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EDITED BY

Xiangjin Shen,
Chinese Academy of Sciences (CAS), China

REVIEWED BY

Jianhua Xiao,
Chinese Academy of Sciences (CAS), China
Yan Ma,
Wuhan Polytechnic University, China

*CORRESPONDENCE

Feng Lu,
✉ 2011110007@gxufe.edu.cn

RECEIVED 16 June 2025

ACCEPTED 30 July 2025

PUBLISHED 25 September 2025

CITATION

Xing X and Lu F (2025) Spatio - temporal evolution trajectories and dynamic interactions of arable land multifunctionality in China's major grain-producing regions.
Front. Environ. Sci. 13:1647659.
doi: 10.3389/fenvs.2025.1647659

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Spatio - temporal evolution trajectories and dynamic interactions of arable land multifunctionality in China's major grain-producing regions

Xiaowei Xing^{1,2} and Feng Lu^{3*}

¹School of Economics and Management, Dongguan University of Technology, Dongguan, China,

²School of Management, University of Science and Technology of China, Hefei, China, ³School of Finance and Insurance, Guangxi University of Finance and Economics, Nanning, China

Promoting the multifunctional utilization of arable land in major grain-producing regions has become a crucial measure for China to safeguard food production security. Systematically analyzing the developmental evolution characteristics and dynamic trade-off relationships of the various functions serves as the foundation for promoting arable land multifunctional utilization. Based on the constructed production-social-ecological multifunctional evaluation system, the entropy method, Kernel density estimation, Markov chain method and PVAR model are comprehensively employed to depict the empirical test. The results are as follows: (1) The production function, social function, and ecological function of arable land in the major grain-producing regions generally remain at relatively low levels overall, exhibiting distinct divergent evolutionary characteristics and heterogeneous spatial distribution patterns, with evident trade-offs among different functions across provinces. (2) While the overall disparities in all functions across the 13 grain-producing provinces have significantly narrowed, there exists a potential widening tendency in inter-provincial gaps for both production and social functions. (3) The inter-provincial differences in all three major functions demonstrate gradual, incremental dynamic evolution with strong state stability. (4) The dynamic utility pathways of the three functions of arable land are obviously different, and a mutually reinforcing interactive relationship exists between the production function and ecological function, whereas the both functions respectively exhibit inhibitory interactions with the social function. This paper effectively investigate the development levels, spatio - temporal evolution, and dynamic interactions among different arable land functions in major grain-producing regions, and provides empirical references for promoting interactive coordination among these functions.

KEYWORDS

arable land multifunctionality, production function, social function, ecological function, dynamic distribution, dynamic interaction

1 Introduction

China has always attached great importance to food security, and its comprehensive grain production capacity has continued to achieve new highs. In 2024, the total grain output reached 1.413 trillion jin (706.5 million tons)¹, with a *per capita* share of 500 kg². This accomplishment not only ensures sufficient domestic food supply for China's 1.4 billion people but also contributes significantly to global food security by stabilizing international grain markets and reducing worldwide hunger (Liu et al., 2021; Xue et al., 2025). Furthermore, China's experience offers replicable solutions for developing countries addressing food security challenges. However, China's arable land, grasslands, rivers and lakes have long been over-exploited and over-utilized, and the management mode of arable land focuses more on quantitative care and commodity production capacity. Under this traditional rough development mode, agricultural surface pollution has been increasing, and agroecosystems have been degraded, with the carrying capacity of the ecological environment approaching its limit (Zhang et al., 2021). In particular, increasingly severe issues such as soil erosion, desertification, and rocky desertification, coupled with the unchecked trends of "non-agriculturalization" and "non-grainification" of farmland, have led to a significant reduction in farmland resources and a continuous decline in soil fertility, severely disrupting the structure and functions of agricultural ecosystems (Miao et al., 2021). This not only poses a serious threat to both China's food security and social stability (Wen et al., 2023), but also exacerbates the potential risks to the stability of the global food supply chain and price volatility (Liu et al., 2021). Moreover, against the backdrop of frequent geopolitical conflicts and increasingly normalized extreme weather events, China's continued efforts to explore its grain production potential and reduce its reliance on foreign grain supplies are intrinsic requirements for enhancing its comprehensive food security capabilities and participating in global food security governance (Jiang et al., 2020). However, this will undoubtedly intensify the utilization pressure on arable land and exacerbate the vulnerability of the farmland ecosystem. These issues have directly or indirectly undermined the coordination among the arable land different functions, such as the ecological function, the social function, and the production function, and even disrupted severed the systemic interconnection among these different functions of arable land, which has made the both practitioners and academia deeply concerned about the integrated sustainable utilization of China's arable land resources and food security.

Achieving coordinated multifunctional utilization of arable land is not only an inherent requirement for high-quality agricultural development and the transition between traditional and new agricultural growth drivers, but also an important cornerstone for implementing the United Nations 2030 Agenda for Sustainable

Development (Guo and Feng, 2015; Miao et al., 2021). While enhancing multifunctional land use has become a consensus around the world for promoting the sustainable use of arable land resources, several pressing challenges remain to be addressed. Firstly, the accurate assessment of multifunctional arable land utilization remains a critical challenge. Given that agricultural land use is influenced by multifaceted determinants and exhibits systemic characteristics, its multifunctional application must comprehensively reflect the quality of socioeconomic and ecological dimensions (Gao et al., 2022; Luo et al., 2012). The qualitative analysis of multifunctional arable land use remains insufficient to provide robust data support for policy formulation, only through precise quantitative measurement can the diverse functions of arable land be effectively quantified. However, current research on evaluating the performance levels of these arable land functions remains underdeveloped, limiting data-driven decision-making. Secondly, achieving synergistic interactions among the multifunctional dimensions of arable land represents a pivotal pathway to enhance its integrated utilization efficiency under current constraints. The coordination of the arable land functions, on one hand, emphasizes the endogenous nature of various arable land functions, suggesting that these functions exhibit a cause-and-effect relationship with one another. On the other hand, it places greater emphasis on the harmony and positive synergy among these multifunctional functions simultaneously (Li et al., 2021; Pang et al., 2023). In other words, coordinated interaction of multifunctional arable land implies that strengthening one particular function does not diminish others, and that different functions should exhibit mutually reinforcing or synergistic effects (Lü et al., 2023; Chai et al., 2024). Effectively discerning the intrinsic relationships—whether synergistic, trade-off, or independent—among different sub-functions of arable land is pivotal for achieving coordinated multifunctional interactions. Moreover, China's major grain-producing, as the core agricultural region comprising 13 provinces, utilizes about 65% of the nation's arable land while bearing principal responsibility for national food production and supply. However, this critical region simultaneously grapples with escalating environmental challenges, including excessive agrochemical inputs, worsening soil contamination, and unsustainable land exploitation practices (Zhang et al., 2021). Therefore, this paper aims to quantitatively assess the production function, the social function, and the ecological function of arable land across 13 major grain-producing provinces from 2007 to 2022, and systematically characterize the spatiotemporal evolution patterns of these multifunctional dimensions and elucidates their dynamic interrelationships, thereby providing empirical evidence and policy references for promoting comprehensive utilization and synergistic development of multifunctional arable land in these critical agricultural provinces.

