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Original Research

The Coupling Coordination Relationship between Green Low-Carbon Agriculture and Socio-Economic Systems: Based on the Empirical Analysis of 31 Provinces in China

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Abstract

This study employs a coupling coordination model to measure the coupling coordination of green low-carbon agriculture and socio-economic development in 31 provinces in China from 2003 to 2021. Additionally, it explores the regional differences in the driving factors of coupling coordination between green low-carbon agriculture and socio-economic development. The findings are as follows:(1) The coupling degree between green low-carbon agriculture and socio-economic development undergoes stages of "antagonism-maturing-high-level coupling," while the coupling coordination experiences stages of "moderate imbalance-mild imbalance-approaching imbalance," indicating the need for further improvement in coordination. (2) The spatial pattern of the coupling development pattern of high-low-high. (3) During the process of coupling coordination between green low-carbon agriculture and socio-economic development, green coverage rate and per capita GDP have a positive impact at the national level. However, the influence of agricultural carbon emission intensity, effective irrigated land ratio, fertilizer application intensity, pesticide application intensity, and plastic film application intensity on coupling coordination varies depending on the characteristics of the local agricultural industry structure.

Keywords: Green low-carbon agriculture, socio-economic systems, coupling coordination model

Introduction

Over the course of more than four decades since the initiation of China's reform and opening-up policy, this nation, with a mere 9% of the world's arable land and 6% of its freshwater resources, has managed to sustain a staggering 18% of the global population. While making commendable contributions towards achieving sustainable development, China has also borne significant costs in terms of its resource and environmental impact. According to the data presented in the "Second National Pollution Source Census Bulletin," it is revealed that in 2014, agricultural activities in China accounted for 7.5% of the total greenhouse gas emissions. Furthermore, in 2017, nitrogen and phosphorus runoff from agricultural activities constituted 24% of each of the nationwide total runoff [1]. From a global perspective, it is noteworthy that agriculture production contributes to nearly a quarter of carbon emissions, with its carbon footprint exceeding one-third of the total emissions [2, 3]. Furthermore, the World

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Bank, in its "World Development Report 2019," highlights the significant potential of agricultural and forestry production technologies in mitigating carbon emissions, estimated to range from 2.3 to 9.6 billion tons annually. This underscores the dual nature of agriculture as both a significant contributor to carbon emissions and a domain with immense potential for emission reduction [4].

Numerous scholarly works have delved into the intricate interplay between agriculture, economy, and society. Tomal et al. (2021) conducted a spatiotemporal analysis on the coupling coordination and convergence behavior of ecological environment and urban economic development based on data spanning from 2003 to 2019 in various cities in Poland. The findings revealed a relatively low level of coupling coordination between the rural-urban ecological environment and socioeconomic factors in Poland. This can primarily be attributed to the inadequacy of infrastructure and environmental conditions in rural areas. Furthermore, the level of economic and social development in a region can significantly impact its facilities construction [5]. Luo et al. (2021) employed the Backpropagation Artificial Neural Network (BPANN) to analyze the influential factors of coupling coordination among the economic, social, and environmental dimensions in the Yangtze River Delta urban agglomeration. The findings demonstrated that economic growth serves as a foundation for the sustainable development of society and the environment. Furthermore, factors such as urbanization rate and industrial structure exert considerable influence on the level of coupling coordination in the economic, social, and environmental realms [6]. Feng et al. (2021) constructed an evaluation system for the coupling coordination among the agricultural economy, ecology, and society using data from Shaanxi Province spanning from 2006 to 2017. The results indicate that achieving a sustainable and prosperous agricultural sector necessitates a balance between resource supply and demand output. Additionally, the level of socioeconomic development in a region serves as a driving force for the coordinated development of the agricultural economy, ecology, and society [7]. Meanwhile, Tian et al. (2021) examined the coupling coordination and evolutionary characteristics of agricultural carbon emissions and economic growth in the Yangtze River Economic Belt. The findings reveal a gradual increase in the level of coupling coordination between agricultural carbon emissions and economic growth [8].

Green and low-carbon agriculture represents an advanced stage of agricultural development, with its level and capacity relying on the systemic coordination of regional development, particularly the support from the social and economic systems. As illustrated in Fig. 1, the development of green and low-carbon agriculture will enhance the supply of high-quality agricultural products, increase farmers' income, and indirectly stimulate economic growth. Simultaneously, as economic growth inevitably leads to an increase in residents' income, it will also enhance their consumption capacity, expand the market demand for high-quality agricultural products, and drive the upgrading and development of agriculture toward a green and low-carbon direction. In response, this will also lead to increased investment in agricultural technology research and development, as well as the enhancement of farmers' cultural proficiency, in order to meet people's pursuit of a socially prosperous development. As Hu et al. (2020) argue, economic growth can guide the formation of new industries and promote the transformation and upgrading of industrial structures

