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The spatiotemporal characteristics and obstacle factors of the coupled and coordinated development of agricultural and rural digitalization and food system sustainability in China

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Introduction: The sustainable development of China's food system is an essential requirement for realizing the digital transformation of agriculture and rural areas and the main target for the big release of agricultural and rural digitalization dividends and the scale of feedback. What are the current trends of change in China's agricultural and rural digitization and sustainable development of the food system? Have they achieved a high level of coordinated development? What are the factors constraining their coordinated development?

Methods: This work is based on 30 Chinese provincial administrative areas from 2011 to 2020. We adopt the entropy weight method to calculate the comprehensive development index of the agricultural and rural digitization and food system sustainability, respectively. The coupling degree and coupling coordination degree of the two systems are calculated by applying the coupling coordination degree model. The obstacle degree model was used to diagnose the obstacles constraining the coupling and coordinated development of the coupled systems.

Results: This study found that the development index of China's provincial agricultural and rural digitization and food system sustainability increased gradually from 2011 to 2020. The coupling of the two systems is mainly in the high-level coupling stage, but the coupling coordination degree is primarily in the low and medium coupling coordination intervals. These results are heterogeneous across China's four geographic regions: east, center, west, and northeast. The level of rural digital platform construction and rural digital industrialization is the most essential indicator-level and element-level barriers to agricultural and rural digitalization, respectively. *Per capita* food possession and food stability are, respectively, the most critical indicator-level and element-level barriers to the food system sustainability.

Discussion: The research in this work contributes to a comprehensive understanding of the evolutionary trends in agriculture and rural digitalization and the food system sustainability in the country as a whole and within the country. Although the two systems have not achieved a high level of coordinated development, the coupling degree and coupled coordination degree show a positive feedback relationship. The analysis of the obstacle factors helps to recognize the main bottlenecks constraining the coupled and coordinated development of the systems at a more specific level.

KEYWORDS

agricultural and rural digitalization, food system sustainability, comprehensive evaluation, coupled and coordinated development, obstacle factors, entropy weight method

1 Introduction

As food systems become increasingly negatively pressurized, the production and availability of food not only affect global environmental change, but the impacts also spill over into human well-being, social inclusion, economic prosperity, and food security (Willett et al., 2019). The global population is expected to reach a staggering 9.7 billion in 2050 and to solve the problem of food supply for this vast population, it is necessary to strive for a more sustainable way of integrated planning and rational use of natural and social resources to build a sustainable food system, to ensure food security (Godfray et al., 2010). MacPherson et al. (2022) found that agricultural digitization has the potential to enhance the sustainability of the entire food system by increasing value along the agri-food value chain. Other studies have found that certain aspects of rural digitalization, such as information and communication technologies (ICTs), e-commerce sales of agricultural products, and the spread of digital financial inclusion, are beneficial to food stability and food security, and thus significantly increase the sustainability of the food system (Guo et al., 2021; Arshad, 2022; Alam et al., 2023; Liu and Ren, 2023). It can be seen that current research on the relationship between the two focuses on analyzing the impact of agricultural or rural digitization on the food system sustainability (FSS). Indeed, agricultural and rural digitalization (ARD) and FSS are naturally inseparable. The two may appear to be joined and interact with each other. China has the dual identity of a big network power and a big agricultural power, with affluent digital resources in the field of the Internet and vast application space in agriculture. The sustainable development of China's food system is necessary for realizing the digital transformation of agriculture and rural areas and the main object of the big release and the scale feedback of digital dividends in agriculture and rural areas. Exploring the coupling coordination degree and obstacle factors of ARD and FSS will be conducive to the in-depth integration and synergistic development of the two, which can not only provide new research perspectives for the digital transformation of China's grain industry at the theoretical level but also help the government to formulate policies related to grain digitization. Therefore, the main question that this work tries to answer is what the changing trend of China's ARD and FSS is. Can the two achieve high-level coordinated development? What are the obstacle factors constraining their high-level coordinated development?

This paper takes Chinese provincial administrative areas (PAAs) as the research object and tries to answer the above questions. Its contribution to the existing corpus is mainly reflected in the following four aspects. First, this paper simultaneously constructs an evaluation index system for ARD and FSS in China's PAAs by combining relevant concepts and data availability, and measures for the first time the development indexes of ARD and FSS in China's PAAs and geographic regions. Understanding these trends is vital for policymaking and planning national development strategies. Second, this paper focuses for the first time on the interaction between China's agricultural and rural digital system and sustainable food system, i.e., the degree of coupled and coordinated development of the two. This work helps to expand the existing theoretical framework and provide new theoretical perspectives and explanations for the linkage between ARD and FSS. Third, the paper specifically identifies the obstacle factors that constrain the coupled and coordinated development of China's agricultural and rural digital systems and sustainable food systems. This work can help policymakers, researchers, and practitioners better identify the current barriers and challenges to the development of high-level coordination between ARD and FSS to develop targeted measures and strategies accordingly.

2 Theoretical foundation and indicator system construction

2.1 Connotation of agricultural and rural digitalization and its indicator system construction

2.1.1 Connotation of agricultural and rural digitalization

The ARD is a composite concept, i.e., formed by the convergence of agriculture digitalization and rural digitalization. Agriculture and rural areas are an inseparable whole. The rural areas support agricultural development and are the spatial carrier of land, population, capital, technology, culture, and other elements necessary to realize agricultural development. On the other hand, agricultural development can provide an industrial base and material security for rural development, bringing more development dividends to rural residents. Therefore, the co-development of agriculture and rural areas is a crucial way to promote the prosperity of both (Pan et al., 2024).

The ARD is a system in which digital technologies are widely used and lead to fundamental changes in the entire agricultural and rural economic environment and activities. ARD is an activity based on the upgraded digital infrastructure in rural areas, utilizing digital information technologies such as the Internet, cloud computing, blockchain, and the Internet of Things (IoT) to promote the rural areas' development of agricultural production and the economy and society. Agriculture digitalization and rural digital industrialization are two keys to realizing the ARD (Mu and Ma, 2021). Agricultural digitalization is the process of ramping up the output and efficiency of China's modern agriculture through the ample utilization of cutting-edge digital technologies and many digital products in China's national economy. Rural digital industrialization refers to digital technological innovations and the production of digital products, such as networked electronic information processing, information and communication industries, Internet industries, and software services. Thus, ARD is a co-development of agriculture digitalization and rural digital industrialization based on new rural infrastructures.

2.1.2 Construction of the indicator system for agricultural and rural digitalization

According to the connotation of ARD, the formation of ARD includes the following three basic elements (Mu and Ma, 2021). First is rural digital infrastructure. Digital infrastructure construction is the foundation of ARD, in which the most important digital infrastructure includes computer software, hardware, telecommunication equipment, etc. (Tang and Chen, 2022; Zhu et al., 2023). Therefore, this paper establishes three secondary indicators (layer of indicators) under the primary indicator (layer of elements) of rural digital infrastructure: rural internet penetration rate, rural mobile penetration rate, and rural computer penetration rate.

The second is agricultural digitalization. Agricultural digitalization enables the effective integration of digital information technology with all aspects of agricultural development, which is significant in transforming conventional agriculture and changing agrarian production methods. Agricultural digitalization includes the information technological application and digital means in the integration of agricultural production and transactions and other links to achieve rational use of agricultural resources, reduce production costs, improve the environmental quality, improve the quality of agricultural products, and reduce the cost of market operations (Adegbola et al., 2019; Lioutas et al., 2019; Ingram and Maye, 2020; Goel et al., 2021). Therefore, this paper establishes two secondary indicators under the primary indicator of agricultural digitization: the digital degree of agricultural production environment and the digital degree of agricultural products trading.