This work offers three critical value-added dimensions to current analysis: Firstly, to more precisely capture the dynamic heterogeneity of arable land's three major functions, the model of Kernel density estimation (KDE) is introduced to analyze the evolution laws of absolute disparities among the three arable land functions, including distribution position, trend, extensibility, and polarization trend. Secondly, the Markov chain method is adopted to construct a Markov transition probability matrix for the three

1 Chinese Government Website: https://www.gov.cn/lianbo/bumen/202412/content_6992479.htm

2 Calculated based on grain production data and population data released by the National Bureau of Statistics (https://www.stats.gov.cn/sj/zxfb/202502/t20250228_1958817.html)

functions of arable land facilitates a more in-depth investigation of the internal dynamics of different functions during the study period, providing a basis for decision-making to better understand the dynamic transition of different functions. Thirdly, addressing the lack of research on the complex interactions between different functions of arable land, this paper incorporates the three functions into a single analytical framework. The model of PVAR is applied, which can account for the endogeneity and lag effects of variables, to dynamically simulate the mutual feedback mechanisms between different functions. This approach enables a more comprehensive understanding of the extent of interaction and mutual influence between different functions. This research method and conclusion are different from previous studies and are more of practical significance, and that is also the main difference between this paper and existing literatures.

2 Literature review

Quantitative change and qualitative change are dialectically unified. Quantitative change serves as the objective of arable land use, while qualitative change represents its essential requirement (Wang, 2022; Chai et al., 2024). Scholars have increasingly recognized that enhancing the multifunctional utilization of arable land is key to improving agricultural environmental governance and driving fundamental transformations in land use practices. The transition from single-function management to multifunctional coordinated development in arable land represents distinct qualitative states at agricultural different developmental stages. Enhancing multifunctional arable land utilization has become an imperative strategy to authentically better satisfy the evolving genuine needs of people (Lü et al., 2023; Chai et al., 2024). The multifunctional arable land utilization extends the traditional single-function approach primarily focused on output maximization to the optimization of production systems, social benefits, and environmental services, as well as the realization of coordinated development in these functions (Wang et al., 2023; Yu et al., 2025).

Originating in the agricultural sector, the concept of arable land multifunctionality has gradually expanded into the field of land use and management with theoretical development (Mander et al., 2007; Helming et al., 2008; Moon, 2015). Different from the simplistic evaluation of the quantity and the growth rate, the assessment of multifunctional arable land utilization exhibits multidimensional and subjective characteristics (Antonio et al., 2007; Pang et al., 2023; Xue et al., 2025). Therefore, establishing a functional indicator system to comprehensively evaluate the multifunctional use of farmland is more in line with practical needs (Antonio et al., 2007; Tao et al., 2014). Banko and Mansberger (2001) summarized previous research and proposed that land functions should encompass economic, social, and ecological dimensions, emphasizing the dominant role of ecological functions in land multifunctionality. This classification method has since been widely recognized by scholars both domestically and internationally, and evaluation indicator systems have been developed to measure the multifunctionality of farmland in countries and regions such as the United States, Canada, Spain, and Southeast Asia (Antonio et al., 2007; Tao et al., 2014; Zhang

et al., 2023). However, due to differing perceptions and demands regarding arable land resources among various groups or individuals, and the significant changes in human-dominated landscapes caused by land consumption resulting from agricultural intensification and urban expansion, discussions on the multifunctionality of land have also emerged (Holmes, 2006). Schöffer et al. (2010) argue that farmland possesses functions such as ecosystem services, maintaining land landscapes, and land use. Coyle et al. (2016) contend that arable land has functions including production, water purification, carbon sequestration, and providing habitats for biodiversity. Xin et al. (2017) propose that the functions of arable land can be divided into explicit and implicit categories, with the former including carbon sequestration and oxygen release, material production, and buffering and filtering, and the latter including cultural heritage and climate regulation. The EU's SENSOR project suggests that the sustainability of multifunctional land use in Europe should be evaluated from multiple perspectives, including economic, environmental, social, and cultural aspects (Helming et al., 2008; Schöffer et al., 2010). Building upon these comprehensive evaluation indicator systems, researchers commonly employ methodologies including grey relational projection, multi-factor weighted summation, full permutation polygon illustration, and principal component analysis to assess arable land multifunctionality (Antonio et al., 2007; Tao et al., 2014; Lü et al., 2023). In summary, while the application of comprehensive measurement approaches for arable land multifunctionality has yielded preliminary results, significant discrepancies persist among different assessments due to variations in indicator selection criteria, research emphases, and computational methods for composite indices.

Beyond the measurement and evaluation of arable land multifunctionality, extant literature has increasingly focused on characterizing the spatial distribution patterns and regional disparities in multifunctional development levels. Currently, the analytical methods can be summarized as follows: (1) Direct Indicator Comparison Method. This approach performs comparative analyses of arable land function disparities across regions or provinces based on calculated functional indicators (Wang et al., 2023; Yu et al., 2025). While it identifies the existence and magnitude of differences, it fails to reveal their underlying causes. (2) Spatial Visualization Method. Utilizing spatial mapping techniques, this method demonstrates functional variations at provincial, regional, or watershed scales (Swetnam et al., 2011; Ayanu et al., 2012; Nemec and Raudsepp-Hearne, 2013; Bastian et al., 2014; Zhang et al., 2023; Xue et al., 2025). However, it merely confirms regional disparities without analyzing their dynamic evolutionary patterns. (3) Relative Disparity Index Methods, such as Theil index or Dagum Gini coefficient. Although these methods quantitatively measure spatial disparities and reveal their evolutionary characteristics (Wang et al., 2023; Zhang et al., 2023; Chai et al., 2024), they primarily focus on subsample differences while neglecting specific distribution patterns. By relying on averaged values, they tend to mask inter-sample variations, consequently failing to capture the dynamic distribution and localized changes of arable land functions. While the above approaches enable comparative assessments of relative disparities across samples, they exhibit inherent limitations in capturing the evolutionary trajectories of absolute differences in

functional performance. The model of Kernel density estimation and the analysis of Markov chain prove more effective for conducting refined examinations of absolute regional disparities in arable land functions and their dynamic evolutionary patterns, and precisely capture the dynamic variations in relative positioning of different functional attributes across regions and quantify the transition probabilities between functional states. However, these methods have not yet been widely applied to multifunctional arable land research, but have been predominantly applied in fields such as regional differences in the supply of basic public services, regional differences in new - type urbanization, and regional differences in residents' consumption upgrading (Wang et al., 2023; Zhang et al., 2023; Xing and Kuang, 2024).