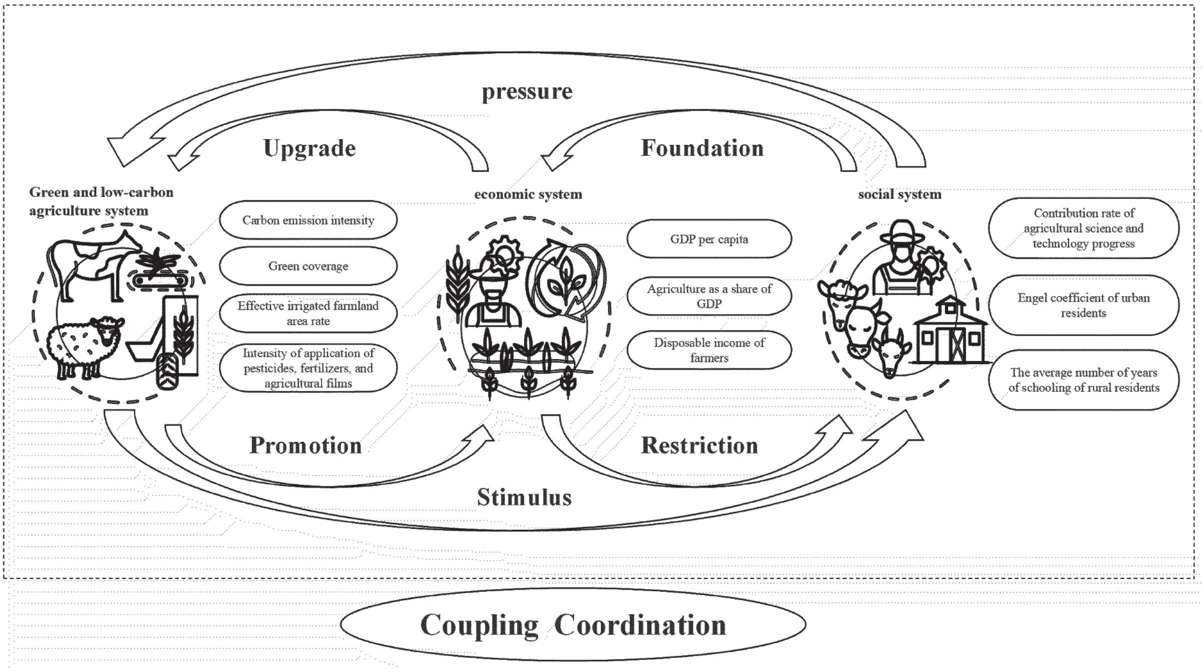

Fig. 1. Diagram depicting the Mechanism of Green Low-Carbon Agriculture and its Interactions with Socio-Economic Factors.

[9]. Social stability serves as the foundation for economic growth, and the development of science and technology, along with the participation of scientific and technological talents, are variable factors that drive economic growth. Conversely, economic growth also reciprocates with social development. When the economy is in a downturn, the pace of social progress is inevitably affected.

As agriculture transitions towards green and low-carbon practices, it necessitates the support of relevant industries in terms of technological advancements and skilled personnel. Additionally, the strong demand from society for environmentally-friendly, high-quality agricultural products serves as a positive driving force. Ultimately, these factors combine to create an intrinsic momentum that promotes the development of green and low-carbon agriculture. Therefore, green and low-carbon agriculture is intricately coupled with the social and economic systems, underscoring the vital importance of conducting research in this area for the transformation and development of agriculture towards sustainability. (Fig. 1)

Material and Methods

Indicator Selection and Data Sources

The establishment of a scientific and rational evaluation indicator system is a prerequisite for accurately grasping the level of coupling and coordination of the "green and low-carbon agriculture and socio-economic" system. Based on the aforementioned analysis of the mechanisms underlying the coupling and coordination of the green and low-carbon agriculture and socio-economic system, and guided by principles such as feasibility, authenticity, and

Table 1. Evaluation indicators system for the coordinated development of green and low-carbon agriculture and socio-economic integration.

Primary Indicators	Evaluation Indicators	Variables	Indicator Nature	Explanation
Green Low-Carbon Agriculture System	Agricultural Economic Development	Agricultural GDP per unit of cultivated land (100 million yuan/hectare)	Positive	Reflects the basic level of agricultural development
	Agricultural Carbon Emission Intensity	Sum of carbon emissions from fertilizers, pesticides, agricultural films, agricultural irrigation, farmland, agricultural machinery, and livestock (10,000 tons)(as shown in Table 2)	Negative	Reflects the carbon emissions situation
	Green Coverage Rate	Total green coverage area in each region/total area of the region (%)	Positive	Reflects the role of forest carbon sinks
	Effective Irrigated Area Ratio	Effective irrigated area/cultivated land area (%)	Positive	Reflects the development of environmentally friendly agriculture
	Fertilizer Application Intensity	Total amount of fertilizer used for crops/total sown area (10,000 tons/hectare)	Negative	
	Pesticide Application Intensity	Total amount of pesticides used for agricultural production/total sown area (10,000 tons/hectare)	Negative	
	Agricultural Film Application Intensity	Total amount of agricultural films used/area covered by agricultural films (10,000 tons/hectare)	Negative	
Economic System	Per Capita GDP	Per capita GDP within the region (10,000 yuan)	Positive	Reflects the overall economic growth in terms of value
	Share of Agriculture in GDP	Value added from agriculture, forestry, animal husbandry, and fisheries/total regional GDP (%)	Positive	Reflects an important indicator of the agricultural industry structure
	Rural Residents' Disposable Income	Per capita disposable income of rural residents (10,000 yuan)	Positive	The economic level of rural residents influences their willingness to develop green low-carbon agriculture
Social System	Agricultural Technological Progress Contribution Rate	Contribution rate of agricultural technological progress (%)	Positive	Reflects the level of agricultural technological development
	Urban Residents' Engel Coefficient	Engel coefficient of urban residents (%)	Negative	Reflects the living standards of residents
	Average Years of Education for Rural Residents	Average years of education for rural residents (years)	Positive	The average years of education for rural residents can affect agricultural production methods

hierarchy, a comprehensive evaluation indicator system for the coordinated development of the "green and low-carbon agriculture and socio-economic" system has been constructed [10-13] (Table 1).

The primary sources of data for this article are the "China Statistical Yearbook," "China Rural Statistical Yearbook," "China Environmental Statistical Yearbook," "China Forestry and Grassland Statistical Yearbook" from the years 2014-2022, as well as relevant government-published data and provincial (municipal) statistical yearbooks. In cases where specific data was missing, interpolation was conducted using neighboring year values.

