Study on the Coordinated Development of Digitization and Greenization of Chinese Agriculture

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Abstract: The coordinated development of agricultural digitization (AD) and agricultural greenization (AG) is a vital initiative for achieving high-quality agricultural development and rural revitalization. By establishing a theoretical framework for their coordinated development and measuring the levels of AD and AG in China from 2013 to 2022, this study employs the CCD model, dynamic panel model, and MGWR model to analyze the spatiotemporal characteristics and driving mechanisms of their coordinated development. The findings indicate: (1) Both AD and AG levels show steady growth, with a spatial pattern generally characterized by a sequential decline from eastern to central and western regions. (2) The CCD between the two continues to strengthen but remains in a marginally coordinated stage overall, far from achieving high-quality coordinated development. Spatial disparities in coupling coordination are pronounced, exhibiting a "multi-core" radiating regional pattern and an overarching trend of "eastern regions leading, while central and western regions strive to catch up." (3) A mutually reinforcing relationship exists between the two, with the pulling effect of AG being stronger than the enabling effect of AD. (4) Various driving mechanisms positively contribute to promoting the coordinated development of the two, with their influence demonstrating marked spatial heterogeneity.

Keywords: agricultural digitization; agricultural greenization; coordinated development; MGWR

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1. Introduction

Driven by the rapid development of digital technologies such as big data, artificial intelligence, and blockchain, a new round of technological revolution and industrial transformation is providing significant strategic opportunities for the modernization of countries worldwide (Jin et al, 2023). Digital transformation, characterized by the application of digital technologies, is increasingly becoming a central issue in the global transformation of government governance (Ahn and Chen, 2022). The Global Digital Economy Development Index 2024 indicates that the global digital economy surpassed 40 trillion USD in 2023, highlighting its growing importance. Concurrently, facing the severe challenges of climate change and environmental pollution, countries are actively formulating green development strategies to address the impacts of digital technological change and global climate change on government governance and societal development (Ning et al, 2023). Undoubtedly, digitization and greenization represent the current trends of the technological revolution and industrial transformation, and their coordinated development has become a crucial strategic choice for countries globally to build competitive advantages in national development. Currently, China's economy has shifted from a phase of high-speed growth to one of high-quality development. Promoting the coordinated development of digitization and greenization is both a spontaneous process resulting from the gradual convergence of these two major trends and an inevitable choice for advancing China's modernization under the guidance of the new development philosophy (Ma et al, 2023; Jin et al, 2024).

Agricultural activities inherently possess dual attributes: generating desired outputs that promote economic growth and undesired outputs that cause ecological and environmental pollution. Under this dual nature, agriculture urgently needs to firmly uphold the dual bottom lines of development and ecology, accelerating the coordinated development of AD and AG. Since the reform and opening-up, China's agricultural development has achieved remarkable accomplishments. Utilizing 9% of the world's arable land and 6% of its freshwater resources, China feeds nearly 20% of the global population, ensuring national food security and steady growth in the agricultural economy. However, the long-term "high-input, high-output" development model has also led to significant agricultural ecological and environmental pollution (Sun et al., 2019). Agricultural development now faces dual constraints of resource scarcity and environmental degradation, alongside an increasingly prominent contradiction between the growing material demands of the population and the insufficient supply of high-quality agricultural products (Yin et al., 2021). Confronted with resource-environmental pressures and structural challenges in agricultural development, China urgently needs to transition toward green agricultural practices. Since the 2016 No. 1 Central Document proposed "strengthening resource conservation, ecological restoration, and promoting green agricultural development," the government has introduced a series of policy frameworks to support ecological civilization and green agricultural transformation. From 2017 to 2022, China established 129 national agricultural green development pilot zones, demonstrating notable progress in this field. These achievements underscore that green agricultural development is an essential pathway to achieving sustainable agriculture (Fan et al., 2021). Digital development, serving as a new engine reshaping agricultural models, is a key force driving AG. With the integration of technology and digitization into agriculture, AD has emerged as a key solution to address resource-environmental constraints and drive high-quality agricultural growth (Lin and Li, 2024; Yi et al., 2021). Research shows that AD not only promotes AG by optimizing industrial structure, improving production efficiency, and providing financial support (Pauschinger and Klauser, 2022; Ullah et al, 2024), but also stimulates agricultural economic growth through deep integration with the agricultural industry (Moreno et al, 2024). In February 2023, the Overall Layout Plan for the Construction of Digital China emphasized accelerating the coordinated transition toward digitization and sustainability. As the foundational industry for human survival and development, the synergy between AD and AG serves as the primary driver for advancing high-quality agricultural and a critical safeguard for implementing the rural revitalization strategy (Du et al., 2023; Wang and Fang, 2023). Therefore, deeply analyzing the logic of coordinated AD and AG, and scientifically evaluating its level, is crucial for promoting deep coordination between the two and enhancing the level of agricultural modernization.

Current academic research on the relationship between AD and AG focuses on three main aspects: (1) Impact of agricultural digital transformation on green agricultural development. Studies suggest that AD significantly promotes green agricultural development with spatial spillover effects, following an inverted U-shaped relationship (Zhou et al., 2023; Sun et al., 2023;

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Lin and Li, 2023). Digital agriculture is shown to advance green practices through technological innovation, income growth, and industrial upgrading (Jiang et al., 2024; Shen et al., 2022). (2) Construction of digital technology systems for green agricultural development. Existing research explores the conceptual framework, architecture, and priorities of digital technology systems for green agriculture. These studies clarify the technical logic and application scenarios of digital empowerment in green agriculture, proposing comprehensive systems that integrate digital technologies across the entire process of green production, processing, sales, and distribution (Yi et al., 2021; Song et al., 2020; Gangwar et al., 2022; Runck et al., 2022). (3) Coordinated development of AD and AG. Research examines the theoretical mechanisms, spatiotemporal evolution, and influencing factors of their coordination at enterprise and regional levels. Findings indicate a steady improvement in their coupling coordination level, showing a spatial distribution pattern of "east-high, west-low" and narrowing regional disparities (Wang and Fang, 2023; Li et al., 2024; Bi et al., 2025). Factors such as economic development, industrial structure, human capital, innovation capacity, and policy frameworks are identified as key drivers enhancing this coordination.