In decision-making processes regarding arable land functional management, divergent objectives and priorities among stakeholders engender complex interfunctional relationships characterized by trade-offs, synergies, and independence (Lee and Lautenbach, 2016). Trade-offs occur when enhancement of one function necessitates diminishment of others, synergies manifest when functions exhibit co-directional changes, while independence indicates functional non-interference. Skinner et al. (2001) analyzed Huzhou City in China, and found that some local governments still tend to sacrifice arable land and the environment for economic growth, leading to a situation where the effectiveness of policies related to the multifunctional protection of farmland diminishes at each level of implementation (Wilson, 2009). India, which has a similar national situation to China, also faces similar issues (Guo and Feng, 2015). Rallings et al. (2019) analyzed the most densely farmed region in British Columbia, Canada, and also found trade-offs and synergies between agricultural production and landscape environmental functions. Therefore, clarifying the driving mechanisms and supporting capacities among different arable land functions has emerged as a pressing research priority (Pang et al., 2023; Lü et al., 2023; Chai et al., 2024). Methods such as graphical analysis, correlation analysis, and regression analysis serve as the most direct approaches to assess trade-offs or synergies among arable land sub-functions. While these methods can preliminarily determine the relationships and strengths between functions, but they cannot characterize the complex relationships among functions, and therefore cannot propose trade-off coordination strategies between multiple functions. To address these shortcomings, scholars such as Zhang et al. (2023) incorporated various arable land functions into a unified system, and applied the coupling coordination mode to analyze the degree of synergy and coordinated development between these functions, focusing on their mutual adaptability and overall harmony within the system. However, as a complex system, the use of arable land often involves complex interactive effects among its sub-functions (OECD, 2001), and the development of each sub-function is often closely related to its own past level and that of other functions. Coupling coordination models are unable to characterize these dynamic characteristics and identify the strength and direction of interactive effects, and therefore cannot provide an in-depth explanation of why coordination or imbalance occurs. The coupling coordination model often fails to capture these dynamic characteristics, consequently limiting its ability to explain the underlying mechanisms driving coordination or discordance. The Vector Autoregression (VAR) model offers distinct advantages

by treating all variables as endogenous and isolating the impulse effects between them through impulse response functions (Ye et al., 2015), which makes the VAR model particularly suitable for analyzing the dynamic interactions and underlying mechanisms among different arable land functions, thereby facilitating deeper understanding of their intrinsic relationships. Regrettably, the current academic literature exhibits a notable paucity in applying this method to the study of the internal logic of multi-functional interactions of arable land.

The existing literature provides both a theoretical foundation and logical starting point for this paper's investigation of arable land multifunctionality in major grain-producing areas. However, whether in empirical research or theoretical analysis, few scholars have conducted in - depth analyses from the perspective of systems theory on the spatio - temporal evolution of different arable land functions in those 13 grain - producing provinces and the dynamic interaction relationships among different functions of arable land. Building upon these, this study integrates spatial visualization methods, Kernel density estimation, and Markov chain methods with distribution dynamics models to analyze the spatial distribution, spatiotemporal variations, and dynamic evolution characteristics of arable land multifunctionality in China's major grain-producing regions. Furthermore, the PAVR model is employed to examine the complex dynamic relationships among the trade-offs or synergies among the arable land sub-functions.

3 Models, methods, and data

3.1 Overview of the study area

China's grain production system exhibits increasing spatial concentration, with regional agglomeration being one of its most prominent features. Based on production and distribution patterns, the 31 provinces in mainland can be divided into seven major grain - selling areas, 11 areas with balanced grain - producing - selling areas, and 13 major grain - producing areas. Unlike the other regions, the major grain-producing areas, not only ensure food self-sufficiency, but also shoulder substantial responsibilities for transferring large quantities of commercial grain, and having long served as a crucial pillar in guaranteeing national food security. For example, the grain output of the three northeastern provinces contribute over 20% of the nation's total output, about a quarter of the commodity grain, about one-third of the amount of grain transferred out. Henan, renowned as the "Granary of Central China," utilizes merely 6% of China's arable land to produce 10% of the country's grain, and annually transfers more than 30 billion kilograms of raw grain and processed products outside the province. Shandong, a major grain - producing province, has ranked first in the country in the total output value of the grain industry for many consecutive years, and provides more than 40 billion kilograms of commercial grain every year.

Simultaneously, by virtue of their geographical advantages, the 13 major grain-producing provinces also perform significant ecological functions. The arable land ecological functions enhancement contributes to protecting soil, water resources, and