Research Methods

The entropy method is used to measure the comprehensive development index of green and low-carbon agriculture $f(x)$, economy $g(y)$, and society $h(z)$. The specific calculation process is as follows:

Step 1: Standardization

In this step, the original value of the j th indicator in the i th year is denoted as x_{ij}, the standardized value of the j th indicator in the i th year is denoted as X_{ij}, and max (x_j) and min (x_j) represent the maximum and minimum values of the j th indicator among all years, respectively.

For positively oriented indicators: $X_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)}$ (1)

For negatively oriented indicators: $X_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)}$ (2)

Step 2: Calculate the weights of each indicator and determine the information entropy of the j th indicator:

In this step, h_j represents the information entropy of the j th indicator, m is the number of evaluation years, r_{ij} represents the proportion of the standardized value of the j th indicator in the i th year to the total value of that indicator, and k is a constant.

$$h_j = -k \sum_{i=1}^{m} (r_{ij} \times \ln r_{ij}) \tag{3}$$

$$k = \frac{1}{\ln m} \tag{4}$$

$$r_{ij} = X_{ij} \Big/ \sum_{i=1}^{m} X_{ij} \tag{5}$$

Determine the redundancy of information entropy and its weight: In this step, g_i represents the redundancy of information entropy for the i-th indicator, w_j represents the weight of the j th indicator, and n is the number of evaluation indicators in the system.

$$g_j = 1 - h_j \tag{6}$$

$$w_j = g_j \Big/ \sum_{j=1}^{n} g_j \tag{7}$$

Step 3: Calculate the comprehensive development indices of each system. In this step, $f(x)$, $g(y)$ and $h(z)$ represent the evaluation index of the green and low-carbon agriculture system, the evaluation index of the economic development system, and the evaluation index of the social development system respectively. a_i, b_j and c_t represent the weights of the evaluation indicators for each system. X_i, Y_j and Z_t represent the standardized values of the evaluation indicators for each system. n represents the number of evaluation indicators for each system.

$$f(x) = \sum_{i=1}^{n} a_i X_i \tag{8}$$

$$g(y) = \sum_{j=1}^{n} b_j Y_j \tag{9}$$

Table 2. Agricultural Carbon Emission Calculation Form.

Primary Indicators	Secondary Indicators	Carbon Emission Calculation Value	Source
Crop Farming	Fertilizers	0.8956kg/kg	US Oak Ridge National Laboratory
	Pesticides	4.9341kg/kg	US Oak Ridge National Laboratory
	Agricultural Films	5.1800kg/kg	IREEA
	Agricultural Irrigation	266.48kg/hm^2	Duan Huaping, et al.
	Farmland Plowing	312.6000kg/km^2	China Agricultural University
	Agricultural Diesel	0.59kg/kg	IPCC(2013)
Livestock Farming	Cattle (enteric fermentation)	320.54kg/(head*year)	Hu Xiangdong
	Sheep (enteric fermentation)	34.1kg/(head*year)	Hu Xiangdong
	Pigs (enteric fermentation)	35.1kg/(head*year)	Hu Xiangdong
	Cattle (manure emissions)	6.82kg/(head*year)	Hu Xiangdong
	Sheep (manure emissions)	1.0912kg/(head*year)	Hu Xiangdong
	Pigs (manure emissions)	27.2800kg/(head*year)	Hu Xiangdong

$$h(z) = \sum_{t=1}^{n} c_j Z_j \tag{10}$$

1. Coupling Coordination Degree Model

The formula for calculating the coupling degree is as follows, where C represents the coupling degree, $C \in [0,1]$. A higher C value indicates a higher level of interaction between the systems. The classification of coupling degree levels is shown in Table 3 [14].

$$C = \left\{ \frac{f(x)g(y)h(z)}{[(f(x)+g(y)+h(z))/3]^3} \right\}^{\frac{1}{3}} \tag{11}$$

The calculation of the coupling coordination degree is as follows. D represents the coupling coordination degree, $D \in [0,1]$. A higher D value indicates a greater tendency towards coordinated development between the systems. S is the comprehensive evaluation index among the three systems. α , β and ε represent the importance levels of the three systems. Based on the reference [15], it is determined that the three systems have equal importance, so $\alpha = \beta = \varepsilon = \frac{1}{3}$. The coupling coordination degree is categorized into 10 types, as shown in Table 3.

$$D = \sqrt{C \times S} \tag{12}$$

$$S = \alpha f(x) + \beta g(y) + \varepsilon h(z) \tag{13}$$

2. Geographic Weighted Regression Analysis Method

The Geographic Weighted Regression (GWR) analysis method is used to explore the driving factors of green low-carbon agriculture development [16, 17]. Where y_i represents the coupling coordination degree between the green low-carbon agriculture system and the socio-economic system. (u_i, v_i) represents the geographic coordinates of the i th region. $\beta_0(u_i, v_i)$ represents the intercept of the i th region, x_{ik} , $\beta_k(u_i, v_i)$ represent the regression coefficients of the k independent variables in region i. X_1i, X_2i, ..., X_ki represent the values of the k independent variables in i th region. n represents the number of independent variables, and ε_i represents the random error.

$$y_i = \beta_0(u_i, v_i) + \sum_{k=1}^{n} \beta_k(u_i, v_i) x_{ik} + \varepsilon_i \tag{14}$$

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Table 3. Classification and Types of Coupling Degree and Coupling Coordination Level.