Third is rural digital industrialization. Rural digital industrialization can be seen as a necessary means to improve and support the agricultural digital transformation. Rural digital industrialization is the degree of digital industrial development in rural areas, which is manifested as a construction mode relying on digital technology to digitally reshape rural daily production and life and other aspects (Sept, 2020; Xia, 2022). Therefore, this paper establishes four secondary indicators under the primary indicator of rural digital industrialization, i.e., the level of rural information technology application, the level of rural digital platform construction, the level of rural residents' consumption of digital products and services, and the level of rural online payment services. The detailed description of each indicator is shown in Table 1.

TABLE 1 Evaluation index system for ARD.

Layer of elements	Layer of indicators	Description of indicators	Indicator weights (attributes)
Rural digital infrastructure	Rural internet penetration rate	"Number of rural broadband access households" as a percentage of "total number of rural households" (%)	0.0657 (+)
	Rural mobile penetration rate	Mobiles per 100 rural households (units/100 households)	0.0181 (+)
	Rural computer penetration rate	Computers per 100 rural households (units/100 households)	0.0470 (+)
Agricultural digitalization	Digital degree of agricultural production environment	Number of agrometeorological observatories (pieces)	0.0339 (+)
	Digital degree of agricultural products trading	E-tailing of agricultural products (RMB 100 million)	0.1657 (+)
Rural digital industrialization	Level of rural information technology application	Average population served by each telecommunication outlet under China post in rural areas (10,000 persons per outlet)	0.0104 (−)
	Level of rural digital platform Construction	Number of Taobao villages (number)	0.4992 (+)
	Level of rural residents' consumption of digital products and services	"Rural households' annual consumption expenditures on the application of various life-oriented digital products and services, such as smart devices and software" as a percentage of "rural households' annual consumption expenditures" (%)	0.1315 (+)
	Level of rural online payment services	Rural digital financial inclusion index	0.0286 (+)

2.2 Connotation of food system sustainability and its construction of indicator system

2.2.1 Connotation of food system sustainability

Giving greater sustainability to food systems has become a global concern and one of the vital agricultural objectives (El Bilali et al., 2019). So far, there are different descriptions in academia about what FSS entails. Béné et al. (2019) argued that nutrition, disaster resilience, sustainable diets, and appropriateness of cultural (dietary) practices should be included in the sustainability goals of FSS, but there may be a conflict between the different dimensions in the process of realizing the FSS, and therefore it should be weighed and navigated. Weber et al. (2020) argue that the potential for developing FSS lies in small-scale, local, and self-reliant community food systems that promote community well-being, social justice, healthy diets, and food security. Viana et al. (2022) argue that FSS must equip food system transformations with the potential to achieve multiple sustainable development goals. Anastasiou et al. (2022) argue that FSS is centered on minimizing environmental impacts and prioritizing the production of nutritious food. A widely applied and relatively authoritative interpretation comes from the Food and Agriculture Organization (FAO) and its subsidiary organization, i.e., the High Level Panel of Experts (HLPE) of the Committee on World Food Security (CFS), which consider FSS to be food systems that aim to achieve food security and nutrition for the current generation without sacrificing the economic, social, and environmental foundations necessary to ensure food security and nutrition for future generations (High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Food and Agriculture Organization of the United Nations, 2014; Food and Agriculture Organization of the United Nations, 2015).

2.2.2 Indicator system construction for food system sustainability

This paper constructs a corresponding indicator system based on FAO's definition of the connotation of a sustainable food system. In this concept, achieving food security is the most fundamental aim. Food security means ensuring sufficient food is available, accessible, and affordable to all people to sustain survival and health (Pérez-Escamilla, 2017). This concept is primarily concerned with ensuring the production of sufficient quantities of food, maximizing the stability of the food supply, and having the capacity to purchase food. Therefore, the indicator system needs to include the three elements of food production security, food stability, and food accessibility. Food production emphasizes the process and activities of food production. Therefore, this paper establishes five secondary indicators under the primary indicator of food production security, i.e., multiple cropping index, total power of agricultural machinery per sown area, energy intensity in agricultural production, intensity of pesticide use in agricultural production, and intensity of fertilizer use in agricultural production. Food supply refers to the quantity and quality of food available in the market. Therefore, this paper establishes four secondary indicators under the primary indicator of food stability: *per capita* food possession, food production per cultivated area, level of food reserves, and quality of food supply. Food accessibility depends on both price and disposable income. Therefore, this paper establishes three secondary indicators under the primary indicator of food accessibility: residents' food purchasing capacity, *per capita* disposable income of rural residents, and Engel's coefficient for rural residents.

In addition, sustainable food systems not only emphasize food security for the present generation but also need to ensure that the economic, social, and environmental foundations necessary for food security for future generations are not sacrificed. Therefore, the indicator system should also include two other primary indicators: economic and social sustainability, resource and environmental sustainability. Under economic and social sustainability, two secondary indicators have been established: value added *per capita* in agriculture, and agricultural labor productivity. Under resource and environmental sustainability, three secondary indicators have been established: the crop damage rate, the effective irrigation of farmland, and the governance level of soil erosion. A detailed description of each indicator is shown in the Table 2.

3 Materials and methods

3.1 Entropy weight method

The entropy weight method is an objective assignment method which can objectively and realistically react to the information implied in the indicator data compared with other subjective assignment methods (Feng and Gong, 2020; Ouadfel and Abd Elaziz, 2021). Therefore, this paper uses the entropy weight method to determine the weights of indicators to provide a basis for comprehensive evaluation.

The first step is the standardization of indicator data. Given that there are certain differences in the evaluation index system among the indicators in terms of the outline, order of magnitude, etc., it is necessary to standardize the data to eliminate the impact of the differences in the indicators on the evaluation results to achieve comparability among the indicators. This paper adopts the method of polar deviation standardization to standardize the evaluation index data, and the calculation process is shown in Equations (1, 2):

$$\text{Positive indicators } Z_{ijt} = \frac{X_{ijt} - X_{j\min}}{X_{j\max} - X_{j\min}} \tag{1}$$

$$\text{Negative indicators } Z_{ijt} = \frac{X_{j\max} - X_{ijt}}{X_{j\max} - X_{j\min}} \tag{2}$$

where x_{ijt} is the original indicator value, i denotes the region ($i = 1$, 2,.., n), j represents the indicator ($j = 1$, 2,.., m), t represents the time ($t = 1$, 2,.., k), and Z_{ijt} is the standardized indicator value. X_{jmax} denotes the maximum value of the j-th indicator in all samples and X_{jmin} denotes the minimum value of the j-th indicator in all samples.

In the second step, we calculate the weight of the j-th indicator for the i-th region in year t [see Equation (3)]:

$$p_{ijt} = Z_{ijt} / \sum_{i=1}^{n}\sum_{t=1}^{k} Z_{ijt} \tag{3}$$

In the third step, we calculate the information entropy of the j-th indicator [see Equation (4)]:

$$e_j = -\frac{1}{\text{In}(m \times k)} \sum_{i=1}^{n}\sum_{t=1}^{k} p_{ijt} \text{In} p_{ijt} \tag{4}$$

If $p_{ijt} = 0$, then define $\lim\limits_{p_{ijt} \to 0} p_{ijt} \text{In} p_{ijt}$

In the fourth step, we calculate the j-th indicator's weight [see Equation (5)]:

TABLE 2 Evaluation index system for FSS.