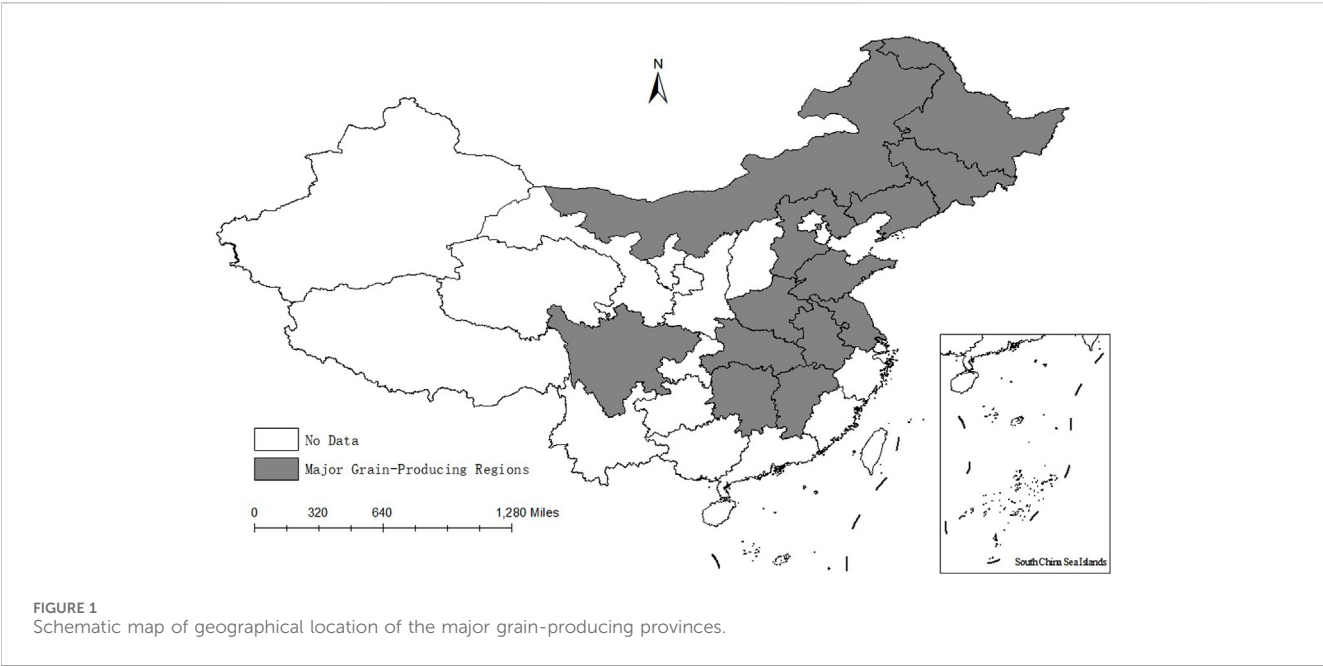


TABLE 1 Comprehensive indicator system of arable land functions.

Function	Specific indicator	Indicator description	Unit	Attribute
Produce	Arable land area <i>per capita</i>	Arable land area/Rural population	hm ² /person	+
	Grain production per unit area	Total grain production/arable land area	kg/hm ²	+
	Contribution to GDP	Agricultural output value/regional GDP	%	+
	Agricultural operation contribution	Value of agricultural output/value added of agriculture, forestry, livestock and fisheries	%	+
Social	Per capita self-sufficiency rate	Grain output/(resident population × 400 kg)	kg/person	+
	Agricultural mechanization level	Total agricultural machinery power/primary industry employment	kW/10,000 people	-
	Urban-rural disposable income ratio	Per capita disposable income of urban residents/ <i>per capita</i> disposable income of rural residents	-	-
Ecology	Chemical load intensity	(Pesticide + fertilizer + agricultural film) usage/arable land area	kg/hm ²	-
	Crop diversity index	$-T_i \ln T_i$, T_i represents the ratio of the sown area of each crop variety to the total sown area of all crops	-	+
	Ecological advantage	Effective irrigated area/total land area	%	+
	Cultivation intensity	arable land area/total regional land area	%	+

biodiversity, while their promotion of green agriculture and eco-agriculture serves as exemplary models with leading influence. Furthermore, agricultural production in these regions provides substantial employment opportunities and lays the foundation for developing rural secondary and tertiary industries, thereby endowing the arable land in those grain-producing provinces with strong social functions. Currently, 13 major grain-producing provinces in China include: Heilongjiang (HL), Inner Mongolia (NM), Jilin (JL), Liaoning (LN), Hebei (HE), Henan (HA), Shandong (SD), Jiangsu (JS), Anhui (AH), Hubei (HB), Jiangxi (JX), Hunan (HN), and Sichuan (SC), with their geographical distribution shown in Figure 1.

3.2 Multifunctional comprehensive evaluation indicator system for arable land

Existing studies have not yet established a unified standard for classifying arable land functions. Previous research has primarily adopted the “Production-Living-Ecological” framework, focusing on production, livelihood, and ecological dimensions to evaluate multifunctional arable land. With reference to the definitions of arable land functional connotations and their covered content scopes established by scholars such as Liu et al. (2021) and Pang et al. (2023), and based on certain extensions of these works, this paper ultimately selected 11 specific indicators were selected from

three aspects of Production Function (Produce), Social Function (Social), and Ecological Function (Ecology) to measure different arable land functions. The specific evaluation index system details in Table 1.

3.3 Research methodology

1. Entropy Method and Linear Weighted Combination. The entropy method enables the assignment of weights to individual indicators within an evaluation system. The linear weighted combination method then synthesizes these entropy-weighted indicators into a composite index. The integration of these two methods has become a standard practice for comprehensive index calculation (Gao et al., 2022), with demonstrated applications across interdisciplinary studies, such as the basic medical and health services, the green industries development, and the consumption upgrading (Xing and Kuang, 2024; Yu et al., 2025). Building on this methodological precedent, this paper applies the integrated entropy-linear combination approach to assess arable land multifunctionality.
2. The model of Kernel density. As a nonparametric estimation method, kernel density estimation (KDE) fits observed data using smooth peak functions. The curve image obtained by kernel density estimation can be adopted to observe the characteristics of the distribution position, shape, extensibility, and polarization trend of random variables. Moreover, this model has the characteristics of strong robustness and does not rely too much on the model. Therefore, it has been widely used by many scholars in the research of spatial non-equilibrium distribution. The general form of the Kernel density estimate is:

$$f(\bar{X}) = \frac{1}{Nh} \sum_{i=1}^N K\left(\frac{X_i - \bar{X}}{h}\right) \quad (1)$$

In Equation 1, N represents the number of observed data points; h is the bandwidth parameter, where increasing bandwidth produces smoother density curves at the cost of reduced estimation accuracy, while decreasing bandwidth yields less smooth curves but improves estimation precision; $K(\cdot)$ denotes the kernel function, with this paper adopting the Gaussian kernel function (as specified in Equation 2) to estimate the dynamic distributional evolution of different arable land functions, X_i denotes i.i.d. Observed data, $\bar{X}$ is the mean value of the observed data.

$$K(\bar{X}) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\bar{X}^2}{2}\right) \quad (2)$$

- (2) The method of Markov chain. The Markov chain, which are Markov processes with discrete time and state, can characterize the internal dynamics of different functions of arable land are characterized by constructing Markov transfer probability matrices. A Markov chain is a state space $\{X(t), t \in T\}$ of a stochastic process if for any v values of time t , the Markov chain satisfies.

$$\begin{aligned} P\{X(t_v) \leq t_v \mid X(t_1) = x_1, \dots, X(t_d) = x_d, \dots, X(t_{v-1}) = x_{v-1}\} \\ = P\{X(t_v) \leq x_v \mid X(t_{v-1}) = x_{v-1}\} \quad x_v \in R \end{aligned} \quad (3)$$

In Equation 3, $X(t_v)$ represents the conditional distribution function undercondition $X(t_i) = x_i$, assuming the transition probability of arable land function levels depends solely on states i and j , that is independent of v , then the time-homogeneous Markov chain can be obtained. Equation 3 can be further revised to Equation 4:

$$\begin{aligned} P\{X_{v+1} = j \mid X_0 = i_0, X_1 = i_1, \dots, X_d = i_d, \dots, X_v = i_v\} \\ = P\{X_{v+1} = j \mid X_v = i\} \end{aligned} \quad (4)$$