Coupling degree	Coupling development stage	Coordination level	Coupling coordination degree	Coupling coordination type
0.00-0.29	low-level coupling stage	Dysfunction and decline	[0.00,0.09]	Extreme imbalance
			[0.10,0.19]	Severe imbalance
0.30-0.49	Antagonistic stage	Near Dysfunction	[0.20,0.29]	Moderate imbalance
			[0.30,0.39]	Mild dysregulation
0.50-0.79	Running in stage	Transition class	[0.40,0.49]	Near Dysfunction
			[0.50,0.59]	Barely coordinate
0.80-1.00	High-level coupling stage	Basic coordination	[0.60,0.69]	Primary coordination
			[0.70,0.79]	Intermediate coordination
		Highly coordinated	[0.80,0.89]	Good coordination
			[0.90,1.00]	Highly coordinated

Results and Discussion

A Spatio-Temporal Analysis of Coupling and Coordination

The development level of green and low-carbon agriculture (0.0938-0.4158) exhibits a "U-shaped" pattern, initially declining and then rising before stabilizing. Moreover, the development of green and low-carbon agriculture significantly surpasses that of socioeconomic development, indicating its superiority over economic and social progress. The level of socioeconomic development (0.0058-0.1862) shows a consistent annual increase, while the economic development level (0.0684-0.1754) experiences fluctuating growth. Since 2012, the level of socioeconomic development has surpassed economic development, marking China's departure from the era of "high growth." This can be attributed to the overall global economic downturn, as well as the domestic impact of slowed investment, foreign trade, and consumption, leading to a sustained deceleration of China's economic growth. The initial decline in the development of green and low-carbon agriculture reflects the inhibitory effect of earlier extensive economic development and an industrial-oriented economic structure. However, the subsequent introduction of ecological civilization construction and the advancement of green and low-carbon technologies have significantly improved the development of green and low-carbon agriculture compared to the earlier period. (Fig. 2)

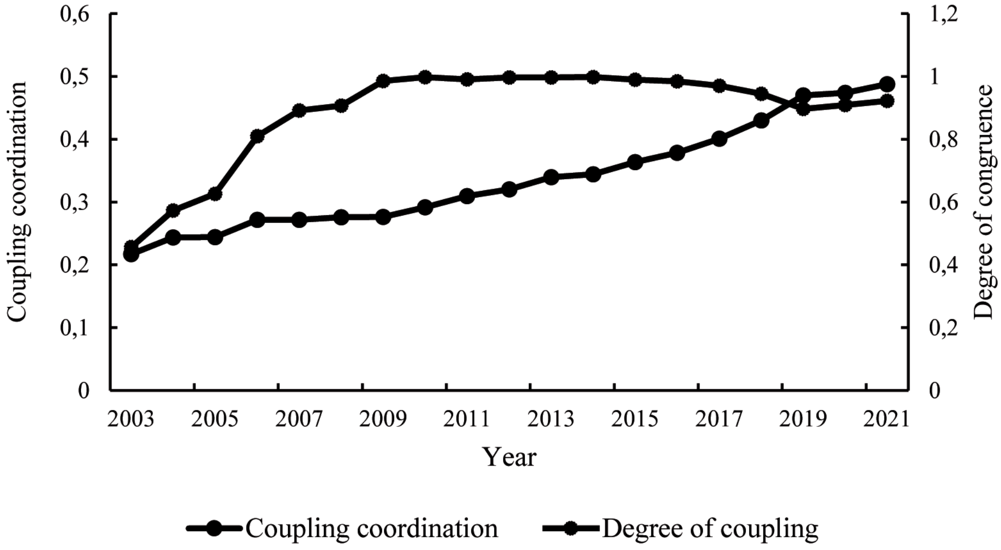

Fig. 2. Indices of Comprehensive Evaluation for National Green Low-Carbon Agriculture and Socio-Economic Systems from 2003 to 2021.

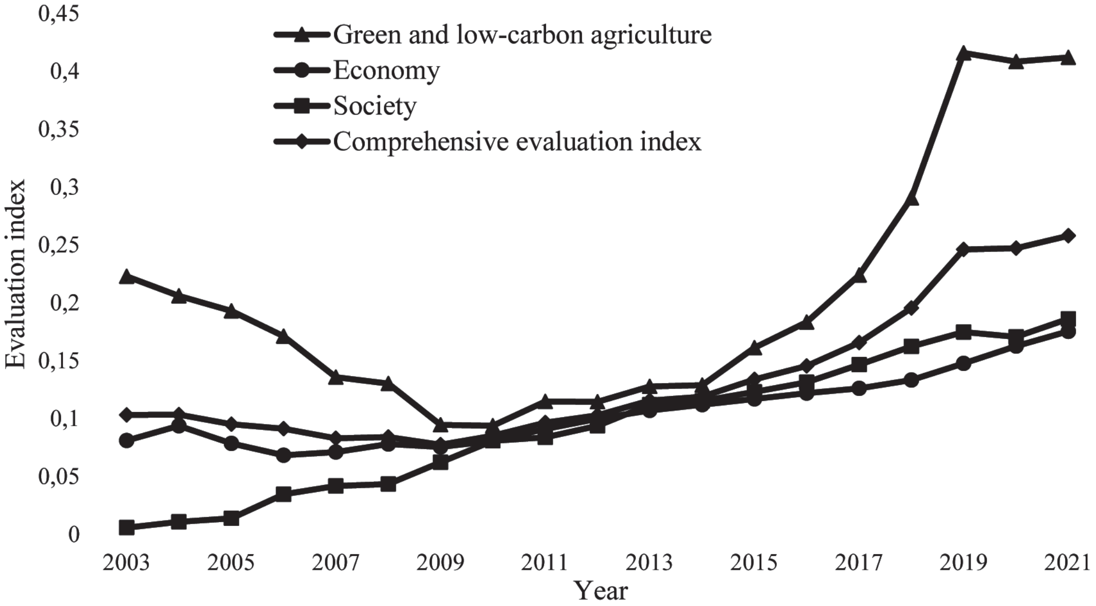

Fig. 3. Coupling Degree and Coupling Coordination of National Green Low-Carbon Agriculture and Socio-Economic Systems from 2003 to 2021.