In summary, existing studies have made valuable explorations into the relationship between AD and AG, yet the following gaps remain: (1) Current research predominantly focuses on the enabling effects of AD on AG, while largely overlooking the pull effect of green agricultural development on digital transformation. There is a lack of analysis from a systemic perspective on the theoretical logic and practical mechanisms for the coordinated development of the two. (2) Existing research on the spatiotemporal differences and interaction mechanisms between the AD and AG systems remains relatively weak. There is a particular lack of detailed exploration into the spatiotemporal evolution characteristics of their coupling coordination level and its driving factors. The relationship between AD and AG is mutually reinforcing rather than one-way facilitation (Fei and An, 2024). Clarifying the theoretical mechanism, spatiotemporal evolution process, and driving mechanisms of their coordinated development is of great significance for promoting high-quality agricultural development. Therefore, this study takes China's 31 provinces from 2013 to 2022 as a case study, constructs a theoretical framework and evaluation index system for the coordinated development of AD and AG. It uses the CCD model, dynamic panel model and MGWR model to analyze the level of coordinated development, interactive effects, and driving mechanisms between the two.

Marginal contributions of this study: (1) From the perspective of synergy theory, this study explores the theoretical mechanism of coordinated development of AD and AG based on the guiding principle of "digitization empowerment and greenization traction", enriching theoretical research on their developmental relationship. (2) By exploring the development level, CCD, interactive effects and driving mechanism of AD and AD, this study enhances a comprehensive understanding of their synergistic dynamics and provides empirical support for local governments to formulate and adjust strategies to advance their coordinated development.

2. Theoretical analysis framework

Production, livelihood, and ecology constitute the three major functions and fundamental attributes of the agricultural system. The basic principle of agricultural development is to achieve the unification of ecological, economic, and social benefits—developing while protecting, and protecting while developing. This aims to strengthen ecological functions while simultaneously

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promoting agricultural production and improving farmers' living standards (Huang et al., 2017). AD refers to the process by which agricultural stakeholders, grounded in regional digital development environments, utilize agricultural big data and digital technologies as production factors, alongside information systems and data platforms as carriers, to upgrade agricultural production, operations, and management, thereby enhancing agricultural productivity and development quality (Li et al., 2024; Wang et al., 2023). AG involves promoting the coordinated development of agricultural and ecological systems through green production as a key method, green lifestyles as developmental goals, and green ecosystems as foundational pillars. It aims to establish an agricultural framework aligned with resource-environmental carrying capacity and harmonized with production, livelihood, and ecological sustainability (Yin et al., 2021; Wang and Fang, 2024). AD drives AG by improving production efficiency, advancing rural economic growth, and strengthening ecological conservation, thereby providing momentum and safeguards for sustainable practices. Conversely, AG sets the direction for digitization by prioritizing goals such as total factor productivity enhancement, green agricultural product output, and resource-environmental protection. Thus, the essence of coordinated digitization-greenization development lies in mutual empowerment: digitization enables greenization, while greenization guides digitization. This synergy optimizes agricultural production, rural livelihoods, and ecological conservation to achieve high-quality development of agriculture.

From the perspective of synergy theory, complex systems consist of internal constituent elements (such as market demand, policy orientation, technological innovation, etc.) and various subsystems. Through dynamic interactions (such as gaming and cooperation), these subsystems can form new ordered structures in dimensions like space and function, thereby optimizing system functionality (Haken, 1983). According to this theory, AD and AG exist within and are embedded in the complex system of the socio-economy. The internal components of the two drive the in-depth transformation of the social economy through continuous development and movement, forming a development order and social structure of higher dimensionality. Specifically, the internal logic of their coordinated development is manifested not only in the high degree of unity of development goals—namely pursuing a win-win situation for economic and environmental benefits to achieve high-quality agricultural development—but also in the deep inter-embedding of development factors. This prompts them to achieve synergistic effects in development and protection, leveraging their respective comparative advantages and systemic synergy to enhance the overall efficiency of their coordinated development. Therefore, their coordinated development constitutes a new development order, effectively balancing socio-economic development with ecological environmental protection, and providing a solid foundation for achieving high-quality agricultural development. In summary, based on the perspective of synergy theory and guided by the principle of "digitization empowerment and greenization traction," this paper constructs a theoretical framework for the coordinated development of AD and AG (Figure 1).

First, AD empowers green agricultural development. First, at the production level, agricultural digital transformation enhances innovation capacity, optimizes factor allocation, and improves agricultural green total factor productivity (AGTFP), thereby fostering coordinated green agricultural development (Lin and Li, 2024; Lin and Li, 2023). Second, at the living level, digitization enables agricultural stakeholders to accurately align market supply and demand, facilitating precise connections between producers and consumers. This reduces production and transaction costs while increasing farmers' income. Higher income levels strengthen

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environmental awareness and pro-environmental behaviors among rural residents, further driving green agricultural practices (Zhou et al., 2023; Sun et al., 2023). Finally, at the ecological level, digital transformation promotes efficient resource allocation and industrial optimization, reduces energy consumption and pollutant emissions, and balances agricultural productivity with environmental conservation (Fei and An, 2024; Fu and Zhang, 2022). Additionally, digital platforms for data sharing and communication enhance awareness of agricultural ecological protection.

Second, AG drives the digitization of agriculture. First, at the production level, the core of green agricultural development lies in improving AGTFP in agriculture, which raises higher demands for the application of digital technologies in agricultural production processes (Du et al., 2023; Jiang et al., 2024). Second, at the living level, green agriculture not only imposes stricter requirements for environmental protection and agricultural product quality but also ensures better health safeguards for consumers. The pursuit of high-quality agricultural products effectively stimulates the growth of digital agriculture (Shen et al., 2022). Finally, at the ecological level, under the dual pressures of resource-environmental conservation and the need to enhance green agricultural productivity, green agricultural development demands advancements in digital infrastructure, technology adoption, and talent cultivation, thereby accelerating agricultural digital transformation (Li et al., 2024; Zhang and Sun, 2023).