If the provincial-level arable land functions are classified into four distinct types, a 4×4 interprovincial state transition probability matrix U can be constructed using the Markov chain method (as specified in Equation 5). This matrix enables the analysis of internal dynamic transition trends among different functional levels of arable land.

$$U = (u_{ij})_{4 \times 4} \quad u_{ij} \geq 0 \quad \sum_{j \in 4} u_{ij} = 1 \quad i, j \in 4 \quad (5)$$

- (3) Dynamic Interaction Analysis among arable land Functions. The Panel Vector Autoregression (PVAR) Model, an advanced extension of traditional VAR, integrates the strengths of both panel data analysis and time-series modeling, can overcome the weakness of insufficient sample size and effectively control the individual and time effects of the research samples. Moreover, the method can observe the dynamic responses of variables by imposing shocks on any variable, providing an effective testing method for studying the dynamic interaction effects of Produce, Social, and Ecology.

$$Y_{it} = a_0 + \sum_{j=1}^p \beta_j Y_{i,t-j} + \mu_i + \varphi_t + \varepsilon_{it} \quad (6)$$

In Equation 6, Y represents vector composed of Produce, Social, and Ecology, p denotes the determined lag order, a_0 and ε_{it} are intercept term vector and normally distributed random disturbance term vector respectively, β_j is the regression coefficient matrix, μ_i and φ_t are individual (provincial) and time effects respectively.

3.4 Data sources

The data Utilized in the study are sourced from the China Statistical Yearbook and the China Rural Statistical Yearbook from 2008 to 2023, along with the website of the National Bureau of Statistics (NBS). Some of the indicators are derived from the original data through collation, such as the per-capita grain security ratio and agricultural cultivation diversity. For the missing data, linear interpolation or extrapolation methods are used for filling. The geographical data mainly obtained from the Center for Resource and Environmental Science and Data of the Chinese Academy of Sciences (<http://www.resdc.cn>).

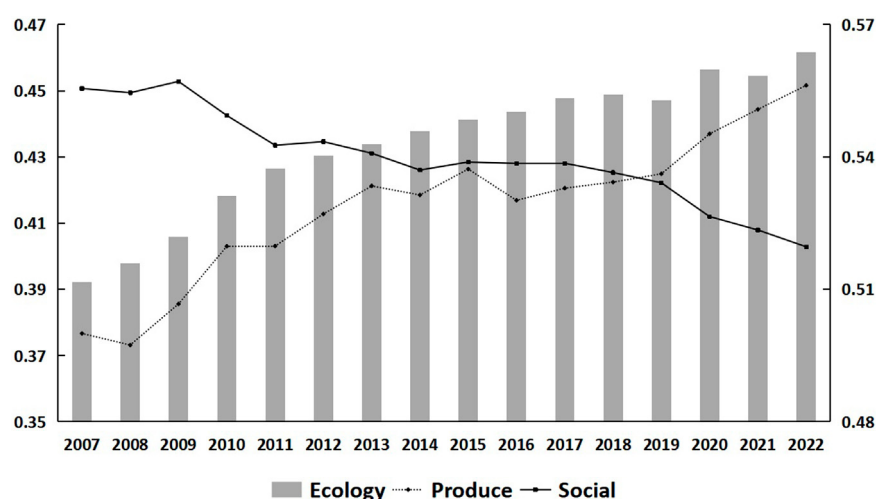


FIGURE 2
Average values and changes of produce, social, and ecology.

4 Calculation results and dynamic distribution of the arable land functions

4.1 Overview of the arable land functions

Figure 2 delineates the evolutionary trends of the three arable land functions include the production function, the social function, and the ecological function in major grain-producing areas during the 2007–2022 period. During the observation period, the production function and ecological function of arable land, ranged between 0.275–0.834 and 0.304–0.753 in each year, with the mean values of 0.415 and 0.543, and the standard deviations of 0.098 and 0.119, respectively. Both functions exhibited fluctuating yet upward trajectories, with overall increases of 19.822% and 10.187%, respectively. In contrast, the social function of arable land demonstrated a steady decline, decreasing by 10.610% over the observation period. This is mainly due to the fact that, through the promotion of green agricultural technology, the improvement of infrastructure, the implementation of ecological restoration projects, the upgrading of mechanization levels and other systematic measures, China has fully tapped the production potential of arable land in 13 major grain-producing provinces while significantly improving the arable land ecological functions, and promoting the transformation and upgrading of arable land's function from a single production to the synergistic transformation and upgrading of the arable land production and ecological function. Simultaneously, China's agricultural production model has undergone structural changes, with capital increasingly replacing labor. The rise of socialized agricultural machinery services and intermediate inputs has driven the flow of rural labor and employment in non-agricultural industries, increasing income from migrant work and business operations, and significantly reducing the dependence of the rural population on land. Additionally, the rapid advancement of industrialization and urbanization, coupled with higher non-agricultural employment opportunities and income levels, has further accelerated land transfers and the differentiation of farming households, driving

more rural labor to migrate to cities and weakening the “buffer” role of agriculture and rural areas.

To further characterize the spatio-temporal evolution of the three functions of arable land across major grain-producing provinces, this paper adopts 5-year analytical cycles aligned with national economic planning periods, the average levels of these three functions for each region using 5-year cycle are calculated. Table 2 details the provincial-level evaluations quantify functional performance metrics and corresponding rankings of the three arable land functions. As clearly evidenced in Table 2, the disparities in the three major functions of arable land across 13 grain-producing provinces primarily manifest in three aspects. Firstly, regarding temporal evolution patterns, the arable land production, social, and ecological functions in all 13 provinces demonstrate distinct divergent evolutionary trends amid fluctuations. The four provinces of Anhui, Jiangxi, Hubei, Hunan and Shandong Province, which are situated within the middle and lower Yangtze River basin, as well as Shandong Province Shandong Province demonstrate a distinct evolutionary pattern characterized by “weakening production-social functions alongside strengthening ecological function”. This phenomenon may stem from rising household incomes in these provinces, which has shifted dietary demands from “basic sustenance” to “quality nutrition”, and market mechanisms can now meet agricultural product consumption needs, which has driven the transformation of arable land toward intensive, high-value-added agriculture, reducing local residents' dependence on farmland and weakening its traditional role in grain production. Additionally, under the constraints of ecological and environmental factors and the trend toward creating a livable and business-friendly development environment, these provinces also have greater willingness and economic capacity to optimize the functions of farmland, leveraging roles in agricultural landscapes, air purification, water regulation, and maintaining biodiversity, thereby effectively releasing the ecological and landscape functions of farmland. In contrast, the provinces of Jilin and Heilongjiang, located on the Northeast Plain, have long invested significant resources in grain production, which has relatively low

TABLE 2 Measurement results of produce, social, and ecology.