The overall coupling between green low-carbon agriculture and socio-economic development in the country has shown a pattern of initial opposition, followed by a period of adjustment, leading to a high-level coupling phase that has been sustained. However, the degree of coordination has gone through three stages: "moderate imbalance, mild imbalance, and approaching imbalance," indicating that a well-coordinated development situation has yet to be achieved, leaving ample room for improvement (Fig. 3).

According to calculations, it has been found that since 2009, the coupling level of all 31 provinces (municipalities, autonomous regions) in the country has reached a high-level coupling phase. From 2003 to 2009, most regions north of the Yellow River were in an opposition stage, while regions south of the Yellow River were mostly in an adjustment stage. However, there has been significant spatial differentiation in the coupling coordination level across the country from 2003 to 2021, as shown in Fig. 4. The proportion of transitional coordination regions has increased, and the types of coordination levels in different regions have varied over time: "moderate imbalance to mild imbalance" (in 2006, 2011 [* taking into account the corresponding policy planning and influences during the 11th Five-Year Plan (2006-2010), 12th Five-Year Plan (2011-2015), 13th Five-Year Plan (2016-2020), and 14th Five-Year Plan (2021-2025) periods, the chosen time nodes are 2006, 2011, 2016, and 2021 (same for subsequent mentions).]), "mild imbalance to approaching imbalance" (in 2016), and "approaching imbalance to precarious coordination" (in 2021*). Overall, the coordination level has been gradually improving over the observed trend.

In 2006, approximately two-thirds of the regions nationwide exhibited a moderate imbalance in the coupling coordination between green low-carbon agriculture and socio-economic development, while one-third showed a mild imbalance. Spatially, the coordination level was higher in the northern regions and lower in the southern regions. In 2011, the coordination level among 29 provinces (municipalities, autonomous regions) nationwide reached a state of mild imbalance, with only Sichuan and Guizhou remaining in a state of moderate imbalance. In 2016, approximately 42% of the regions nationwide experienced a moderate imbalance, while the remaining areas approached a state of imminent imbalance in terms of the development level of green low-carbon agriculture. The overall pattern mirrored that of "medium-low-high," with the central regions exhibiting a "south-high-north-low" and an "east-high-west-low" distribution. By 2021, half of the regions achieved a precarious level of coordination, while the other half approached a state of imbalance. In that year, the development level of green low-carbon agriculture in the northern regions was notably lower than that in the southern regions. The southeastern areas had a relatively higher level of development, surpassing the northwestern regions. The spatial characteristics of

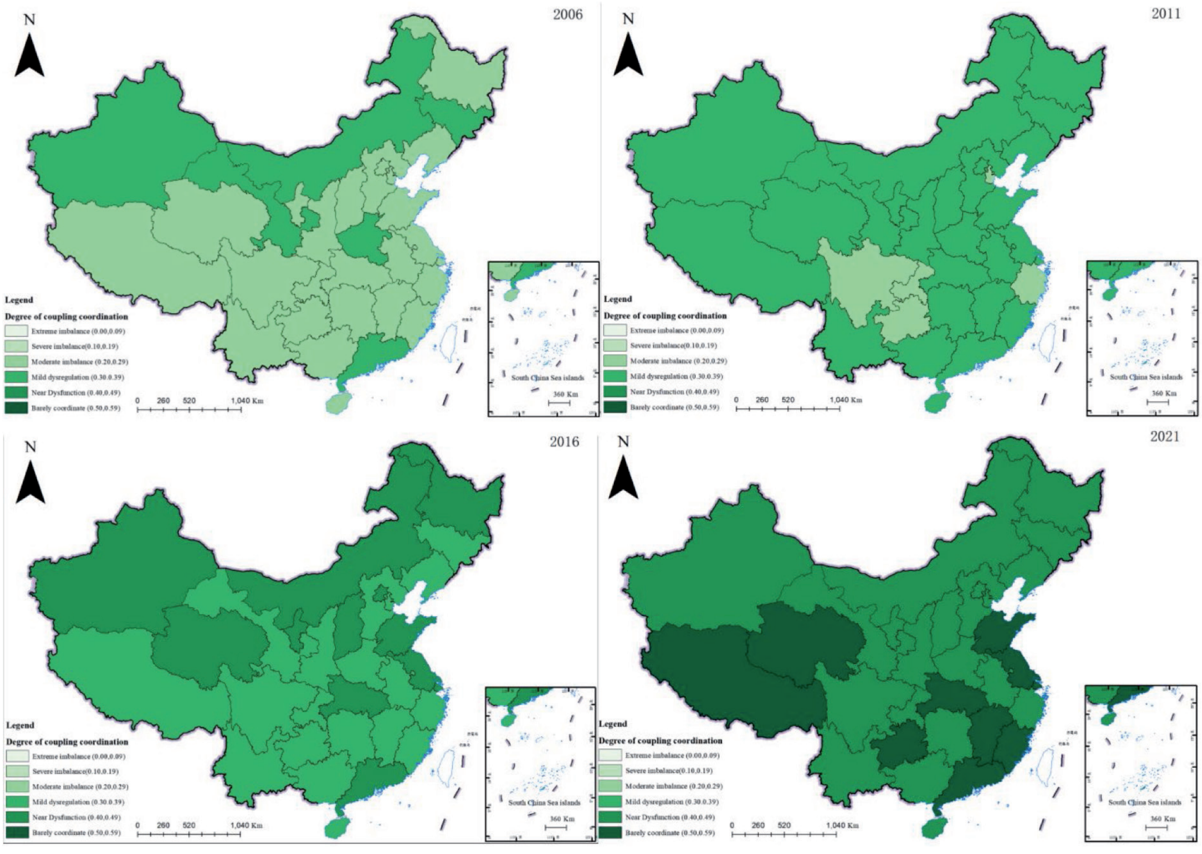

Fig. 4. Scatter plot of Global Autocorrelation Moran's Index for Coupling Coordination in 2006, 2011, 2016, and 2021.

coupling coordination were also consistent with this pattern. Since 2016, adjustments in national agricultural policies have prioritized the development of green agriculture and economic restructuring in the eastern and southern regions. Consequently, the coordination level in these areas has gradually transitioned towards a state of basic coordination.