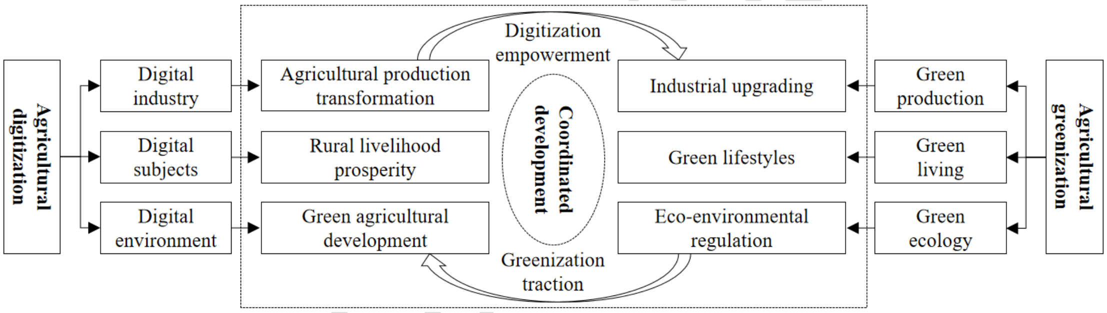

Fig. 1 Theoretical analysis framework for the coordinated development of AD and AG

3. Research methodology and data sources

3.1. Construction of the indicator system

3.1.1. Indicator system for AD

Referring to the existing research (Wang et al., 2023), the evaluation indicator system of AD is constructed from the three levels of “digital industry, digital subjects and digital environment” (Table 1).

Table 1 Indicator system for AD

Standardized layer	Formula	Causality
Digital industry	Scale of facility agriculture (10,000 acres)	+
	Number of agrometeorological observation stations (number)	+
	Income from rural courier operations (in millions of dollars)	+
	Average population served by rural postal outlets (10,000)	+
	Rural delivery routes per capita (kilometers per 10,000 people)	+
	Rural e-commerce sales as a share of agricultural output	+
	Number of rural "Taobao villages" (nos.)	+
Digital	Per capita transportation and communication consumption expenditure of rural	+

subjects	residents (yuan)	
	Depth of use of digital financial inclusion	+
	Number of cell phones per 100 rural households (units)	+
	Number of websites per 100 enterprises (number)	+
	Share of enterprises with e-commerce trading activities (%)	+
	Frequency of digitized words for government agriculture (in number)	+
	Rural per capita expenditure on agriculture, forestry and water affairs (yuan)	+
	Per capita consumption expenditure of rural residents (yuan)	+
	Revenue from information transmission, software and information technology services (billions of dollars)	+
	Digital Inclusive Finance Index	+
Digital environment	Rural per capita agriculture-related loans (yuan)	+
	Number of employees in information transmission, software and information technology services per 10,000 persons (persons)	+
	Rural Internet penetration (%)	+
	Per capita investment in fixed assets in transportation, storage and postal services (yuan)	+

3.1.2. Indicator system for AG

Referring to the existing research (Fan et al., 2021), the evaluation indicator system of AG is constructed from the three levels of "green production, green living and green ecology" (Table 2).

Table 2 Indicator system for AG

Standardized layer	Formula	Causality
Green production	Average total land power of agricultural machinery (kw/ha)	+
	Number of persons employed in the primary sector (persons)	+
	Cultivated land area (ha)	+
	Share of investment in fixed assets in the primary sector in the total value of the primary sector (%)	+
	Gross land value of agricultural production (yuan per hectare)	+
	Total per capita food production (tons/ha)	+
	Per capita agricultural carbon emissions (tons/ha)	−
	Land average agricultural ammonia emissions (tons/ha)	−
Green living	Per capita disposable income of rural residents (yuan)	+
	GDP per capita in agriculture (yuan)	+
	Environmental monitoring area of green food production areas as a proportion of cultivated area (%)	+
	Number of certified green agricultural products (units)	+
Green ecology	Share of forest area in total land area (%)	+
	Share of soil erosion control area in total land area (%)	+
	Expenditures on environmental protection as a share of GDP (%)	+
	Total investment in environmental pollution control as a share of GDP (%)	+
	Average land use of fertilizers (t/ha)	−
	Average land application of pesticides (t/ha)	−
	Average land use of agricultural films (tons/ha)	−

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Per capita agricultural water use (tons/ha)	−
Average land consumption of agricultural diesel fuel (tons/ha)	−

3.1.3. Indicator selection for driving mechanisms

Based on the theoretical framework of coordinated development of AD and AG, this study selects driving factors from the perspectives of digitization empowerment and greenization traction: (1) Agricultural production innovation empowerment mechanism (X1): Agricultural digital transformation drives technological innovation in production, serving as an effective means to achieve green agricultural practices. Therefore, this study uses the number of digital agriculture patents granted to characterize this mechanism. (2) Industrial upgrading traction mechanism (X2): A key indicator of agricultural industrial upgrading is AGTFP. Thus, this study employs AGTFP to represent this mechanism. (3) Farmer prosperity empowerment mechanism (X3): The deep integration of digitization with agricultural production and rural livelihoods fosters new agricultural business models, boosting farmers' income and creating a virtuous cycle. Accordingly, this study adopts rural per capita disposable income as the metric for this mechanism. (4) Green lifestyles traction mechanism (X4): Higher living standards increase public receptiveness to green lifestyles, which helps drive the integration of greenization and digitization from the consumption side. Hence, this study uses the number of green food products per 10,000 people to quantify this mechanism. (5) Agricultural green development empowerment mechanism (X5): Low-carbon agricultural plays a pivotal role in advancing the coordination of digitization and greenization. Therefore, agricultural carbon emission intensity is selected to measure this mechanism. (6) Ecological regulation traction mechanism (X6): Research shows that stronger governmental focus on green development correlates with higher environmental governance performance and elevated greenization levels. Consequently, this study utilizes the frequency of eco-friendly terms in government work reports to reflect this mechanism.

