is consistent with the conclusion that China's agroecological security lags behind rural green development.

Indicator layer barrier factors
Taking the indicator layer as the benchmark, the barrier degree model is applied again to analyze and list the top ten barrier factors of the indicator layer in the order of 2011–2021 according to the degree of the barrier, as shown in Table 11: electricity consumption per unit of GDP, total amount of water resources, per capita arable land area, ratio of effective irrigated area, local financial expenditures on agriculture, forestry and water affairs per unit of GDP, local financial expenditures on environmental protection per unit of GDP, ratio of waterlogged area, soil erosion control ratio, per capita grain production, and total power of agricultural machinery with the highest frequency of occurrence of barrier factors are mainly concentrated in the ecological response subsystem, which is consistent with the results of the analysis of barrier factors at the guideline level. The expenditures of local finance on agriculture, forestry and water affairs per unit of GDP, the ratio of waterlogged area, and the ratio of soil erosion control are always the biggest barriers to China's agroecological security and rural green development.

Discussion
The comprehensive indices of China's agroecological security and rural green development are low, but both show a steady increase. A comparison of the findings of this paper with those of the literature is found. This finding is consistent with the findings of many scholars at home and abroad. For example, Zhong Jiawei and Zheng Jun (2024) divided the level of agroecology and food security into high-, medium- and low-level zones according to the main zones; at present, 30 provinces in China are dominated by medium- and low-level zones, but all of them are showing increasing trends[29].

At the same time, the research in this paper also revealed some new phenomena and problems. (1) The type of coupled and coordinated development of agroecological security and rural green development in China is the primarily coordinated agroecological security lag type. The degree of coordination between agroecological security and rural green development is low and still in the preliminary stage. Although there have been some positive measures and progress, overall, there are still more deficiencies and room for improvement. Developments in agroecological security have lagged behind relatively and have failed to keep pace with rural green development. This is mainly because, in recent years, the state has attached great importance to the construction of an ecological civilization and the strategy of rural revitalization and has introduced a series of policies and measures to safeguard the country's agroecological security and promote green development in the countryside. These policies not only include direct support for agricultural production but also cover many aspects of rural infrastructure construction, ecological environmental protection, cultural heritage, etc., thus promoting the coordinated development of agroecological security and rural green development. However, for a long time in the past, China's agricultural development focused on yield growth, adopting a more chemical fertilizer and pesticide use approach to ensure food security and the supply of agricultural products. Although this approach has increased yields in the short term, it has also led to problems such as soil degradation and water pollution, which have adversely affected agroecological security. Although the state has increased its support for agricultural science and technology in recent years, in some areas, especially remote and economically underdeveloped areas, the pace of agricultural technology upgrading is still slow, and the popularization rate of highly efficient and environmentally friendly agricultural production technology and equipment is not high, which restricts the enhancement of the level of agroecological security. The problems of environmental pollution and resource waste in traditional agricultural production activities need more time to improve.

(2) The results revealed that the regions characterized by "high-high" spatial agglomeration during the study period were mainly concentrated in the eastern coastal region. Jiangsu and Zhejiang maintain the spatial agglomeration characteristics of "high-high", and through the radiation trickle-down effect, they lead to an increase in the degree of coordination in neighboring provinces. The main reason is that these provinces have significant advantages in terms of agroecological security and rural green development. They have relatively well-developed agricultural infrastructure, such as efficient irrigation systems, advanced agricultural machinery and excellent transportation networks, which provide strong support for the stability and sustainability of agricultural production. Moreover, these provinces also excel in scientific and technological innovation and talent cultivation, improving the efficiency and quality of agricultural production through the introduction and application of modern agricultural technologies. For example, Jiangsu and Zhejiang have made remarkable progress in smart agriculture and eco-agriculture, whereas Fujian and Guangdong have unique advantages in tropical agriculture and marine resource development. Although Anhui and Jiangxi are central provinces, they have accelerated the pace of agricultural modernization and ecological construction in recent years through the implementation of the rural revitalization strategy, enhancing their own agroecological safety and green development. In addition, the number of "H-H" provinces is relatively stable, indicating that the trickle-down effect of the leading provinces on the degree of coordination of the surrounding backward provinces is smaller than its polarization effect and that the radiation-driven effect is still relatively weak. This is mainly due to the high concentration of resources and factors in the leading provinces, forming a strong "siphon effect", attracting high-quality resources and talent from neighboring regions, and exacerbating interregional imbalances. On the other hand, there are large gaps in agricultural infrastructure, scientific and technological innovation, and