Analysis of the Driving Factors Behind the Coupling Coordination Degree

Considering the limitations of the GWR model, which only allows for cross-sectional data [18], we have selected four time points, namely 2006, 2011, 2016, and 2021, to capture the average values of the influencing factors and the coupling coordination degree. Adaptive kernel type and bandwidth have been chosen accordingly. The parameter results of each influencing factor in the GWR model are presented in Table 4, with a model value of 0.6001, indicating a satisfactory fit of the twelve influencing factors in the GWR model.

Table 4. Table of Statistical Tests for GWR Model Parameter Estimation.

Model Parameter	Value	Model Parameter	Value
bandwidth	2273396.68	AICc	62.2678
Sum of squared residuals	4.0467	Goodness of Fit	0.6001
Significant digits	12.7883	Adjust goodness of fit	0.3412
Sigma value	0.4714		

The impact of green and low-carbon agricultural factors on the coupling coordination degree varies across different regions, as illustrated in Fig. 5. From an analysis of the factors influencing agricultural carbon emissions intensity, it becomes apparent that the eastern and northern regions exhibit a notable positive effect, while the western and southern regions show a negative effect. This can be attributed to the inherent agricultural resource endowment and industrial structure characteristics in China. Provinces such as Jiangsu, Anhui, and Jiangxi predominantly engage in rice cultivation for grain production, which serves as the primary source of agricultural carbon emissions (accounting for over 45% of the total).In Shanghai and Zhejiang, the agricultural industry is primarily focused on cultivation. Production heavily relies on high inputs of energy and agricultural materials, resulting in higher carbon emissions intensity. In regions such as Beijing, Shanxi, Tianjin, and Liaoning, dryland areas are more prevalent, leading to a significant

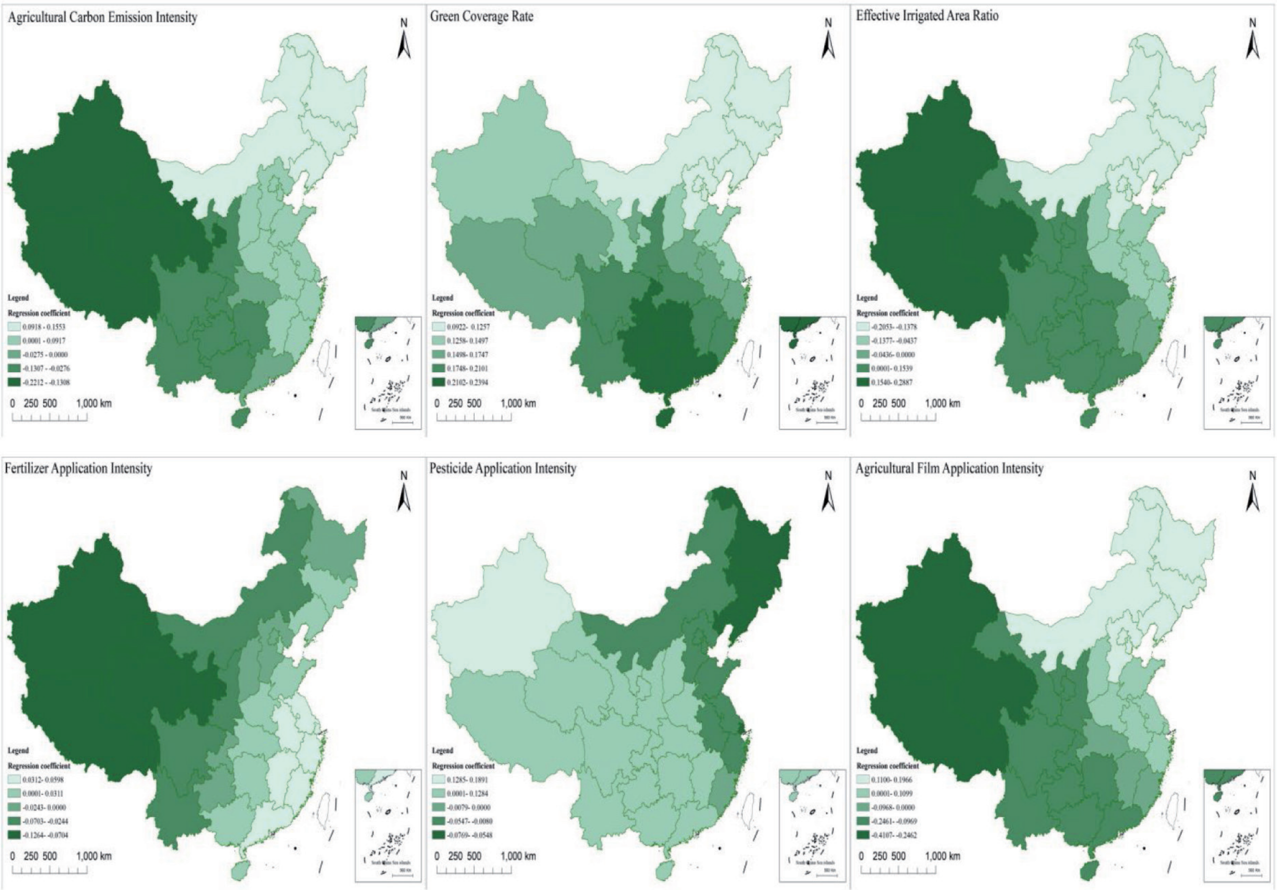

Fig. 5. Spatial Distribution of Regression Coefficients for Factors Influencing Coupling Coordination of Green Low-Carbon Agriculture from 2003 to 2021.

dependence on water resources and substantial irrigation consumption in agricultural fields.