Layer of elements	Layer of indicators	Description of indicators	Indicator weights (attributes)
Food production security	Multiple cropping index	"Area sown with food crops" as a percentage of "total area under cultivation"	0.0442 (+)
	Total Power of agricultural machinery per sown area	The ratio of "total power of agricultural machinery" to "Total area sown in crops" (10,000 kW/1,000 ha)	0.0698 (+)
	Energy intensity in agricultural production	The ratio of "agricultural diesel usage" to "gross agricultural output" (10,000 t/100 million RMB)	0.0160 (−)
	Intensity of pesticide use in agricultural production	The ratio of "pesticide usage" to "total area sown in crops" (10,000 t/1,000 ha)	0.0107 (−)
	Intensity of fertilizer use in agricultural production	The ratio of "fertilizer usage" to "total area sown in crops" (10,000 t/1,000 ha)	0.0259 (−)
Food stability	*Per capita* food possession	*Per capita* food possession (kilogram/person)	0.3170 (+)
	Food production per cultivated area	Food production per unit cultivated area (kilogram/hectare)	0.0350 (+)
	Level of food reserves	The ratio of the "difference between food production and total food consumption" to "food production"	0.0042 (+)
	Quality of food supply	Quality's compliance rate of centralized food reserves (%)	0.0027 (+)
Food accessibility	Residents' food purchasing capacity	Consumer price index for food (previous year = 100)	0.0187 (−)
	Per capita disposable income of rural residents	*Per capita* disposable income of rural residents (RMB)	0.0757 (+)
	Engel's coefficient for rural residents	"Total food expenditures of rural residents" as a percentage of "total personal consumption expenditures" (%)	0.0230 (−)
Economic and social sustainability	Value added *per capita* in agriculture	Value added in agriculture *per capita* (10, 000 RMB/person)	0.0591 (+)
	Agricultural labor productivity	The ratio of "gross agricultural output" to "number of people employed in agriculture" (10, 000 RMB/person)	0.0580 (+)
Resource-based and environmental sustainability	Crop damage rate	"Crop damage area" as a percentage of "total area sown in crops" (%)	0.0164 (−)
	Effective irrigation of farmland	"Effective irrigated area" as a percentage of "total area under cultivation" (%)	0.1006 (+)
	Governance level of soil erosion	The area of farmland soil erosion control (1,000 ha)	0.1232 (+)

1. To eliminate the effect of price factors, the gross value of agricultural output is adjusted to 2011 constant prices. 2. Food is the general term for plant seeds and tubers in people's culinary food, both raw and finished grains. Including wheat (wheat, barley, barley, rye, oats), rice, legumes (soybeans, pinto beans, mung beans), coarse grains (corn, sorghum, buckwheat, cereals, millets, etc.), potatoes (cassava, sweet potatoes, potatoes). Food accounts for a larger portion of the Chinese diet (Yu et al., 2020), so this was used as the object of study.

$$\omega_j = \left(1 - e_j\right) / \sum_{j=1}^{m} \left(1 - e_j\right) \tag{5}$$

$$\text{where } \omega_j \in [0,1]; \ \sum_{j=1}^{m} \omega_j = 1$$

In the fifth step, we calculate the *i*-th region's composite index in year *t* [see Equation (6)]:

$$E_{it} \left(or \ \ F_{it}\right) = \sum_{j=1}^{m} \omega_j Z_{ijt} \tag{6}$$

E_{it} and F_{it} are development indexes for agricultural and rural digital and sustainable food systems, respectively.

3.2 Coupling coordination degree model

The coupling coordination degree (CCD) originates from the concept of physics, which characterizes the influence degree of two or more systems interacting. The coupling role and the degree of coordination determine the coupled system's evolutionary development. The coupling degree, as an important indicator reflecting the degree of coupling between ARD and FSS, is of great significance in determining the strength of the coupling between the two, the time interval of the coupling action, and the development order of early warning of the two. However, the coupling degree in some cases is difficult to reflect the overall development level of ARD and FSS. For this reason, the ARD and FSS coupling coordination degree model is constructed to judge the high level of coordinated development of ARD and FSS. The CCD model of the two systems can be expressed as (Cheng et al., 2019; Li, 2022):

$$D_{it} = \sqrt{C_{it} \times T_{it}} \tag{7}$$

Among them:

$$C_{it} = \left\{ \frac{E_{it} \times F_{it}}{\left[\left(E_{it} + F_{it} \right) / 2 \right]^2} \right\}^{1/2} \tag{8}$$

$$T_{it} = \alpha E_{it} + \beta F_{it} \tag{9}$$

In Equations (7)–(9), C_{it} is the degree of coupling. When $C_{it} = 1$, it indicates that the two systems are in the optimal coupling state; when $C_{it} = 0$, it indicates that the development between the two systems is irrelevant, i.e., the coupled system develops to disorder. The degree of coupling can only indicate the degree of system interaction, i.e., the consistency between the two systems, but cannot reflect the level of coordinated development of the system. E_{it} and F_{it} are development indexes for agricultural and rural digital and sustainable food systems, respectively. T_{it} is the comprehensive development index of the two systems. α and β are the undetermined coefficients, for the two systems are usually taken to be 0.5. D_{it} reflects the CCD of the two systems, the value of which ranges from 0 to 1. The bigger D_{it} is, the stronger the two systems' coupling coordination is, i.e., the level of development of the two systems is high and coordinated. This paper draws on the "four-point method" of (Lai et al., 2020; Yan et al., 2021) to divide the CCD interval, shown in Table 3.

3.3 Obstacle degree model

Coordinated development is an evolutionary process from low to high level, from disorder to order, from simple to complex, formed by mutual adaptation, collaboration, and promotion of the systems and their system elements. The coordinated development of the coupled system is closely related to the subsystems and their elements. To effectively promote the coupled and coordinated progression of ARD and FSS, we use the obstacle degree model to diagnose the obstacle factors affecting the coupled and coordinated development of the two. The equations for the model are as follows:

$$I_{ijt} = 1 - Z_{ijt} \tag{10}$$

$$h_{ijt} = \left(\frac{\omega_j I_{ijt}}{\sum_{j=1}^{m} \omega_j I_{ijt}} \right) \times 100\% \tag{11}$$

$$H_{ij't} = \sum_j h_{ijt} \tag{12}$$

In Equations (10)–(12), Z_{ijt} is the standardized indicator value; I_{ijt} is the indicator deviation, i.e., the gap between the corresponding indicator's standardized value and 1; ω_j is the factor contribution, i.e., the weight of a single indicator to the coupling coordination goal; h_{ijt} and H_{ijt} are the obstacle degree of the indicator layer indicator j and the factor layer indicator of the i-th region in the year t, respectively.

TABLE 3 Criteria for classifying the coupling coordination degree.