3.2. Research methodology

3.2.1. Coupling coordination degree (CCD) model

This study employs the entropy weight method to calculate the development indices of AD and AG in China from 2013 to 2022. Subsequently, the CCD model (Fei and An, 2024) is applied to measure the CCD between the two:

$$C=\sqrt{x\times y/\left((x+y)/2\right)^2} \tag{1}$$

$$D=\sqrt{C\times T}\,,\quad T=\alpha\times x+\beta\times y \tag{2}$$

Where c is the coupling degree; x is the level of AD, y is the level of AG; T is the development degree; D is the CCD; α, β is the contribution weights of x and y, with $\alpha = \beta = 0.5$. The coupling coordination degree is classified into 10 levels: extreme dysfunction (0, 0.1], severe dysfunction (0.1, 0.2], moderate dysfunction (0.2, 0.3], mild dysfunction (0.3, 0.4], borderline dysfunction (0.4, 0.5], barely coordinated (0.5, 0.6], primary coordination (0.6, 0.7], intermediate coordination (0.7, 0.8], good Coordination (0.8, 0.9], Quality Coordination (0.9, 1.0].

3.2.2. Dynamic Panel Model

The CCD model fails to reflect the dynamic interrelationships between AD and AG. Therefore, this paper employs a dynamic panel model to investigate their dynamic interactive effects (Du et al., 2023).

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$$y_{it} = \alpha\, y_{it-1} + \beta\, x_{it} + \gamma\, z_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{3}$$

Where y_{it} is the explained variable; y_{it-1} is the lagged term of the dependent variable; x_{it} is the explanatory variable; α is the coefficient of the lagged term; z_{it} is the other control variable; β and γ are the coefficients of the independent variables; μ_i is the unit fixed effect; λ_t is the time fixed effect; ε_{it} is the error term.

3.2.3. Multiscale Geographically Weighted Regression (MGWR) model

The MGWR model can detect spatial non-stationarity and identify scale differences of influencing factors (Li et al., 2020). Therefore, this study employs the MGWR model to explore the driving mechanisms of coordinated development of AD and AG:

$$Y_i = \beta_0(u_i, v_i) + \sum_{j=1}^{k} \beta_{bwj}(u_i, v_i) X_{ij} + \varepsilon_i \tag{4}$$

where Y_i is the dependent variable (coupling coordination degree index of province i); X_{ij} is the independent variables (driving mechanisms $X_1 \sim X_6$); $\beta_0(u_i, v_i)$ is the location-specific intercept for province i; β_{bwj} is the local regression coefficient for the *j-th* independent variable in province i; *bwj* is the bandwidth used to estimate *the jth* explanatory variable; ε_i is the error term. To eliminate dimensional effects, all independent variables were normalized.

3.3. Data sources

This study takes 31 Chinese provinces from 2013 to 2022 as the research sample. Original data were sourced from: National Bureau of Statistics Online Database (https://data.stats.gov.cn/); China Statistical Yearbook; China Tertiary Industry Statistical Yearbook; China Financial Yearbook; China Rural Statistical Yearbook; China Environmental Statistical Yearbook; China Agricultural Statistical Yearbook; Green Food Statistical Annual Report; Digital Inclusive Finance Index (Peking University); Government Work Reports (for digital agriculture and green-related term frequencies); Patent Data (National Intellectual Property Administration); Taobao Village Data (Alibaba Research Institute).

4. Results analysis

4.1. Analysis of the Level of AD and AG

4.1.1. Temporal evolution characteristics

The development levels of AD and AG are shown in Fig. 2: From 2013 to 2022, China's AD level increased from 0.085 to 0.226, with an annual average growth rate of 11.45%, indicating a relatively low overall level but rapid development. The Gini coefficient rose from 0.196 to 0.227, reflecting a widening regional disparity. Moran's I values fluctuated between 0.212 and 0.275, suggesting positive spatial correlation in digitization levels. Regionally, the eastern region exhibited the highest digitization level, with its lead over other regions expanding over time. The central, western, and northeast regions showed closely clustered digitization levels.

In contrast, China's AG level rose from 0.442 to 0.588, with an annual average growth rate of 3.22%, characterized by a relatively high overall level but slower growth pace. The Gini coefficient declined from 0.106 to 0.086, signaling narrowing regional gaps. Moran's I values increased from 0.227 to 0.325, highlighting strengthening spatial clustering intensity in greenization levels. By region, the northeast maintained the highest greenization level but saw sluggish growth; the eastern region has the fastest growth rate, while the central and western regions demonstrated steady upward trends.

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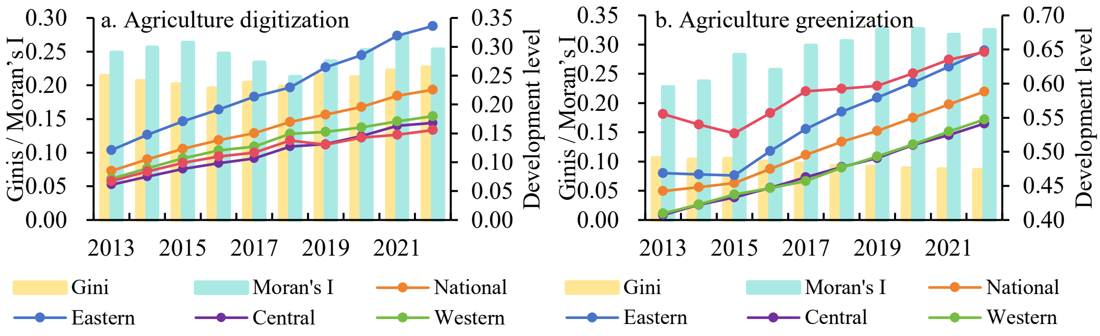
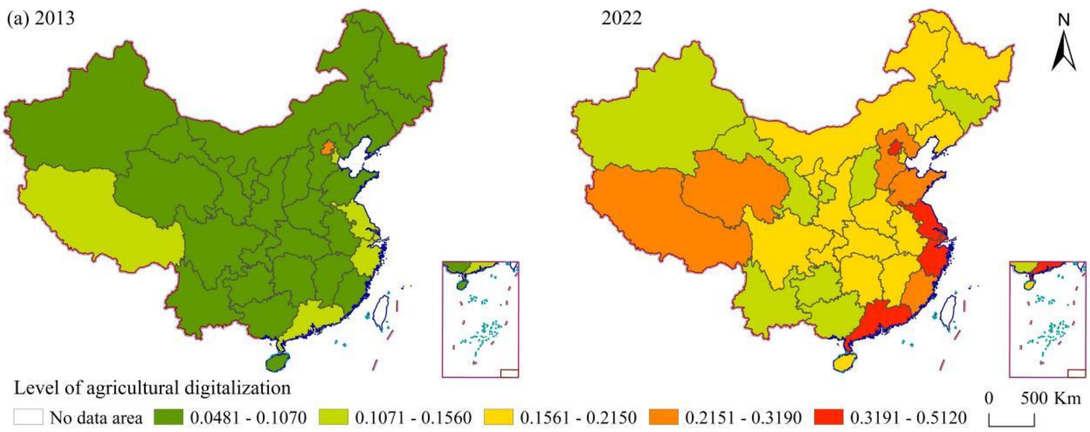