ecological environmental protection in the neighboring backward provinces, making it difficult to effectively undertake the radiation effect of the leading provinces and leading to a blockage in the transmission path of the trickle-down effect.

(3) As an important indicator of the intensity of government financial support for agriculture, forestry, water conservancy and other fields, local financial expenditure on agriculture, forestry and water affairs per unit of GDP is one of the key barriers to the coordinated development of agroecological security and rural green development. The local financial expenditures on agriculture, forestry and water affairs per unit of GDP in China in 2011 and 2021 were 2.04% and 1.92%, respectively, representing a decline of 5.86%. The lower level of local fiscal expenditure on agriculture, forestry and water affairs per unit of GDP often means that the government has not invested enough in agricultural infrastructure construction, agricultural science and technology R&D and promotion, or ecological environment protection and restoration. This not only restricts improvements in agricultural productivity and the quality of agricultural products but also weakens the ability of agroecosystems to withstand natural disasters and exacerbates problems such as soil erosion and environmental pollution. In addition, insufficient financial investment also affects the improvement of socioeconomic conditions in rural areas, such as the slow growth of farmers' income and the backwardness of rural infrastructures, all of which directly or indirectly constrain the agroecological security and green development of the countryside. The ratio of flooded area and the ratio of soil erosion control are key barriers to the coordinated development of agroecological security and rural green development. The flood-removing area ratio reflects the effective coverage of farmland drainage systems and flood control facilities, which directly affects the stability and disaster resistance of agricultural production. A low waterlogged area ratio means that farmland is vulnerable to flooding and crop loss in the face of extreme weather events such as heavy rainfall and flooding, which in turn affects food security and farmer incomes. The erosion control ratio measures the degree of management of the phenomenon of soil erosion, which not only leads to a decline in soil fertility and affects crop yields but also exacerbates the siltation of rivers and damages aquatic ecosystems, reducing the sustainability of the regional ecological environment. Therefore, the insufficient ratios of flood-removing areas and soil erosion control seriously restrict the coupled and coordinated development of agroecological security and rural green development.

(4) The findings of this paper are important for the sustainable development of agriculture in China and the realization of the United Nations Sustainable Development Goals. Sustainable agricultural development emphasizes the coordinated development of resource conservation and efficient use, environmental protection and ecological restoration, scientific and technological progress and innovation, social equity and farmer well-being. The coupling and coordination of agroecological security and rural green development is a key way to achieve sustainable agricultural development. Agroecological security ensures the environmental foundation of agricultural production, maintains the health and stability of the ecosystem through the rational utilization and protection of natural resources, and provides a solid foundation for the long-term development of agriculture. Rural green development promotes the coordinated development of the economy, society and environment by promoting green production methods and lifestyles, reducing negative impacts on the environment and improving resource utilization efficiency. The coupled coordination between these two factors forms a virtuous circle: good agroecological security supports the implementation of rural green development, which in turn further protects and improves the agroecological environment, thus realizing the sustainability of the agricultural system. This coupled coordination not only enhances the efficiency and quality of agricultural production but also strengthens the resilience and adaptability of the agricultural system, providing important theoretical and practical support for realizing sustainable agricultural development. The coupled coordination of agroecological security and rural green development plays a crucial role in realizing the United Nations Sustainable Development Goals (SDGs). The UN SDGs aim to promote sustainable economic, social and environmental development through an integrated, inclusive and balanced approach. Agroecological security ensures the rational use of natural resources and the protection of the ecosystem, in line with SDG 15 (life on land) and SDG 14 (life under water), and provides the basis for sustainable agricultural production and rural ecological services through the maintenance of biodiversity and the health of ecosystems. Rural green development reduces negative impacts on the environment, improves resource efficiency and promotes coordinated economic and social development through the promotion of green production methods and lifestyles, directly echoing SDG 2 (Zero Hunger), SDG 7 (Clean Energy), SDG 8 (Decent Work and Economic Growth), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible Consumption and Production). The coupled coordination between these two factors creates a virtuous circle that not only improves the efficiency and quality of agricultural production but also enhances the resilience and adaptability of agricultural systems, providing important support for the realization of SDG 13 (Climate Action). In addition, coupled coordination is also closely linked to SDG 1 (No Poverty) and SDG 10 (Reducing Inequality) by improving farmers' incomes and quality of life and contributing to socially equitable and inclusive development. In summary, coupling and harmonizing agroecological security and rural green development constitute an important pathway for achieving the United Nations Sustainable Development Goals, and the two mutually reinforce and contribute to the process of global sustainable development.