Function	Provinces	2007–2011	2011–2015	2016–2020	2021–2022	Average	Ranking
Produce	HE	0.378	0.394	0.387	0.396	0.388	5
	NM	0.408	0.489	0.530	0.615	0.497	2
	LN	0.307	0.357	0.395	0.432	0.366	11
	JL	0.451	0.493	0.471	0.536	0.481	3
	HL	0.489	0.667	0.746	0.832	0.668	1
	JS	0.350	0.364	0.372	0.389	0.366	10
	AH	0.352	0.353	0.336	0.338	0.345	12
	JX	0.320	0.326	0.338	0.320	0.327	13
	SD	0.405	0.383	0.376	0.389	0.387	6
	HA	0.442	0.441	0.450	0.467	0.447	4
	HB	0.385	0.397	0.363	0.360	0.378	7
	HN	0.380	0.379	0.362	0.365	0.372	8
	SC	0.334	0.371	0.392	0.385	0.370	9
	Average	0.385	0.416	0.424	0.448	0.415	-
Social	HE	0.432	0.400	0.390	0.368	0.401	10
	NM	0.520	0.530	0.528	0.501	0.523	1
	LN	0.438	0.427	0.413	0.384	0.420	6
	JL	0.451	0.453	0.469	0.459	0.458	3
	HL	0.490	0.507	0.523	0.520	0.509	2
	JS	0.399	0.382	0.373	0.358	0.380	13
	AH	0.456	0.432	0.419	0.404	0.430	5
	JX	0.431	0.401	0.387	0.372	0.401	11
	SD	0.438	0.413	0.401	0.381	0.412	9
	HA	0.449	0.415	0.398	0.374	0.413	8
	HB	0.412	0.386	0.382	0.367	0.389	12
	HN	0.465	0.433	0.418	0.399	0.432	4
	SC	0.453	0.422	0.401	0.382	0.418	7
	Average	0.449	0.431	0.423	0.405	0.430	-
Ecology	HE	0.568	0.576	0.574	0.561	0.572	6
	NM	0.312	0.330	0.357	0.389	0.341	13
	LN	0.418	0.439	0.450	0.476	0.442	11
	JL	0.447	0.469	0.478	0.489	0.469	9
	HL	0.368	0.425	0.449	0.469	0.423	12
	JS	0.733	0.738	0.749	0.727	0.739	1
	AH	0.619	0.641	0.643	0.653	0.638	4
	JX	0.442	0.465	0.472	0.484	0.464	10
	SD	0.692	0.694	0.694	0.683	0.692	3
	HA	0.680	0.697	0.708	0.730	0.700	2

(Continued on following page)

TABLE 2 (Continued) Measurement results of produce, social, and ecology.

Function	Provinces	2007–2011	2011–2015	2016–2020	2021–2022	Average	Ranking
	HB	0.538	0.580	0.590	0.603	0.575	5
	HN	0.463	0.492	0.507	0.503	0.491	8
	SC	0.482	0.514	0.530	0.527	0.513	7
	Average	0.520	0.543	0.554	0.561	0.543	-

economic returns, and the state has continuously strengthened their grain production capacity through policies such as high-standard farmland construction, agricultural machinery subsidies, and grain subsidies. This has, to a certain extent, hindered the industrialization process, reduced non-agricultural employment opportunities for rural residents, and increased their dependence on farmland. At the same time, strict black soil protection policies have also made Jilin and Heilongjiang responsible for comprehensively advancing the construction of high-standard arable land, improving soil structure, and enhancing soil fertility, thereby improving the comprehensive management and utilization of farmland and achieving the coordinated enhancement of its production, social, and ecological functions.

Secondly, regarding spatial disparities, significant variations existed among the three functions across all 13 provinces during the observation period. Taking the arable land production function as an example, the provincial-level regions with the top three average production function values in arable land are Heilongjiang, Inner Mongolia, and Jilin, with average values of 0.668, 0.497, and 0.481 respectively. Conversely, the bottom three performers in this category are Liaoning (0.366), Anhui (0.345), and Jiangxi (0.327), accounting for only 54.77%, 51.70%, and 49.03% of the average value of Heilongjiang, which holds the leading position in the arable land production function. The empirical results presented in Table 2 demonstrate substantial heterogeneity in both social and ecological functional performance across the 13 major grain-producing provinces.