Fig. 2 Levels of AD and AG, 2013–2022

4.1.2. Spatial differentiation characteristics

Overall, the spatial pattern of AD levels follows a descending gradient from the eastern to central to western regions (Fig. 3a). High-level provinces cluster in the southeastern coastal areas, primarily due to their robust economic foundations, advanced digital industries, and superior technological infrastructure, which provide ample financial and technical support for AD. Additionally, the rapid development of rural e-commerce has effectively boosted agricultural income, further propelling digitization. In the western region, only Tibet and Qinghai exhibit relatively high digitization levels, largely due to their small populations, which result in higher per capita indicators—particularly in digital infrastructure.

Meanwhile, AG levels display a spatial pattern of higher levels in the southeastern and northeastern regions and lower levels in the northwest (Fig. 3b). High-performing provinces are predominantly located east of the Hu Huanyong Line (Heihe-Tengchong Line), consistent with existing findings that economically developed (or underdeveloped) provinces tend to exhibit higher (or lower) green development levels (Gai et al., 2021). This disparity arises because areas southeast of the Hu Huanyong Line—characterized by plains, hills, flat terrain, and abundant rainfall—concentrate approximately 94% of China's population and economic activity, making them more suitable for agriculture and habitation. This underscores that economic development levels and natural resource endowments are critical factors influencing AG.



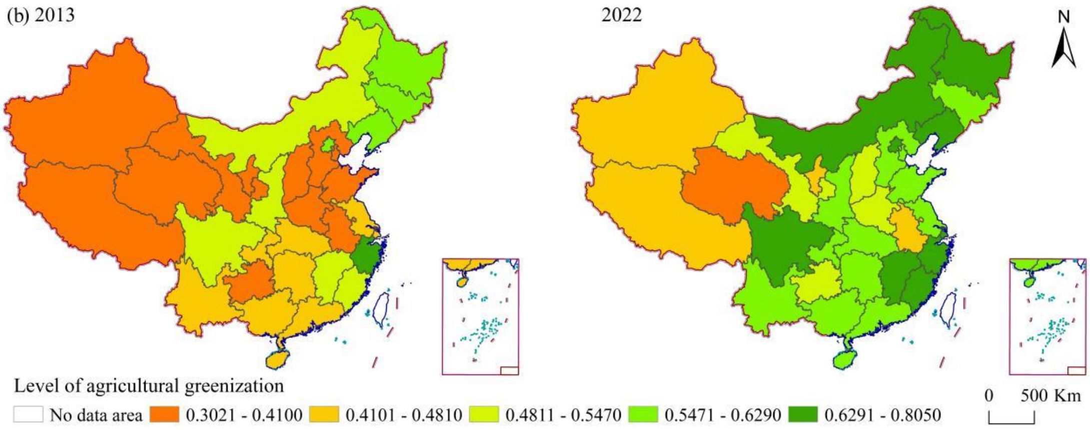


Fig. 3 Spatial Patterns of AD and AG development, 2013–2022

4.2. Analysis of the CCD of AD and AG

4.2.1. Temporal evolution characteristics

From 2013 to 2022, the CCD between AD and AG increased from 0.433 to 0.594, evolving from "borderline dysfunction" to "barely coordinated" (Fig. 4). This indicates that high-quality coordinated development of AD and AG remains far from achieved. Among them, the coordination level in the eastern region increased from 0.482 to 0.675, with the coordination level and growth rate higher than those in other regions. The coordination level in the northeastern, central and western regions rose from 0.396, 0.410 and 0.437 to 0.548, 0.556 and 0.563 respectively, showing gradually narrowing regional gaps.

Based on the trend of the CCD type, the research period can be roughly divided into three distinct phases: 2013–2015 (borderline dysfunction): Characterized by the gradual dominance of "imminent dissonance" as "mild dissonance" phases disappeared. This aligns with the early-stage challenges of low digitization levels and extensive agricultural practices across provinces. 2016–2020 (transition from borderline dysfunction to barely coordinated): At this stage, the borderline dysfunction gradually decreases, and barely coordinated becomes the dominant type of development. This shift was driven by the Cyberpower Strategy and New Development Philosophy proposed in 2015, which accelerated the process of digital industry development and ecological environmental protection, and improved the coordination between AD and AG. 2021–2022 (transition from barely coordinated to primary coordination): The application of digital technologies in agriculture has been accelerated as a result of the country's continued promotion of the digital economy and green development. Primary and intermediate coordination types gradually increase in this stage and enter the rapid growth stage.