Conclusions and suggestions

Conclusions

Starting from the current research and development status of China's agroecological security and rural green development, this paper explores the coupling and coordination of the two as well as the barrier factors and draws the following key conclusions: (1) The composite indices of China's agroecological security and rural green development from 2011 to 2021 are low, but both show a steady increase. (2) The type of coupled and coordinated development of China's agroecological security and rural green development is the primarily coordinated of agroecological security lag type, and the coupled and coordinated relationship needs to be further improved. (3) The coupling and coordination of agroecological security and rural green development in

China shows a spatial pattern of "high in the east, low in the west, high in the south and low in the north", with unbalanced development among regions and significant spatial correlation. (4) The coupled and coordinated development of China's agroecological security and rural green development mainly comes from the ecological response and ecological status criterion layer. The local financial expenditures on agriculture, forestry and water affairs per unit of GDP, the ratio of flood-removing area, and the ratio of soil erosion control are always the greatest barriers to China's agroecological security and rural green development.

Suggestions

On this basis, the following recommendations are made:

(1) Establishing an agroecological security system and continuously enhancing ecological environment management capabilities are imperative. Proactively enforcing a zero-growth policy for pesticides and fertilizers is crucial. Additionally, advocating for the research, development, and implementation of soil measurements and formulated fertilization methods, as well as increasing the utilization of organic fertilizers and low-toxicity biopesticides, is essential to increase fertilizer efficiency and reduce arable land pollution. Efforts should also focus on researching and developing biodegradable and easily recyclable agricultural films to minimize their environmental impact. The construction and enhancement of a green agricultural technology system, the development of key technologies for sustainable agriculture, and the implementation of low-input, low-pollution, high-efficiency agricultural models are vital for optimizing agricultural resource utilization. Strengthening ecological environmental protection oversight, harnessing the potential of artificial intelligence, big data, and other information technologies, and establishing an adaptive early warning system for monitoring agricultural ecological security are essential to detect and address ecological issues promptly.

(2) The optimization of rural production and living styles is a central objective for advancing green development in rural areas. Innovations in rural industrial business models and the establishment of high-quality industrial consortia are paramount. Promoting the scaling and modernization of rural industries and intensifying the integration of agriculture with other sectors are crucial. Exploring novel roles and values for agriculture, such as "agriculture + tourism," "agriculture + culture," and "agriculture + internet," is pivotal. Infrastructure enhancement and improved living conditions in rural areas are imperative. Improving hardware facilities for rural life and ensuring robust transportation, networking, water supply, power supply, garbage disposal, and sewage treatment are vital. Increased investment in modern agricultural facilities and addressing deficiencies in farmland water conservancy and irrigation and drainage systems are necessary to bolster agricultural resilience. Priority should be given to tackling agricultural production waste and managing household waste, reducing endogenous pollution in rural areas, and safeguarding and managing the rural environment.