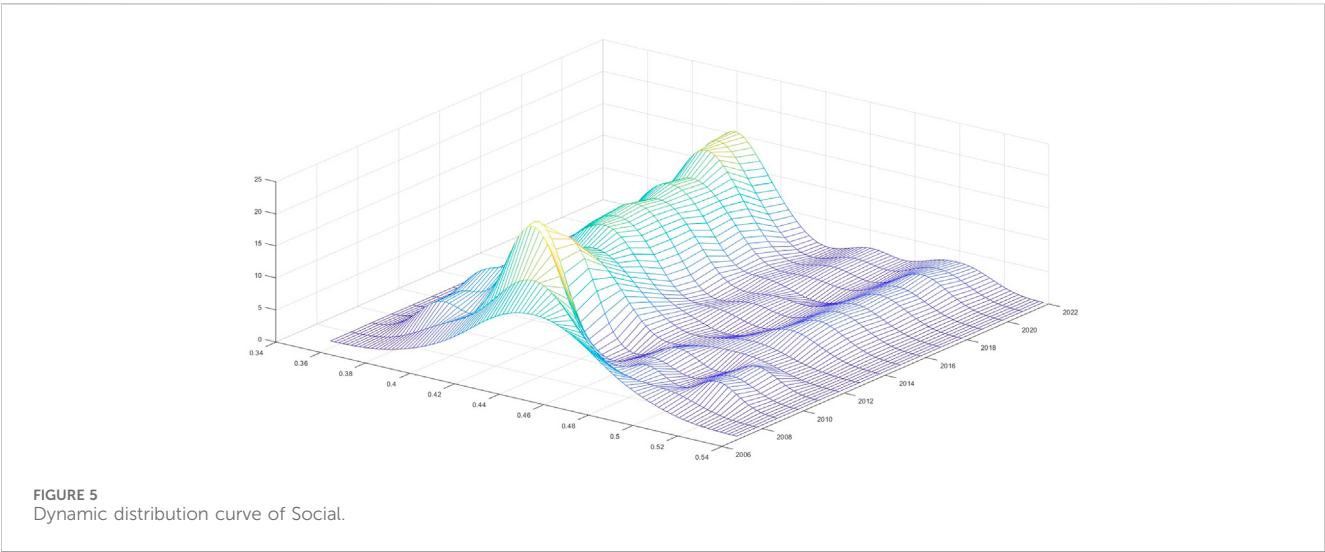
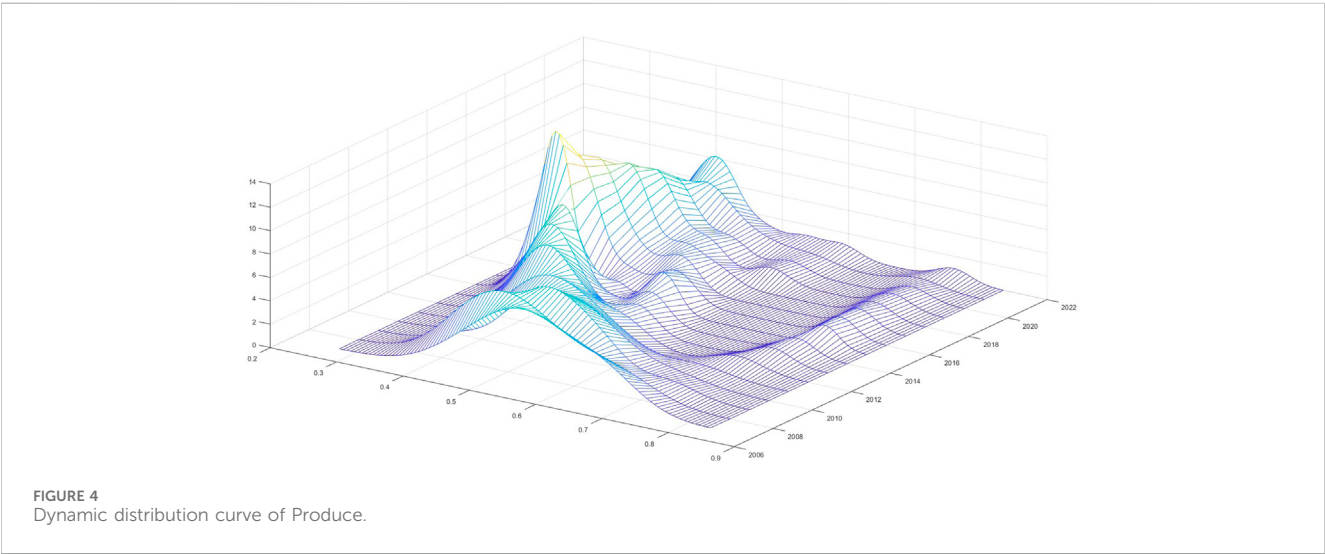
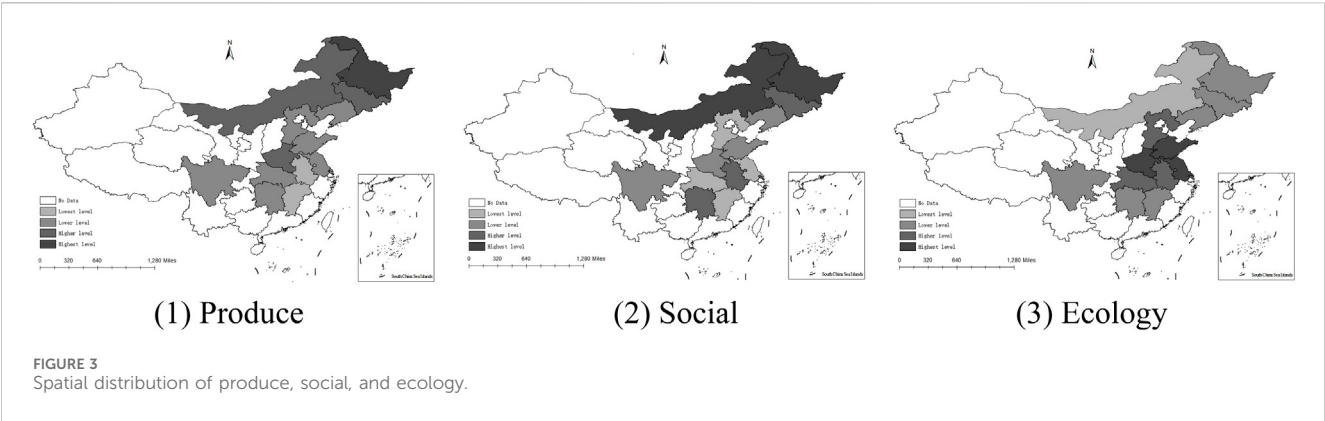
Thirdly, from the perspective of functional trade-off relationship, significant disparities exist in the functional emphasis of cultivated land among these 13 grain-producing provinces during the observation period. For example, Heilongjiang, Inner Mongolia and Jilin are China's traditional core agricultural regions. Their expansive fertile black soils, favorable climate, and political responsibilities have established these areas as vital bases for grain and agro-pastoral production, severely constraining the development space and opportunities for other industries. This has led to a large concentration of local labor in the primary sector, with arable land becoming the foundation for maintaining and achieving stable rural development. Meanwhile, their primary responsibility for protecting black soil has led them to focus not only on ensuring the secure supply of agricultural products and social security but also on expanding the multifunctional attributes such as ecological landscape functions. The rapid industrialization and urbanization in Jiangsu, Shandong, and Henan have provided rural laborers with better employment opportunities and the possibility of higher incomes. While this reduces dependence on local arable land for grain production and diminishes the traditional productive and social functions of

arable land, rising living standards have simultaneously heightened public demand for the landscape and ecological regulation functions of arable land. And, under stringent environmental regulations and sustainable development requirements, local governments in Jiangsu, Shandong, and Henan will actively promote green agricultural technologies and eco-friendly arable land management, balancing environmental protection and restoration in agricultural production processes, and enhancing the ecological functions of arable land through the agricultural green transformation.

Furthermore, this paper conducted clustering analysis of the three arable land functions' average values from 2007 to 2022 in all 13 grain-producing provinces using the Natural Breaks (Jenks) method in ArcGIS, with spatial clustering visualization results presented in Figure 3. According to the spatial distribution patterns of the mean values of Produce, Social, and Ecology in major grain-producing areas depicted in Figures 3a–c, all three functions show significant regional disparities. Among them, only a few provinces demonstrate obvious spatial clustering characteristics, while most provinces exhibit pronounced spatial heterogeneity. Furthermore, comparative analysis of Figures 3a–c demonstrates distinct spatial distribution patterns among production, social, and ecological functions of arable land. These spatial variations reflect significant divergences in land use strategies and functional priorities across the 13 provinces, stemming from differentials in agricultural positioning, economic structure, ecological and natural conditions, and policy orientation. Therefore, developing province-specific arable land use plans based on functional zoning and regional development needs remains a pivotal challenge for achieving sustainable agricultural intensification in these critical production zones.