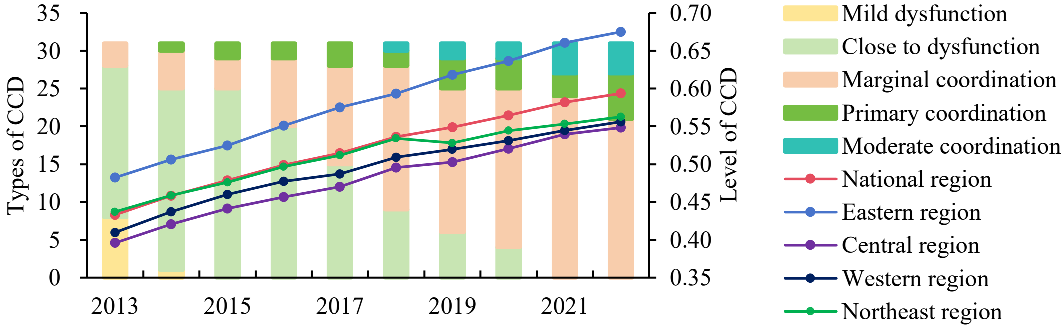


Fig. 4 Level of coupling harmonization, 2013-2022

4.2.2. Spatial distribution characteristics

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The CCD between AD and AG exhibited distinct spatial heterogeneity (Fig. 5). Compared to 2013, provincial coupling coordination degrees in 2022 achieved leapfrog improvements, forming "multi-core" growth poles centered on Beijing, Shanghai, Zhejiang, and Guangdong. These cores radiated outward, driving provinces in the intermediate coordination stage to expand from eastern coastal areas to inland regions. The eastern region maintained its dominance due to location advantages, robust economic foundations, and advanced technological infrastructure, which enabling synergistic interactions between AD and AG. In contrast, the Central and Western regions lagged in CCD due to relatively underdeveloped digital economies and weaker technological innovation capacity. Furthermore, the Moran's I values of CCD increased from 0.253 to 0.350 ($p < 0.01$), indicating a positive correlation between regions and the spatial agglomeration trend is further enhanced. This is because the eastern region is significantly faster than other regions, and the polarization effect is more obvious. The gap between the central, western and northeastern regions has gradually narrowed, tending towards balanced development.

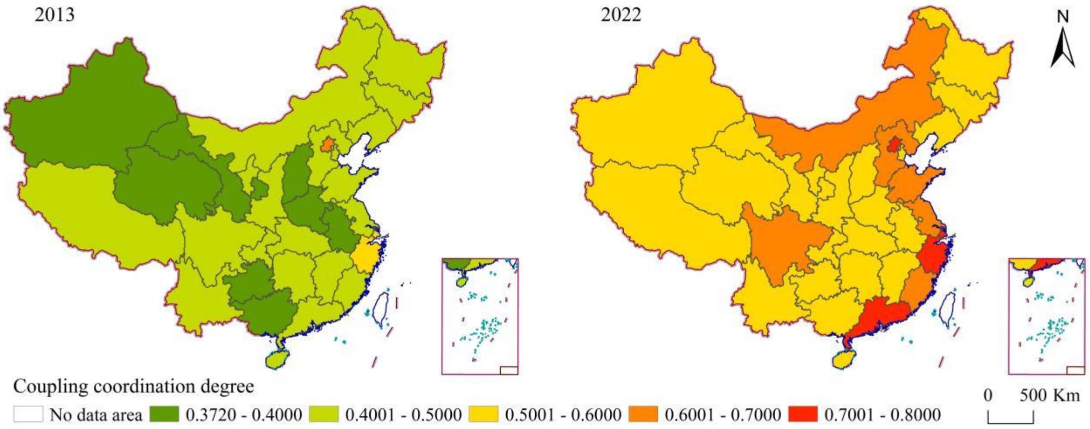

Fig. 5 Spatial pattern of CCD, 2013-2022

4.3. Dynamic interactive effects of AD and AG

The dynamic interaction effects between AD and AG are presented in Table 3. The p-values for both the Hansen test and AR(2) test exceed 0.05, indicating that the model construction results are satisfactory. When AG serves as the dependent variable, the coefficient for the impact of AD on AG is 0.023. Although this effect size is modest, it exerts a positive and significant influence on the development of AG. Currently, AD in China is at an initial stage, with significant disparities among provinces. Consequently, its enabling effects on AG has not been fully realized, and there remains significant potential and scope for enhancement. Conversely, when AD is the dependent variable, the coefficient for the impact of AG on AD is 0.417. This demonstrates that AG significantly promotes AD. This is primarily because China's AG faces urgent practical demands such as pollution and carbon reduction, clean production, and resource recycling, which provide extensive application scenarios and opportunities for the advancement of AD. Furthermore, both AD and AG at the first lag period exhibit significant positive effects on their respective current-period values, with coefficients of 0.698 and 0.960, respectively. This indicates that the development of AD and AG exhibits dynamic persistence over time, where current development is substantially influenced by prior levels. Therefore, in promoting the coordinated development of AD and AG, policymakers should emphasize the cumulative effects of their developmental levels.

Table 3 Estimation results of the dynamic panel model

Explanatory variable	Dependent variable	
	ln(AG)	ln(AD)

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L1_ln(AG)	0.960***	
ln(AD)	0.023**	
L1_ln(AD)		0.698***
ln(AG)		0.417***
sample size	310	310
Hasen test	p =0.209	p =0.314
AR(1)	p=0.003	p=0.006
AR(2)	p=0.086	p=0.243

Note: ** p<0.05, *** p<0.01

4.4. Driving mechanisms of coordinated development

OLS and GWR regression are required before the MGWR regression analysis. The results demonstrate that the MGWR model achieves superior goodness-of-fit with an R^2 value of 0.908, outperforming both the OLS model (0.781) and GWR model (0.877). This comparative advantage in model performance justifies the selection of MGWR for investigating the spatial heterogeneity of driving mechanisms underlying the coordinated development of AD and AG. The variation of driving mechanisms is shown in Fig. 6.

The agricultural production innovation empowerment mechanism (X1) exhibits positive externalities. Areas with high influence are concentrated north of the Qinling–Huaihe Line, while low-influence regions cluster south of this line. This may be attributed to the superior agricultural production conditions in southern China, where relatively mature agricultural systems leave limited room for further green productivity gains.