(3) Identify the main barriers hindering the coordinated development of China's agroecological security and rural green development and identify the main contradictions. A diversified rural financial service system should be constructed, investment channels should be broadened, and diversified financial security. The central government should set up special funds to focus on supporting relatively backward regions and ensure sufficient financial support for agricultural infrastructure construction, agricultural science and technology research and development and ecological restoration projects to enhance the comprehensive production capacity of agriculture and the level of ecological environmental protection. It is recommended to reduce the impact of flooding and soil erosion on agricultural production through scientific planning and rational layout of farmland water conservancy facilities, improve the efficiency of farmland drainage systems, and establish a sound monitoring and assessment system for soil erosion, to comprehensively enhance the function and stability of natural ecosystems.

(4) The relationship between ecological security and the coordinated development of agriculture and the countryside should be considered in an integrated manner. On the basis of the current state of regional development, a virtuous cycle mechanism for the synergistic development of agroecological security and rural green development should be built in a differentiated manner. The model of interprovincial point-to-point assistance should be improved while the radiation-driven capacity of the dominant provinces to the surrounding areas should be fully utilized. Breaking down barriers between regions, relying on transportation arteries and hubs to form a collaborative and interoperable network, and promoting the free flow of production factors. Specifically, for the eastern area, owing to its relatively strong economic foundation and abundant scientific and technological resources, it should focus on promoting agricultural modernization and intelligence and, through the introduction of advanced agricultural technology and management experience, develop smart agriculture and high-tech agriculture, and improve agricultural production efficiency and product quality. Moreover, ecological environmental protection should be strengthened, green production and a circular economy mode should be promoted, and the coordination between economic development and ecological environmental protection should be ensured. The central area should make full use of its advantages of abundant agricultural resources and relatively low labor costs to optimize the structure of the agricultural industry and develop characteristic agriculture and ecological agriculture. Through the implementation of scientific planting and breeding techniques, the utilization efficiency of agricultural resources should be improved, the use of chemical fertilizers and pesticides should be reduced, and soil and water resources should be protected. In addition, the construction of rural infrastructure has strengthened, the rural human environment has improved, and the development of rural tourism has been promoted, realizing the integrated development of agriculture and tourism. Given the fragile ecology and scattered resources of the western area, emphasis should be placed on strengthening ecological protection and restoration, establishing a sound ecological compensation mechanism and implementing strict environmental

protection policies. Through the development of eco-agriculture, specialty agriculture and rural tourism, the diversification of the rural economy should be promoted. Moreover, investments in agricultural science and technology should be increased, the scientific and technological quality of farmers should be improved, adaptive technologies such as water-saving irrigation and dry farming should be promoted, and the risk-resistant capacity of agriculture should be improved. The northeastern area should fully exploit its advantages of rich agricultural resources and vast land to promote the development of large-scale and intensive agriculture. Through the implementation of modern agricultural production technologies, food production capacity should be increased, and national food security should be guaranteed. Moreover, the protection and comprehensive management of black soil should be strengthened to prevent soil degradation and erosion and ensure the sustainability of agricultural production. In addition, the development of the agricultural product processing industry and the rural service industry will extend the industrial chain, increase farmers' incomes and promote the overall development of the rural economy.

Agroecological security belongs to agricultural security, and in the future, food security, agricultural product quality security and other contents can be specifically studied. This paper explores the coupled and coordinated relationship between agroecological security and rural green development among Chinese provinces, and in the future, comparative studies of the Yangtze River Economic Belt, Liaoning coastal economic belt and other regions can be conducted. Agroecological security and rural green development are affected by a variety of factors, and in the future, we should explore the influence of national policies, the level of economic development, the degree of transportation accessibility, etc. on them.

Data availability

The data used in this study are available upon request from the corresponding author.

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Author contributions
Dandan Gao wrote the manuscript text .

Declarations

Competing interests
The authors declare no competing interests.

Additional information
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