The value range for the coupling coordination degree	(0, 0.4]	(0.4, 0.5]	(0.5, 0.8]	(0.8, 1)
Level of coupling coordination	Low	Medium	High	Extremely high

3.4 Data sources

This paper takes 30 PAAs in China (excluding Tibet, Hong Kong, Macau, and Taiwan region) as the study area, with a sample period of 2011–2020 (given the availability of data). Raw data were obtained from the National Bureau of Statistics of China, China Statistical Yearbook, China Rural Statistical Yearbook, China Agricultural Yearbook, China Grain Yearbook, China Grain and Material Reserve Yearbook, China Taobao Village Research Report, Peking University Digital Inclusive Finance Index, Statistical Yearbooks of PAAs (provinces, autonomous regions, and centrally administered municipalities), and China's provincial Food and Strategic Reserves Bureaus. Missing data for individual years are filled in by interpolation. We interpolate the missing data for individual years to fill in the gaps.

4 Results

4.1 Analysis of the agricultural and rural digital systems and sustainable food systems' development index

This paper first calculates the development indexes of agricultural and rural digital systems and sustainable food systems in each provincial administrative area (PAA) of China from 2011 to 2020. To clearly show the gap between the development indexes of the two systems, the two development indexes are written in fraction form. The numerator and denominator denote the ARD and the FSS development index, respectively. After entering the 21st century, China has divided the country into four major regions, namely, eastern, central, western, and northeastern regions, based on the natural conditions, economic foundation, development level, and opening degree to the outside world, to promote coordinated regional development. Therefore, this paper further averages the national, eastern, central, northeastern, and western regions, which can more clearly show the regional differences between the two development indexes (see Table 4).

At the national level, the ARD and the FSS Index are on an upward trend over the sample period. Although the ARD Index is generally smaller than the FSS Index, the gap between the two has gradually narrowed throughout the evolution. As of 2020, there are individual years and PAAs where the ARD is larger than the FSS development index. This phenomenon indicates that the growth rate of ARD is greater than that of FSS, and this development trend is conducive to the coupled system's evolution to a higher order. However, both are generally low overall, and the growth rate is usually slow. For example, in 2020, the national averages of the ARD index and FSS indexes' national averages are 0.190 and 0.350, respectively.

Locally, eastern China is leading the way in ARD. And the differences in FSS across regions are not noticeable. However, the growth rates show significant differences in different regions, such as the fast growth rate of ARD in the eastern region and FSS in the western region. This indicates that the evolution of ARD is synchronized with the evolution of FSS at different speeds, which may be due to the different foundations of ARD and FSS.

4.2 Analysis of the coupling and coordination degree of agricultural and rural digital systems and sustainable food systems

This section calculates the coupling degree and CCD of the agricultural rural digital system and sustainable food system in each PAA of China from 2011 to 2020. To be able to clearly show the gap between the coupled systems' coupling degree and the CCD, this paper writes both in the form of a fraction. The numerator and denominator represent the coupling degree and CCD of the coupled system, respectively. In this paper, we further find the mean value for the whole country, the eastern, central, northeast, and western China, to show the regional differences between the coupling degree and the CCD (see Table 5).

At the national level, the coupling degree of the vast majority of Chinese PAAs has been stabilized above 0.8, which is at a high level of coupling. This phenomenon indicates that there is a close interdependence and interaction between China's agricultural and rural digital system and the sustainable food system, i.e., there is a strong correlation between the two systems. However, having a high coupling level does not mean a high level of coordination between the two. From the Equations (7–9), the CCD is not only related to the coupling degree but also closely related to the comprehensive development index of the two systems. Therefore, when the development index of both systems is high, i.e., when the CCD is high, the high-level coordinated development of ARD and FSS can be realized. As can be seen from Table 5, the CCD of Chinese PAAs is generally low; the vast majority of PAAs are in the low and medium coupling coordination range, and a few PAAs have barely reached the high coupling coordination range in individual years. The CCD is about half of the coupling degree. Still, the CCD has increased at a faster rate, indicating that the coordinated development level of ARD and FSS has been significantly improved. This is mainly due to the relevant policy drivers of the digital economy and the safeguarding of food security in rural areas in recent years (Du et al., 2022; Lv et al., 2022).

From a localized point of view, the coupling degree, and the CCD of the northeastern, western, central, and eastern China are all increasing in turn. This indicates that the correlation between the ARD and the FSS in the northeast, west, central, and east regions is gradually increasing in that order, and the coordinated development level is also gradually increasing. The coupling degree in the central region increased the fastest, and the CCD in the eastern region increased the fastest. This phenomenon indicates that the coordinated development level of both ARD and FSS in the eastern region is ahead of other regions. The possible reason for this is the favorable geographic conditions in eastern China. Eastern China is flat (Wang et al., 2023), and the limited arable land is mainly concentrated in the plains of the monsoon zone in eastern China (Chen et al., 2023). In contrast, the geography of the central and western parts of the country is more diverse and complex. The complex geographical environment is unfavorable to food production and limits the promotion and popularization of digitization. For example, suppose the government needs to install a 5G communication base station at a high altitude. In that case, the tower firmware of the base station weighs several 100 kg, and the poor traffic conditions often limit the use of transportation or even the use of workforce to carry these bulky components. Even after the installation of the base station, preventing the climate from interfering with the signal and the maintenance of the room at a later stage is very difficult (Pangestu, 2022). This reason is why the first high-altitude 5G base station in Xinjiang was not set up until the end of 2021 in the Hotan region, which is 3,700 meters above sea level. In comparison, China opened its first 5G base station in Guangzhou, Guangdong Province, in 2017 (Liu et al., 2018). The northeast has the slowest growth rate in both coupling and coupling coordination, with the region lagging behind the other regions in both coupling and coupling coordination by 2020. This may be because the northeast has experienced significant population loss and aging in recent years, causing the rural digital economy and food system sustainable development to lag other regions (Mitra et al., 2021; Zhou et al., 2022).

4.3 Analysis of obstacle factors for coupled and coordinated development of coupled systems

In order to explore which indicators are obstacle factors affecting the development of agricultural and rural digital system and sustainable food system, we use Equations (10)–(12) to calculate the obstacle degree of each indicator in the indicator layer of the ARD and FSS evaluation index system. The obstacle factors are ranked according to the size of the obstacle degree. In this paper, the top 3 ranking obstacle factors in each PAA and each year are called the main obstacle factors, and the screening results are shown in Table 6. Where E_i is the obstacle factor (indicator) affecting the development of ARD and F_i is the obstacle factor (indicator) affecting the development of FSS. In Table 6, we use "forward slash" to separate the different factors.

As far as the indicator layer is concerned, the main obstacle factors vary from province to province and year to year. Still, they can reflect the main obstacle factors of the coordinated evolution of the system to a certain extent. For the agricultural and rural digital system, the top three major obstacle factors in 2011–2020 are the level of rural digital platform construction, the digital degree of agricultural products trading, and the level of rural residents' consumption of digital products and services. The main obstacle factors to this system are relatively stable in time and space, showing differences only in individual PAAs and individual years. As seen in Table 6, the obstacle factors of the four large economic and population PAAs, Beijing, Shanghai, Zhejiang, and Guangdong, differed from those of the other PAAs in individual years. For example, Beijing's ranking of major obstacle factors was $E_7/E_5/E_8$ in 2011, $E_7/E_8/E_5$ in 2015, but evolved to $E_7/E_8/E_1$ in 2020, which may be inextricably linked to the basis of digital development in different districts. For sustainable food systems,

TABLE 4 Development indexes for ARD and FSS.