The industrial upgrading traction mechanism (X2) demonstrates both positive and negative externalities, with significant polarization effects. Regions with positive externalities are primarily in the northwestern, southwestern, and northeastern regions, whereas negative externalities dominate the southeastern coastal areas. This divergence likely stems from the advanced agricultural industries in eastern China, where growth rates of AGTFP have slowed, contrasting with the late-mover advantages of underdeveloped agricultural systems in western and northeastern regions.

The farmer prosperity empowerment mechanism (X3) demonstrates positive externalities. Areas with high influence are concentrated in the southeastern region, exhibiting a spatial pattern that descends from eastern to central to western regions. In contrast, low-influence areas cluster in the northeastern region. This disparity may be attributed to the advanced development of digital agriculture in the southeast, where higher farmers' income levels and stronger willingness to adopt digital and green agricultural practices drive regional progress.

The green lifestyles traction mechanisms (X4) demonstrates both positive and negative externalities. Regions with positive externalities are concentrated north of the Qinling–Huaihe Line, while those with negative externalities cluster south of the line. This divergence may arise because northern regions, with weaker economic foundations and lower public awareness of green living, experience stronger impacts from green lifestyle transition mechanisms. Conversely, southern regions, characterized by stronger economic development and higher baseline levels of green lifestyles, exhibit diminishing marginal effects from such mechanisms.

The agricultural green development empowerment mechanism (X5) and the ecological regulation traction mechanism (X6) both exhibit positive externalities, with their spatial influence distributions showing a strong correlation. Regions with high influence are primarily concentrated

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in Northeast China, Inner Mongolia, Hebei and Shandong. Low-influence areas are mainly distributed in central and southeastern regions. This indicates that stronger ecological-environmental regulation correlates with more significant outcomes in agricultural low-carbon development. Notably, northwestern regions display lower influence from ecological-environmental regulation but higher influence from green agricultural development. This anomaly may stem from a disconnect between policy enforcement intensity and the environmental emphasis in government work reports, suggesting gaps in translating regulatory attention into actionable results.

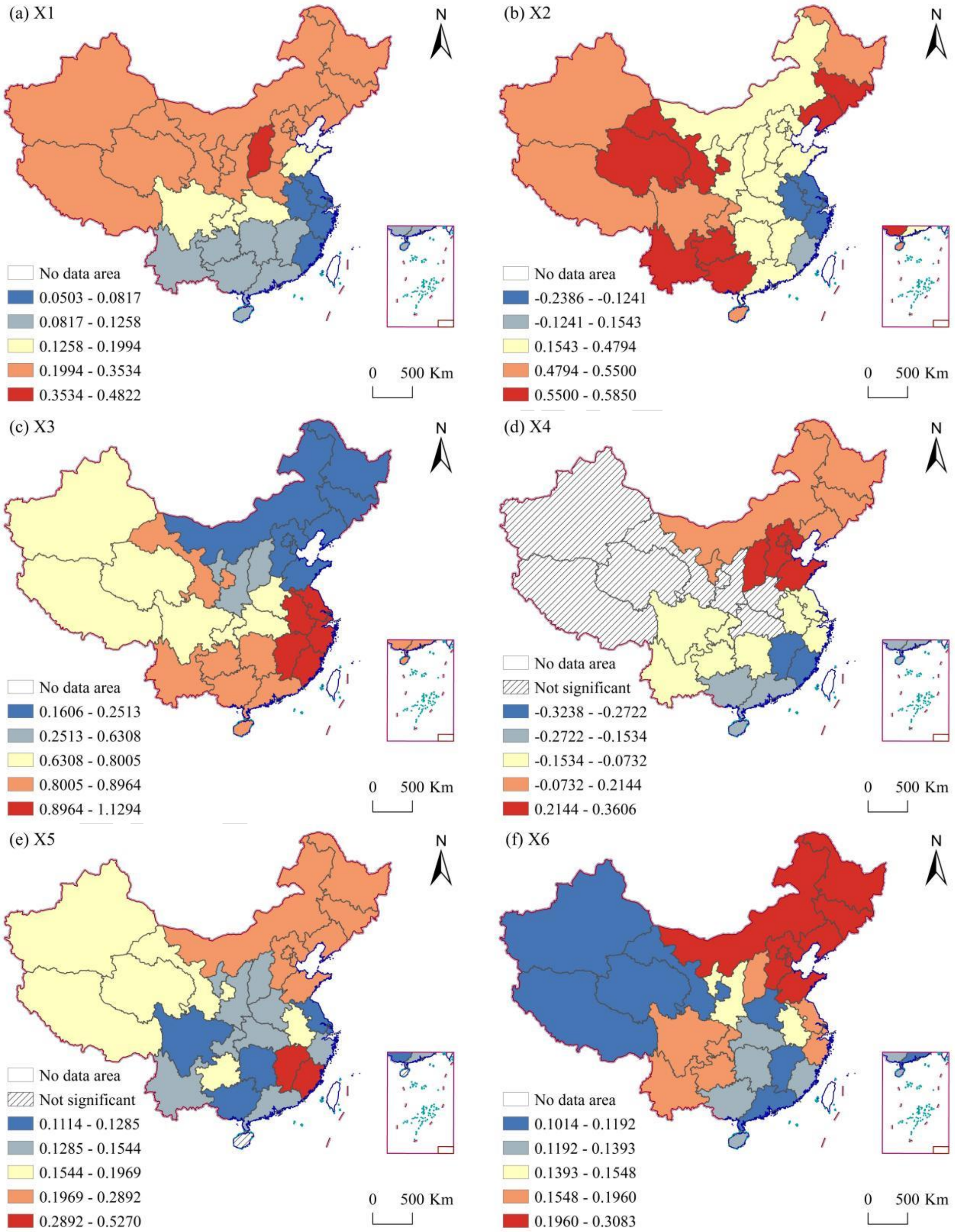

Fig. 6 Patterns of spatial heterogeneity in driving mechanisms

5. Discussion

This study systematically investigates the theoretical mechanisms, spatiotemporal characteristics, and driving forces underlying the coordinated development of AD and AG, aiming to provide theoretical and practical references for optimizing their synergistic advancement. The research findings reveal:

(1) Both China's AD and AG levels have shown steady growth, generally following a spatial pattern descending from eastern to central to western regions (Lin and Li, 2024; Du et al., 2023; Wang and Fang, 2024). AD progresses in tandem with economic development. The Eastern region, with its robust economic foundations, long-standing leadership in digital infrastructure and industrial applications, drives digital transformation in central and western regions by empowering agricultural production and technological modernization (Wang and Fang, 2024). Socioeconomic development is a decisive factor for AG. Compared to western regions, the eastern and central regions benefit from more advanced agricultural technologies, higher levels of intensification and scaling, and greater socioeconomic efficiency (Lin and Li, 2024). Meanwhile, AG exhibits strong spatial clustering, with high-level areas concentrated southeast of the Hu Huanyong Line, underscoring the significant influence of geographic and locational factors on green development (Fan et al., 2021).