In Hebei, Jilin, Shandong, and Henan, wheat and corn cultivation takes precedence, accompanied by a thriving livestock and poultry farming industry. In comparison, the southwestern regions of China, characterized by mountainous terrain and high plateaus, are not conducive to large-scale cultivation due to adverse natural conditions. Consequently, these areas exhibit lower carbon emissions intensity and relatively better ecological environments, aligning with the general assumption of a negative impact on the development of green and low-carbon agriculture.

The impact of greening coverage on the harmonious coupling degree between national green and low-carbon agriculture and socio-economic development exhibits a positive correlation. The coefficient in the southern region is more pronounced, signifying a higher degree of greening coverage in the south, whereas the north is comparatively disadvantaged due to climatic and environmental factors. The pattern of the irrigation area ratio of arable land is inversely related to the intensity of agricultural carbon emissions. In the eastern and northern regions, it primarily exerts a negative effect on the harmonious coupling degree between green and low-carbon agriculture and socio-economic development. Conversely, it exhibits a positive effect in the western and southern regions. This correlation can be attributed to the distinctive characteristics of China's agricultural industry structure. Regions with a predominant focus on cultivation have larger irrigated areas, with significant consumption concentrated in areas such as Zhejiang, Shanghai, Anhui, Liaoning, and Jilin. Similarly, Beijing, Tianjin, Jilin, Shanxi, and other regions face constraints on water resources. Consequently, the irrigation area ratio of these regions does not serve as a positive catalyst for the harmonious coupling of green and low-carbon agriculture with socio-economic development.

The intensity of fertilizer application continues to play a positive role in the harmonious coupling of green and low-carbon agriculture with socio-economic development in the southeastern regions, where cultivation remains predominant. The production process in the cultivation industry inevitably involves high input of agricultural materials such as fertilizers. Conversely, the intensity of pesticide and agricultural film application has a negative impact on the harmonious coupling of green and low-carbon agriculture with socio-economic development in the eastern and northern regions. This is closely related to recent national policies that promote standardized prevention and control of pesticide application, targeted and appropriate use of pesticides, and strict control over their precise application. There has also been increased regulatory oversight on agricultural films, with the implementation of admission and application standards. Provinces such as Zhejiang, Fujian, Shandong, and Jiangsu are leading

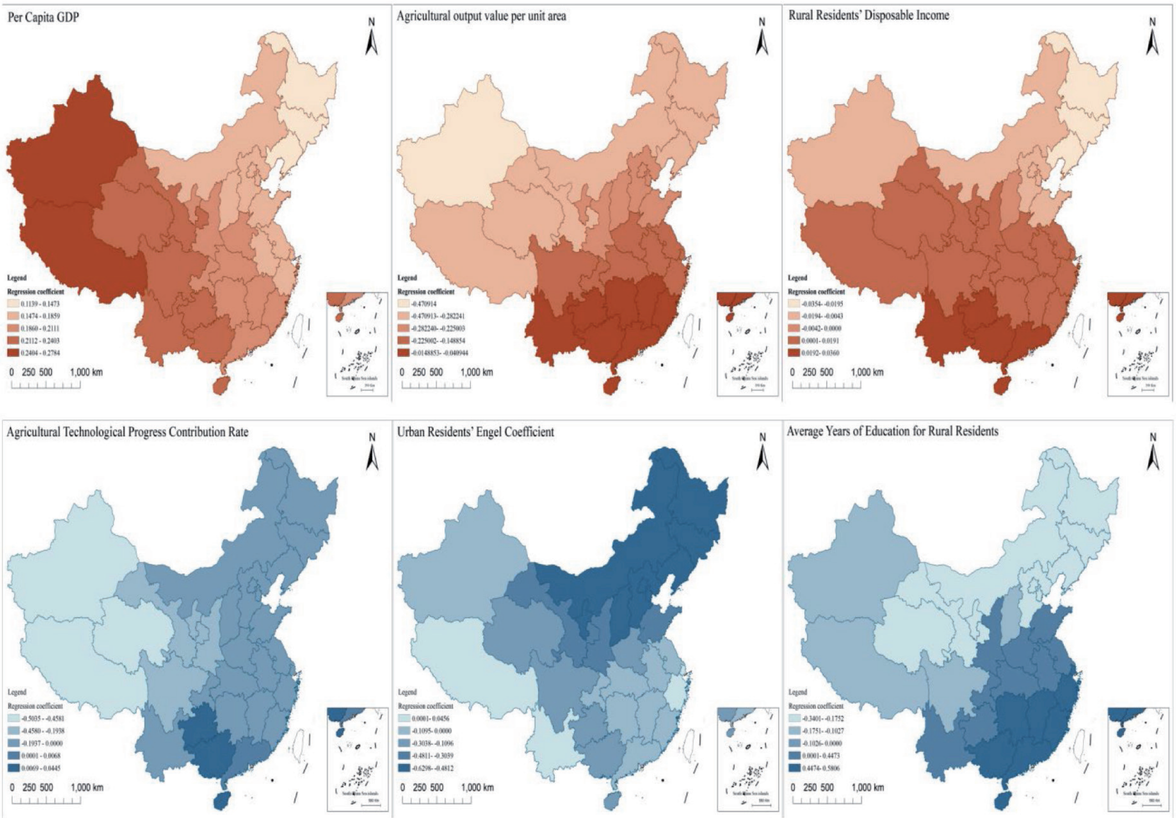

Fig. 6. Spatial Distribution of Regression Coefficients for Economic-Social Factors Influencing Coupling Coordination from 2003 to 2021.

the way in promoting green agricultural development at the national level. However, in some central regions, the level of green pest control is relatively weaker. For example, in major grain-producing areas for rice, corn, and wheat like Hunan, Hubei, and Jiangxi, a positive effect on the harmonious coupling of green and low-carbon agriculture with socio-economic development is observed.