Area	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Beijing	0.215/0.366	0.283/0.376	0.163/0.370	0.171/0.413	0.176/0.430	0.170/0.441	0.215/0.497	0.212/0.547	0.236/0.684	0.268/0.657
Tianjin	0.059/0.300	0.066/0.300	0.069/0.305	0.074/0.319	0.087/0.329	0.090/0.321	0.093/0.333	0.096/0.331	0.109/0.367	0.126/0.372
Heibei	0.062/0.326	0.067/0.339	0.084/0.328	0.096/0.340	0.115/0.348	0.137/0.336	0.161/0.344	0.192/0.353	0.237/0.370	0.289/0.376
Shanxi	0.056/0.220	0.061/0.235	0.065/0.238	0.062/0.254	0.079/0.262	0.080/0.248	0.086/0.244	0.095/0.249	0.096/0.258	0.101/0.264
Inner Mongolia	0.045/0.265	0.056/0.278	0.067/0.296	0.065/0.309	0.085/0.316	0.090/0.317	0.094/0.327	0.093/0.347	0.096/0.352	0.100/0.358
Liaoning	0.055/0.265	0.065/0.286	0.067/0.273	0.070/0.267	0.092/0.288	0.100/0.283	0.105/0.289	0.106/0.293	0.104/0.308	0.101/0.313
Jilin	0.049/0.214	0.057/0.232	0.070/0.221	0.070/0.234	0.081/0.247	0.079/0.252	0.083/0.258	0.084/0.259	0.085/0.267	0.088/0.269
Heilongjiang	0.052/0.222	0.059/0.245	0.067/0.253	0.064/0.276	0.080/0.282	0.081/0.288	0.093/0.305	0.101/0.311	0.107/0.318	0.098/0.321
Shanghai	0.090/0.370	0.089/0.372	0.093/0.369	0.133/0.383	0.143/0.386	0.157/0.399	0.157/0.413	0.157/0.422	0.179/0.445	0.204/0.440
Jiangsu	0.109/0.296	0.125/0.319	0.140/0.322	0.138/0.338	0.187/0.350	0.213/0.362	0.246/0.373	0.310/0.385	0.368/0.401	0.404/0.416
Zhejiang	0.115/0.301	0.122/0.320	0.126/0.326	0.134/0.352	0.223/0.356	0.287/0.362	0.375/0.371	0.512/0.397	0.643/0.430	0.699/0.437
Anhui	0.049/0.228	0.054/0.249	0.067/0.263	0.068/0.279	0.087/0.287	0.091/0.300	0.104/0.305	0.131/0.312	0.142/0.321	0.155/0.335
Fujian	0.092/0.246	0.104/0.266	0.112/0.305	0.120/0.319	0.148/0.321	0.153/0.324	0.189/0.339	0.213/0.369	0.264/0.407	0.285/0.422
Jiangxi	0.049/0.266	0.054/0.289	0.067/0.272	0.068/0.287	0.090/0.299	0.090/0.306	0.103/0.316	0.114/0.332	0.124/0.347	0.134/0.356
Shandong	0.081/0.315	0.091/0.330	0.097/0.319	0.102/0.337	0.134/0.348	0.173/0.342	0.241/0.349	0.291/0.360	0.305/0.387	0.354/0.393
Henan	0.066/0.278	0.072/0.294	0.085/0.285	0.089/0.299	0.109/0.313	0.120/0.312	0.134/0.317	0.150/0.326	0.157/0.347	0.180/0.353
Hubei	0.066/0.241	0.075/0.263	0.086/0.281	0.086/0.303	0.098/0.316	0.100/0.315	0.117/0.331	0.133/0.345	0.148/0.366	0.160/0.370
Hunan	0.052/0.256	0.058/0.274	0.070/0.287	0.069/0.308	0.085/0.319	0.087/0.327	0.098/0.336	0.113/0.348	0.122/0.374	0.132/0.381
Guangdong	0.136/0.247	0.143/0.259	0.152/0.261	0.179/0.274	0.223/0.279	0.274/0.286	0.353/0.294	0.433/0.307	0.511/0.353	0.581/0.320
Guangxi	0.046/0.176	0.053/0.199	0.065/0.210	0.064/0.218	0.080/0.230	0.084/0.237	0.094/0.248	0.107/0.269	0.120/0.290	0.129/0.297
Hainan	0.040/0.157	0.046/0.194	0.054/0.200	0.058/0.208	0.068/0.231	0.077/0.240	0.087/0.262	0.091/0.309	0.103/0.314	0.107/0.324
Chongqing	0.046/0.178	0.049/0.195	0.058/0.201	0.067/0.214	0.079/0.225	0.086/0.234	0.094/0.248	0.102/0.269	0.112/0.288	0.121/0.297
Sichuan	0.060/0.231	0.065/0.249	0.077/0.270	0.080/0.281	0.098/0.293	0.107/0.304	0.122/0.317	0.130/0.329	0.143/0.364	0.156/0.373
Guizhou	0.028/0.136	0.031/0.178	0.045/0.191	0.047/0.215	0.059/0.233	0.069/0.239	0.075/0.251	0.077/0.269	0.081/0.293	0.087/0.304
Yunnan	0.041/0.175	0.048/0.197	0.057/0.217	0.060/0.233	0.073/0.241	0.065/0.255	0.070/0.267	0.087/0.277	0.096/0.292	0.103/0.294
Shaanxi	0.049/0.248	0.054/0.263	0.061/0.238	0.064/0.254	0.076/0.263	0.087/0.267	0.095/0.275	0.096/0.284	0.103/0.316	0.112/0.324
Gansu	0.033/0.200	0.040/0.222	0.050/0.217	0.051/0.225	0.065/0.240	0.070/0.228	0.089/0.249	0.108/0.260	0.117/0.276	0.119/0.281
Qinghai	0.031/0.193	0.036/0.202	0.045/0.194	0.044/0.201	0.060/0.203	0.061/0.217	0.064/0.219	0.076/0.239	0.086/0.253	0.092/0.260
Ningxia	0.036/0.190	0.042/0.208	0.049/0.208	0.047/0.223	0.058/0.232	0.060/0.224	0.067/0.237	0.082/0.246	0.093/0.263	0.099/0.270
Xinjiang	0.054/0.243	0.063/0.256	0.072/0.290	0.069/0.291	0.094/0.306	0.093/0.307	0.102/0.319	0.112/0.327	0.126/0.314	0.122/0.315
Eastern	0.100/0.292	0.114/0.307	0.109/0.311	0.121/0.328	0.150/0.338	0.173/0.341	0.212/0.357	0.251/0.378	0.296/0.416	0.332/0.416
Central	0.056/0.248	0.062/0.268	0.074/0.271	0.074/0.288	0.091/0.299	0.094/0.301	0.107/0.308	0.123/0.319	0.132/0.336	0.144/0.343
Northeast	0.052/0.234	0.060/0.254	0.068/0.249	0.068/0.259	0.084/0.272	0.087/0.274	0.094/0.284	0.097/0.288	0.099/0.298	0.096/0.301
Western	0.043/0.203	0.049/0.223	0.059/0.230	0.060/0.242	0.075/0.253	0.079/0.257	0.088/0.269	0.097/0.283	0.107/0.300	0.113/0.307
Nationwide	0.065/0.245	0.074/0.263	0.079/0.267	0.084/0.282	0.104/ 0.292	0.114/0.296	0.134/0.308	0.153/0.322	0.174/0.346	0.190/0.350

overall, the top 3 main obstacle factors for 2011–2020 are *per capita* food possession, governance level of soil erosion, and the effective irrigation of farmland. *Per capita* food possession has always been the primary factor impeding the FSS in space and time. This result suggests an urgent need to address the generally low *per capita* food possession in China on the way to achieving FSS. The second-and third-ranked obstacle factors vary across provinces and years, suggesting that the remaining ones are not static but constantly adjusted as the system evolves.