(2) The CCD between AD and AG has steadily improved, gradually converging toward a coordinated development stage (Wang and Fang, 2024; Li et al., 2024). The Eastern region maintains a leading advantage in CCD, while the Central, Western, and Northeastern regions exhibit relatively similar coordination levels with minor spatial differences (Wang and Fang, 2024; Fei and An, 2024). This regional imbalance stems from distinct economic development models: Eastern coastal regions, focusing on high-tech industries, leverage economic, technological, and talent advantages to foster digitization-greenization synergy (Li et al., 2024). The Northeastern region, a traditional heavy industrial base, prioritizes non-agricultural sectors, resulting in slower AD and lower CCD. Central and Western regions, as conventional agricultural zones, face underdeveloped internet infrastructure and weak innovation capacity, leading to lower digitization levels and misalignment with greenization development (Wang and Fang, 2024).

(3) There exists a mutually reinforcing dynamic interaction between AD and AG. Among these, AD exerts a relatively minor influence on AG, indicating that the effectiveness of the current digital transformation in agriculture remains insufficient. More effective measures are required to advance this digital transformation. Conversely, AG significantly impacts AD and serves as a key driver in promoting its transformation. The government should continually improve institutional mechanisms and development environments, persistently driving the coordinated development of AD and AG to provide robust support for advancing high-quality agricultural development.

(4) Analysis of driving mechanisms reveals that, with the exception of the traction mechanism of green lifestyles (X4), which shows limited significance, all other factors positively promote the coordinated development of AD and AG, albeit with spatial heterogeneity in their influence. This underscores that advancing agricultural technological innovation, enhancing total factor productivity, increasing farmers' economic income, strengthening ecological-environmental regulations, and expanding digital infrastructure will be critical to achieving coordinated digitization-greenization development in Chinese agriculture, steering it toward higher quality and sustainability (Wang and Fang, 2024; Fei and An, 2024).

6. Conclusions

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This study examines the spatiotemporal characteristics and driving mechanisms of coordinated AD and AG in China from 2013 to 2022 from a system coupling perspective. The conclusions are as follows:

(1) Both AD and AG levels in China exhibited upward trends, with greenization levels significantly higher than digitization levels, though digitization grew faster. Both displayed regional imbalance (eastern regions > western regions) and insufficient development (low baseline with substantial room for improvement).

(2) The CCD between AD and AG continued to strengthen but remained in the "barely coordinated" stage overall. Spatial disparities in coordination were pronounced, gradually forming a "multi-core" regional pattern radiating from Beijing, Shanghai, Zhejiang, and Guangdong, alongside an overarching trend of "eastern leadership with central and western regions catching up."

(3) There exists a positive dynamic interaction effect between AD and AG, with no significant lag effects. Their development exhibits dynamic persistence, serving as endogenous drivers sustaining their own advancement.

(4) Driving mechanisms—including agricultural production transformation, farmer prosperity, agricultural green development, industrial upgrading, green lifestyles, and ecological-environmental regulation—significantly promoted their coordinated development. The influence of these mechanisms exhibited marked spatial heterogeneity.

Based on the aforementioned research findings, this study proposes the following policy recommendations:

(1) Accelerate rural digital infrastructure development to promote AD. For central and western regions, strengthen rural digital infrastructure, enhance digital talent cultivation, improve the digital literacy of agricultural stakeholders, promote the construction of agricultural digital platforms, and narrow regional digital divides. For eastern regions, continuously advance the integrated development of digital technologies and the agricultural industry, build agricultural digital ecosystems, and explore new models for agricultural digital transformation.

(2) Enhance agricultural resource utilization efficiency and advance agricultural green development. For central and western regions, transform agricultural development models by leveraging new technologies and approaches as entry points. Focus on improving resource utilization efficiency, strengthening pollution prevention and control, and driving high-quality agricultural development through innovation. For eastern regions, further strengthen the role of science and technology in safeguarding agricultural green development. Enhance big data monitoring of the agricultural ecological environment and increase the promotion and application of green technologies in agriculture.

(3) Emphasize the coupling and coordination between AD and AG, implementing dynamic and differentiated regional development strategies. Increase policy support for less developed regions, fully leveraging their advantages in land and labor resources to accelerate coordinated development of both dimensions. Promote the establishment of AD and AG pilot zones and experimental areas. Foster sustainable chains for shared scientific R&D and value chains for factor flow. Enable high-performing provinces to drive development in low-performing provinces, thereby narrowing inter-provincial disparities.

Limitations of this study: (1) Due to data availability constraints, the analysis is limited to the provincial level. Future research should investigate regional disparities and driving mechanisms at

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city and county scales to offer more granular insights for implementing high-quality agricultural strategies. (2) The coordinated development of AD and AG constitutes a complex system. Subsequent studies should employ more diverse data and methodologies for deeper analysis. Additionally, the interactions among driving mechanisms remain unclear and warrant further exploration.

CRediT authorship contribution statement

Pengchao Zhou: Writing – review & editing, Writing – original draft. **Erling Li:** Writing – original draft, Resources, Project administration. **Ruolan Li:** Software, Methodology, Data curation.

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Data Availability

The datasets generated during and/or analyzed during the current study are available at: https://pan.baidu.com/s/1Bzbi1e_Io_6WhD43xZcgYQ?pwd=6b4d.

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Declaration of Competing interest

The authors declare no conflicts of interest.

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