From an economic perspective (as depicted in Fig. 6), the per capita GDP exerts a positive impact, with regression coefficients increasing from east to west. These coefficients signify the marginal utility of per capita GDP, which, in turn, exhibits a diminishing marginal utility. Thus, this phenomenon arises as a result. The agricultural production value per unit area has a negative effect, with the highest negative values occurring in the northern regions. These areas have a large agricultural population and relatively underdeveloped agricultural production technology. In contrast, the southern regions are economically developed and have a high degree of coupling and coordination. Rural residents' disposable income has both positive and negative effects, with a larger proportion in the negative direction, concentrated in the northern regions. The higher positive values are distributed in the south. The increase in rural residents' disposable income promotes the coordinated development of green and low-carbon agriculture with socio-economic development.

From a social perspective (as depicted in Fig. 6), the degree of influence of agricultural technological progress contribution rate, urban residents' Engel coefficient, and the proportion of average education years in rural areas is significant. Among them, the urban residents' Engel coefficient has the most notable impact, mainly exerting a negative effect. The absolute value of the regression coefficient is larger in the northeast region, which is a major grain-producing area and a key focus for the development of green agriculture. In the future, it will be necessary to accelerate the pace of transformation towards green and low-carbon agriculture in these areas. In the western regions, the Engel coefficient is relatively lower, and the population is more dispersed, indicating a lower dependence of the degree of coupling and coordination on the urban residents' Engel coefficient. The proportion of regions where the contribution rate of agricultural technological progress has a negative effect is significant. At the national level, the level of agricultural technological progress still needs to be further strengthened, and the dependence of the degree of coupling and coordination on it is not strong. The positive and negative impacts of the average education years in rural areas are relatively balanced. In northern rural areas, the negative effect of average education years is evident. This is consistent with the relatively lower economic and social development in the northern regions, where rural residents generally have a lower level of education. Therefore, the degree of coupling and coordination in these areas does not strongly depend on the average education years in rural areas.

Conclusions

Based on an analysis of the mechanisms underlying the interplay between green and low-carbon agriculture, as well as its impact on society and the economy, this study constructs an evaluation index system for the coordinated development of green and low-carbon agriculture and the socio-economic sphere. By employing a model that measures the degree of coupling coordination, the spatio-temporal patterns of the coupling coordination between green and low-carbon agriculture and the socio-economic sphere in 31 provinces (municipalities and autonomous regions) of China from 2003 to 2021 were calculated. Furthermore, leveraging the GWR model, the driving factors behind the coupling coordination between green and low-carbon agriculture and the socio-economic sphere were explored. The main conclusions are as follows:

1. In terms of temporal changes, the development level of green and low-carbon agriculture in China follows a "U-shaped" trajectory, initially declining, then rising, and ultimately stabilizing. The level of societal development has been steadily increasing over the years, while the economic development level exhibits a fluctuating pattern of growth. The national coupling coordination between green and low-carbon agriculture and the socio-economic sphere has transitioned from an antagonistic phase to a phase of gradual adjustment, ultimately reaching a high-level coupling stage. However, the degree of coupling coordination has undergone three stages: "moderate imbalance = mild imbalance - nearing imbalance." It is yet to achieve a favorable state of coordinated development, indicating significant room for improvement [19].

2. Since 2006, there has been a notable shift in the spatial distribution of the coupling coordination between green and low-carbon agriculture and the socio-economic sphere across China. The spatio-temporal patterns of this coupling coordination have undergone distinct changes. The southeastern region has gradually transitioned from a lower level to a higher level of coordination. In contrast, the western region has predominantly remained at lower levels of coordination. The northern region, on the other hand, has exhibited a fluctuating development pattern, characterized by periods of high coordination, followed by lower coordination, and then returning to high coordination [20].

3. When analyzing the driving factors of coupling coordination between green and low-carbon agriculture and the socio-economic sphere, the impact of different factors varies across regions. Green coverage and per capita GDP have positive influences on the coupling coordination in all 31 provinces, municipalities, and autonomous regions in China. However, the agricultural production value per unit area has a negative impact on the national coupling coordination. The intensity of agricultural carbon emissions, the rate of effective irrigation area, and the intensity of fertilizer, pesticide, and plastic film usage, exhibit both positive and negative effects on the coupling coordination, closely related to the

characteristics of China’s agricultural industry structure. Rural residents’ disposable income has a significant negative impact on the coupling coordination in the northern region. The contribution rate of agricultural technological progress and the average years of rural education have positive effects on the coupling coordination in the southern region. The Engel coefficient of urban residents has a noticeable negative impact on the coupling coordination in the northeastern region [21, 22].

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Conflict of Interest

The purpose of this study is to delve into the interplay and coordination between green low-carbon agriculture and socio-economic development. Throughout the writing process of this paper, we have adhered to the principles of scientific research objectivity and fairness, ensuring the independence and objectivity of the study.

1.All authors involved in this study declare that the research has not been influenced, either directly or indirectly, by any commercial entities, organizations, or individuals.

2.Our research findings, data analysis, interpretations, and conclusions are independently formed based on scientific evidence and academic standards, without interference from any external factors.

3. Should any circumstances arise during or after the research process that may affect the impartiality of the study, we will immediately notify the relevant journal editors and take appropriate measures.

We pledge that the above statements are accurate and are willing to accept peer review and public scrutiny. Our aim is to ensure the transparency and credibility of this study, thereby facilitating a deeper understanding of the coupling coordination and driving factors of green low-carbon agriculture with the socio-economic system among the academic community and the public.

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