As far as the factor level is concerned, the main obstacle factors of the agricultural and rural digital system are, in descending order, rural digital industrialization, agricultural digitalization, and rural digital infrastructure. This ranking is stable in both time and space, indicating that China's current ARD is still in its infancy, and there is still much room for the development of digital industrialization (Chen et al., 2022; Lee et al., 2023).

The main barriers to the sustainable food system are, in descending order, food stability, environmental and resource sustainability, food production security, economic and social sustainability, and food accessibility. Among them, food stability and resource and environmental sustainability have always been the top two obstacles in different times and spaces. Food accessibility was the

TABLE 5 Coupling and coupling coordination degree of ARD and FSS.

Area	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Beijing	0.97/0.53	0.99/0.57	0.92/0.50	0.91/0.52	0.91/0.52	0.90/0.52	0.92/0.57	0.90/0.58	0.87/0.63	0.91/0.65
Tianjin	0.74/0.36	0.77/0.37	0.77/0.38	0.78/0.39	0.81/0.41	0.83/0.41	0.83/0.42	0.84/0.42	0.84/0.45	0.87/0.47
Heibei	0.73/0.38	0.74/0.39	0.81/0.41	0.83/0.42	0.86/0.45	0.91/0.46	0.93/0.49	0.96/0.51	0.98/0.54	0.99/0.57
Shanxi	0.80/0.33	0.81/0.35	0.82/0.35	0.79/0.35	0.84/0.38	0.86/0.38	0.88/0.38	0.89/0.39	0.89/0.40	0.90/0.40
Inner Mongolia	0.70/0.33	0.75/0.35	0.77/0.37	0.76/0.38	0.82/0.41	0.83/0.41	0.83/0.42	0.82/0.42	0.82/0.43	0.83/0.44
Liaoning	0.76/0.35	0.78/0.37	0.79/0.37	0.81/0.37	0.86/0.40	0.88/0.41	0.88/0.42	0.88/0.42	0.87/0.42	0.86/0.42
Jilin	0.78/0.32	0.80/0.34	0.85/0.35	0.84/0.36	0.86/0.38	0.85/0.38	0.86/0.38	0.86/0.38	0.86/0.39	0.86/0.39
Heilongjiang	0.79/0.33	0.79/0.35	0.82/0.36	0.78/0.36	0.83/0.39	0.83/0.39	0.85/0.41	0.86/0.42	0.87/0.43	0.85/0.42
Shanghai	0.79/0.43	0.79/0.43	0.80/0.43	0.87/0.47	0.89/0.49	0.90/0.50	0.89/0.50	0.89/0.51	0.90/0.53	0.93/0.55
Jiangsu	0.89/0.42	0.90/0.45	0.92/0.46	0.91/0.46	0.95/0.51	0.97/0.53	0.98/0.55	0.99/0.59	1.00/0.62	1.00/0.64
Zhejiang	0.89/0.43	0.90/0.44	0.90/0.45	0.89/0.47	0.97/0.53	0.99/0.57	1.00/0.61	0.99/0.67	0.98/0.73	0.97/0.74
Anhui	0.77/0.33	0.77/0.34	0.81/0.36	0.79/0.37	0.85/0.40	0.84/0.41	0.87/0.42	0.91/0.45	0.92/0.46	0.93/0.48
Fujian	0.89/0.39	0.90/0.41	0.89/0.43	0.89/0.44	0.93/0.47	0.93/0.47	0.96/0.50	0.96/0.53	0.98/0.57	0.98/0.59
Jiangxi	0.72/0.34	0.73/0.35	0.80/0.37	0.79/0.37	0.84/0.41	0.84/0.41	0.86/0.42	0.87/0.44	0.88/0.46	0.89/0.47
Shandong	0.81/0.40	0.82/0.42	0.85/0.42	0.84/0.43	0.90/0.46	0.94/0.49	0.98/0.54	0.99/0.57	0.99/0.59	1.00/0.61
Henan	0.79/0.37	0.79/0.38	0.84/0.39	0.84/0.40	0.88/0.43	0.90/0.44	0.91/0.45	0.93/0.47	0.93/0.48	0.95/0.50
Hubei	0.82/0.35	0.83/0.37	0.85/0.39	0.83/0.40	0.85/0.42	0.85/0.42	0.88/0.44	0.90/0.46	0.91/0.48	0.92/0.49
Hunan	0.75/0.34	0.76/0.35	0.79/0.38	0.77/0.38	0.81/0.41	0.81/0.41	0.84/0.43	0.86/0.45	0.86/0.46	0.87/0.47
Guangdong	0.96/0.43	0.96/0.44	0.96/0.45	0.98/0.47	0.99/0.50	1.00/0.53	1.00/0.57	0.99/0.60	0.98/0.65	0.96/0.66
Guangxi	0.81/0.30	0.82/0.32	0.85/0.34	0.84/0.34	0.88/0.37	0.88/0.38	0.89/0.39	0.90/0.41	0.91/0.43	0.92/0.44
Hainan	0.81/0.28	0.78/0.31	0.82/0.32	0.82/0.33	0.84/0.35	0.86/0.37	0.86/0.39	0.84/0.41	0.86/0.42	0.86/0.43
Chongqing	0.81/0.30	0.80/0.31	0.83/0.33	0.85/0.35	0.88/0.36	0.89/0.38	0.89/0.39	0.89/0.41	0.90/0.42	0.91/0.44
Sichuan	0.81/0.34	0.81/0.36	0.83/0.38	0.83/0.39	0.87/0.41	0.88/0.42	0.90/0.44	0.90/0.45	0.90/0.48	0.91/0.49
Guizhou	0.76/0.25	0.71/0.27	0.79/0.30	0.77/0.32	0.80/0.34	0.83/0.36	0.84/0.37	0.83/0.38	0.82/0.39	0.83/0.40
Yunan	0.78/0.29	0.80/0.31	0.81/0.33	0.81/0.34	0.84/0.36	0.81/0.36	0.81/0.37	0.85/0.39	0.86/0.41	0.88/0.42
Shaanxi	0.74/0.33	0.75/0.34	0.81/0.35	0.80/0.36	0.83/0.38	0.86/0.39	0.87/0.40	0.87/0.41	0.86/0.42	0.87/0.44
Gansu	0.70/0.29	0.72/0.31	0.78/0.32	0.78/0.33	0.82/0.35	0.85/0.36	0.88/0.39	0.91/0.41	0.91/0.42	0.91/0.43
Qinghai	0.69/0.28	0.72/0.29	0.78/0.30	0.77/0.31	0.84/0.33	0.83/0.34	0.84/0.34	0.86/0.37	0.87/0.38	0.88/0.39
Ningxia	0.73/0.29	0.75/0.31	0.79/0.32	0.76/0.32	0.80/0.34	0.82/0.34	0.83/0.36	0.87/0.38	0.88/0.40	0.89/0.40
Xinjiang	0.77/0.34	0.79/0.36	0.80/0.38	0.79/0.38	0.85/0.41	0.84/0.41	0.86/0.42	0.87/0.44	0.90/0.45	0.90/0.44
Eastern	0.85/0.40	0.85/0.42	0.86/0.42	0.87/0.44	0.91/0.47	0.92/0.49	0.94/0.51	0.93/0.54	0.94/0.57	0.95/0.59
Central	0.77/0.34	0.78/0.36	0.82/0.38	0.80/0.38	0.85/0.41	0.85/0.41	0.87/0.43	0.89/0.44	0.90/0.46	0.91/0.47
Northeast	0.77/0.33	0.79/0.35	0.82/0.36	0.81/0.36	0.85/0.39	0.85/0.39	0.86/0.40	0.87/0.41	0.86/0.41	0.86/0.41
Western	0.75/0.30	0.76/0.32	0.80/0.34	0.79/0.35	0.84/0.37	0.85/0.38	0.86/0.39	0.87/0.41	0.88/0.42	0.88/0.43
Nationwide	0.79/0.35	0.80/0.37	0.83/0.38	0.82/0.39	0.86/0.41	0.87/0.42	0.89/0.44	0.90/0.46	0.90/0.48	0.91/0.49

third most obstacle factor for most PAAs in 2011. Still, by 2020 it had improved and had become the least obstacle factor for most PAAs. This phenomenon is due to the gradual realization of China's poverty eradication task, the living standards of rural residents have been improving (Gao et al., 2019), and their purchasing power for food is increasing. In contrast, food production security became the third-ranked obstacle in most PAAs in 2020, indicating that China's food production security has deteriorated recently. This may be due to the overuse of agrochemicals such as pesticides and fertilizers in the agricultural production process, which threatens food production security (Kopittke et al., 2019).

5 Discussion and conclusion

5.1 Results discussion and policy implications

In this study, based on the theoretical connotation and practical operability of the ARD and FSS, the evaluation indicator system of the development level of the two was constructed, respectively. It also takes Chinese PAAs as the research object and measures the comprehensive development index of each PAA from 2011 to 2020, respectively, using the entropy weight method. The results show that the development

TABLE 6 Main obstacle factors in the indicator layer for ARD and FSS.

Provincial administrative areas	Agricultural and rural digital system			Sustainable food system		
	2011	2015	2020	2011	2015	2020
Beijing	$E_7/E_5/E_8$	$E_7/E_8/E_5$	$E_7/E_8/E_1$	$F_6/F_{17}/F_{13}$	$F_6/F_{17}/F_{16}$	$F_{17}/F_{13}/F_{14}$
Tianjin	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{17}/F_{11}$	$F_6/F_{17}/F_{13}$	$F_6/F_{17}/F_{13}$
Hebei	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{17}/F_{11}$	$F_6/F_{17}/F_{11}$	$F_6/F_{17}/F_{16}$
Shanxi	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{16}/F_{17}$	$F_6/F_{16}/F_{17}$	$F_6/F_{16}/F_{17}$
Inner Mongolia	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{16}/F_{11}$	$F_6/F_{16}/F_{11}$	$F_6/F_{16}/F_2$
Liaoning	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{16}/F_{17}$	$F_6/F_{17}/F_{16}$	$F_6/F_{16}/F_{17}$
Jilin	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{16}/F_{17}$	$F_6/F_{17}/F_{16}$	$F_6/F_{17}/F_{16}$
Heilongjiang	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{16}/F_{17}$	$F_6/F_{17}/F_{16}$	$F_6/F_{16}/F_{17}$
Shanghai	$E_7/E_5/E_8$	$E_7/E_8/E_5$	$E_7/E_8/E_1$	$F_6/F_{17}/F_2$	$F_6/F_{17}/F_2$	$F_6/F_{17}/F_2$
Jiangsu	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_8/E_5$	$F_6/F_{17}/F_{11}$	$F_6/F_{17}/F_2$	$F_6/F_{17}/F_2$
Zhejiang	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_8/E_5/E_4$	$F_6/F_{17}/F_{11}$	$F_6/F_{17}/F_{16}$	$F_6/F_{17}/F_{13}$
Anhui	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{17}/F_{11}$	$F_6/F_{17}/F_{11}$	$F_6/F_{17}/F_{11}$
Fujian	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{17}/F_{11}$	$F_6/F_{17}/F_{11}$	$F_6/F_{17}/F_2$
Jiangxi	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{17}/F_{11}$	$F_6/F_{17}/F_2$	$F_6/F_{17}/F_2$
Shandong	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_8/E_5$	$F_6/F_{17}/F_{11}$	$F_6/F_{17}/F_{16}$	$F_6/F_{17}/F_{11}$
Henan	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{17}/F_{11}$	$F_6/F_{17}/F_{11}$	$F_6/F_{17}/F_{16}$
Hubei	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{17}/F_{16}$	$F_6/F_{17}/F_{16}$	$F_6/F_{17}/F_{16}$
Hunan	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{17}/F_{11}$	$F_6/F_{17}/F_{11}$	$F_6/F_{17}/F_{11}$
Guangdong	$E_7/E_8/E_5$	$E_7/E_8/E_5$	$E_7/E_8/E_1$	$F_6/F_{17}/F_{11}$	$F_6/F_{17}/F_{16}$	$F_6/F_{17}/F_{16}$
Guangxi	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{17}/F_{16}$	$F_6/F_{17}/F_{16}$	$F_6/F_{17}/F_{16}$
Hainan	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{17}/F_{16}$	$F_6/F_{17}/F_{16}$	$F_6/F_{17}/F_{16}$
Chongqing	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{17}/F_{16}$	$F_6/F_{17}/F_{16}$	$F_6/F_{17}/F_{16}$
Sichuan	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{17}/F_{16}$	$F_6/F_{16}/F_{11}$	$F_6/F_{16}/F_2$
Guizhou	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{17}/F_{16}$	$F_6/F_{16}/F_{17}$	$F_6/F_{16}/F_{17}$
Yunnan	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{16}/F_{17}$	$F_6/F_{16}/F_{11}$	$F_6/F_{16}/F_2$
Shaanxi	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{16}/F_{11}$	$F_6/F_{16}/F_{11}$	$F_6/F_{16}/F_{17}$
Gansu	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{16}/F_{11}$	$F_6/F_{16}/F_{11}$	$F_6/F_{16}/F_{11}$
Qinghai	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{17}/F_{16}$	$F_6/F_{17}/F_{16}$	$F_6/F_{17}/F_{16}$
Ningxia	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{17}/F_{16}$	$F_6/F_{17}/F_{16}$	$F_6/F_{17}/F_{16}$
Xinjiang	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$E_7/E_5/E_8$	$F_6/F_{17}/F_{11}$	$F_6/F_{17}/F_{11}$	$F_6/F_{17}/F_2$

In the table, E_j represents the j-th ($j=1, 2..,9$) indicator in the agricultural and rural digital systems indicator layer; F_j represents the j-th ($j=1, 2,..,17$) indicator in the sustainable food systems indicator layer.

indexes of ARD and FSS in most Chinese PAAs have gradually increased during the sample period, but the levels are still low overall. The ARD is generally smaller than the FSS development index, but the gap between the two gradually narrowing during evolution. The results of this paper's ARD measurement validate existing studies' findings (Tang and Chen, 2022; Xu et al., 2022). For the measurement of FSS, existing studies mainly focus on economically developed countries, including the United States (Heller and Keoleian, 2003), the United Kingdom (Yakovleva, 2007), Japan (Tsuchiya et al., 2021), and Germany (Keuter et al., 2021), etc., while studies for developing countries are still scarce.

In addition, existing measurement studies on the ARD mainly focus on a local area (Zhao and Li, 2022; Zhu et al., 2023) and regions (states, provinces, or cities, etc.) within a country (Tang and Chen, 2022; Xu et al., 2022), and there is a lack of comparative studies on different regions within a country. In contrast, current measures of FSS tend to be based on characteristic facts and national policies from a holistic perspective but do not specifically address FSS in regions (states, provinces, cities, etc.) within countries. The coarse granularity of the existing studies does not consider the characteristics of different regions within the country. It cannot provide precise and objective countermeasure recommendations for establishing a sustainable food system for smaller research objects (states, provinces, cities, etc.). This paper thus further explores the developmental heterogeneity between regions. The results show that the eastern region of China is leading in the ARD. FSS does not differ significantly across China's regions, but growth rates show significant differences. The growth rate of ARD is faster in the eastern region, while FSS grows faster in the western region. The research in this paper contributes to a comprehensive understanding of the evolutionary trends of ARD and FSS in the country as a whole and within the country.

This paper further analyzes the relationship between the roles of agricultural and rural digital systems and sustainable food systems.

Unlike existing studies focusing only on the unidirectional impact of agricultural or rural digitization on FSS, this study approaches from a system-coupling perspective. It innovatively explores the coupled and coordinated progression degree of ARD and FSS. In our work, the coupling degree and CCD of the agricultural rural digital system and sustainable food system in each PAA of China from 2011 to 2020 are calculated using the CCD model. The results show that the coupling degree of the vast majority of Chinese PAAs has been stabilized above 0.8, which is at a high level of coupling stage. However, the CCD of Chinese PAAs is generally low, and the vast majority of PAAs are in the low and medium coupling coordination intervals, with a few PAAs barely reaching the high coupling coordination interval in individual years. This phenomenon suggests a close interaction between China's agricultural and rural digital systems and sustainable food systems. However, the two systems have not achieved a high level of coordinated development. Further analysis shows that the coupling and CCD in northeast, western, central, and eastern China all increase in sequence, meaning that regions with a high level of development of both systems have a higher coupling degree than regions with a low level of development. This phenomenon indicates that both in time and space, the role of the agricultural and rural digital system and the sustainable food system increases as the development level of the respective systems rises, i.e., the coupling and CCD of the two systems show a positive feedback relationship. This suggests that China has now united the two important goals of ARD and FSS, and this finding is of great significance for realizing the two's high-level coordinated development in the future.

Using the obstacle degree model, this paper analyzes the main obstacle factors affecting the coupled and coordinated development of agricultural and rural digital systems and sustainable food systems. The results show that in terms of the indicator level, the top 3 main obstacle factors of the agricultural and rural digital system are the level of rural digital platform construction, the digital degree of agricultural products trading, and the level of rural residents' consumption of digital products and services. The top 3 major obstacle factors of the sustainable food system are *per capita* food possession, governance level of soil erosion, and the effective irrigation of farmland. At the element level, the main obstacles to the agricultural and rural digital system are, in descending order, rural digital industrialization, agricultural digitalization, and rural digital infrastructure. The main obstacles to a sustainable food system are, in descending order, food stability, resource and environmental sustainability, food production security, economic and social sustainability, and food accessibility. The ARD and FSS both belong to the concept of conformity. It is difficult to accurately grasp the internal structure of their development by only analyzing the total development level index, so analyzing the obstacle factors can help us understand the main bottlenecks restricting the development of the system coupling and coordination at a more specific level.

Our study combines with the research findings and puts forward the following countermeasure suggestions. First, the Chinese government should continue to improve agricultural digitization, including the application of technologies such as the Internet of Things in agriculture, big data, and artificial intelligence. The government should strengthen the construction of rural information infrastructure, including network coverage and IT training, to promote farmers' application and acceptance of digital technologies. The Government should formulate and improve policies to encourage agricultural enterprises and farmers to adopt digital technologies by providing financial support, tax incentives, and other incentives.

Secondly, government departments should formulate comprehensive plans to promote the coordinated development of agricultural and rural digital systems and sustainable food systems. Moreover, the government should actively establish cross-sectoral and cross-regional coordination mechanisms to facilitate the synergistic development of agricultural and rural digital systems and sustainable food systems among different regions. The government and enterprises should increase training and support for research institutions and farmers to improve their understanding and application of digital technology and the concept of sustainable food development, to promote the coordinated development of the two systems.

Thirdly, in response to the main obstacle factors in the agricultural and rural digital system, the government and relevant departments should increase investment to promote the construction of rural digital platforms, enhance their coverage and functions, and provide farmers with more digital services and support. The government should encourage the digital development of agricultural markets, promote the establishment of electronic trading platforms for agricultural products, improve the transparency and efficiency of agricultural transactions, and reduce information asymmetry. The government should strengthen digital literacy training for rural residents, promote digital products and services, and facilitate rural residents' participation in the digital economy to improve their quality of life and economic income.

Fourthly, in response to the major obstacles to a sustainable food system, the government should increase food production, including improving agricultural technology, strengthening farmland management, and improving the cropping structure to raise the *per capita* food share. It should also increase investment in soil erosion management and the construction and maintenance of farmland irrigation facilities to improve land-use efficiency and farmland production capacity.

5.2 Research limitations and future directions

Although the findings of this paper expand existing research to some extent, there are still some limitations and elements that can be further deepened in the future.

First, this paper, like most studies (Qu et al., 2022), adopts the entropy weight method to measure the comprehensive development index, which, although it can objectively assign weights based on the data information, lacks qualitative thinking, i.e., it does not consider the actual development needs and development goals of each region. Therefore, in the future, we can formulate differentiated evaluation standards and evaluation systems according to different regions' fundamental development stages and development needs. Also, how outliers affect the results of the indicator measure is something we need to discuss in detail in the future.

Second, the indicators chosen to measure ARD in this manuscript refer to existing literature. Although there is some basis for such an approach, the fact that relevant data characterizing digitization in China are still scarce, and the panel data involving provincial areas are even more insufficient, prevents some more relevant variables from being included in the indicator system. As the database is continuously updated, we will replace the existing indicators with more compelling ones and re-analyze them.

Third, this paper mainly focuses on analyzing the facts that have already happened, which can help us digest the rules from past experiences but does not use this existing information to predict future development. We want to try to simulate the system's future evolution based on the system evolution theories and system dynamics in our subsequent research and adjust the current strategic decisions based on the prediction results.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: raw data were obtained from the National Bureau of Statistics of China, China Statistical Yearbook, China Rural Statistical Yearbook, China Agricultural Yearbook, China Grain Yearbook, China Grain and Material Reserve Yearbook, China Taobao Village Research Report, Peking University Digital Inclusive Finance Index, Statistical Yearbooks of Provincial administration areas (provinces, autonomous regions, and centrally administered municipalities), and China's provincial Food and Strategic Reserves Bureaus. https://www.stats.gov.cn/sj/, http://www.aliresearch.com/cn/presentation, https://idf.pku.edu.cn/zsbz/index.htm. Further inquiries should be directed to corresponding author YC townjam_sovietnia@163.com.

Author contributions

YL: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Software, Writing – original draft. YC: Conceptualization, Investigation, Resources, Supervision, Validation, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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