4.2 Kernel density estimation analysis and discussion

To systematically examine the dynamic characteristics and evolutionary trends in the regional distribution of the three arable land functions, this paper conducted kernel density estimation for each function across all 13 grain-producing provinces, with the three-dimensional visualization results presented in Figures 4–6. Based on the Kernel density estimation of the arable land production function shown in Figure 4, this paper finds: Firstly, during the observation period, the overall distribution of the arable land production function shifted to the right with fluctuations, which represents that the arable land production function in each province has been continuously improving with fluctuations. Secondly, the kernel density plot showed initial



increase followed by decrease in peak height, while the peak width first narrowed and then slightly widened. This pattern suggests that inter - provincial disparities in production functionality first

narrowed before experiencing modest expansion, though this widening trend remained statistically insignificant. The persistent right-tail characteristic further confirms that production capacity

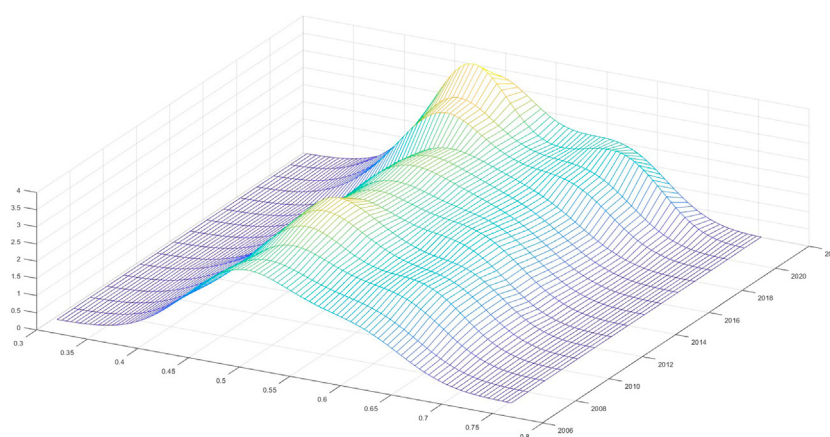


FIGURE 6
Dynamic distribution curve of Ecology.

remains relatively low in most regions. Thirdly, the peak configuration evolved from a “one dominant peak with two minor peaks” pattern to a “one dominant peak with one minor peak” during the observation period, indicating significant improvement in reversing the multipolar differentiation and spatially unbalanced development characteristics of arable land production functions in grain-producing areas, with continuously narrowing intra - regional disparities though certain bipolar differentiation phenomena persist.

The kernel density estimation of the arable land social function is shown in Figure 5. Firstly, during the observation period, the overall distribution of the social function of arable land shifted to the left, which implies that the arable land social function in each province has been continuously declining. Secondly, the peak height in the kernel density estimation graph shows an evolutionary characteristic of “rising - falling - slowly rising”, and the peak width becomes narrower and narrower. This means that the gap in the arable land social function among the major grain - producing provinces has been significantly reduced overall, but this gap shows a weak tendency to widen in recent years. Thirdly, the overall distribution of the peaks presents a pattern of “one main peak and two small peaks” during the period from 2007 to 2022, which indicates that there are obvious polarization and spatial differentiation phenomena in the social function of arable land, and the gap between high - level and low - level provinces is widening.

The kernel density estimation of the arable land ecological function is shown in Figure 6. Firstly, the distribution of ecological functions across all 13 provinces exhibited an overall rightward shift during the entire observation period, indicating continuous improvement and sustained positive evolutionary trends in ecological functioning. Secondly, the peak height of the distribution progressively increased while the peak width showed a modest narrowing tendency, suggesting a gradual convergence in ecological performance among provinces. Thirdly, while the density distribution maintained a predominantly unimodal pattern throughout the study period, the emergence of a right-side protrusion revealed latent but not yet fully manifested divergence tendencies in ecological function development among regions.

4.3 Markov transition probability matrix analysis and discussion

While kernel density estimation effectively characterizes the overall distribution patterns and temporal trends of arable land functions across major grain-producing areas, it cannot precisely quantify the dynamic positional changes or state transition probabilities among regions, the Markov chain method addresses this limitation. Using the Natural Breaks Classification method in ArcGIS, this paper classified the 2007–2022 average values of the three arable land functions into four distinct types: Lowest, Lower, Higher, and Highest. Subsequently, through the application of Markov chain analytical methodology, the state transition probability matrix is derived, and Table 3 presents the detailed computational results.

Firstly, Table 3 presents the estimated results of Markov chain transition probabilities for the three arable land functions. During 2007–2022, the diagonal transition probabilities of the three arable land functions were significantly higher than their off-diagonal counterparts, and the maximum diagonal probabilities reached 0.975, 0.981, and 0.989 respectively, while the minimum values were 0.731, 0.706, and 0.889. These findings demonstrate that the three functions exhibited low mobility between different development states, with their transitions being substantially constrained by path dependence on prior development levels, resulting in strong state stability across all functional dimensions in these agricultural provinces.

Secondly, the upward transition of the three arable land functions remains challenging, with certain risks of functional downgrading. Taking the arable land production function as an example, the probabilities of lowest level, lower level, and higher level areas advancing to the highest level after 1 year are 26.9%, 13.1%, and 9.8% respectively, this indicates that while upward mobility in production functionality is possible, the difficulty increases significantly with higher tiers. Meanwhile, the transition from the lower level to the lowest level registered a probability of 7.1%, while the transition from the higher level to the lower level occurred at 11.5%, and the shift from the higher level to the highest

TABLE 3 Markov transition probability matrix of produce, social and ecology.

Function	Level	Initial probability	Lowest	Lower	Higher	Highest
Produce	Lowest	0.133	0.731	0.269	0.000	0.000
	Lower	0.431	0.071	0.798	0.131	0.000
	Higher	0.313	0.000	0.115	0.787	0.098
	Highest	0.123	0.000	0.000	0.125	0.875
Social	Lowest	0.277	0.981	0.019	0.000	0.000
	Lower	0.174	0.265	0.706	0.029	0.000
	Higher	0.328	0.000	0.156	0.813	0.031
	Highest	0.221	0.000	0.000	0.116	0.884
Ecology	Lowest	0.046	0.889	0.111	0.000	0.000
	Lower	0.451	0.000	0.989	0.011	0.000
	Higher	0.231	0.000	0.000	0.956	0.044
	Highest	0.272	0.000	0.000	0.019	0.981

level registered a probability of 12.5%, which indicates that the risk of downward transition in the arable land production function escalates progressively as the initial functional level increases.

Thirdly, the non-diagonal transition probabilities are non-zero and symmetrically distributed on both sides of the diagonal, this indicates that in the major grain-producing areas, the three major functions of arable land can transition to adjacent states. However, no probabilities were observed for either cross-level upward leaps or cross-level downward drops, which suggests that the inter-provincial evolution of these arable land functional disparities follows a gradual process with relatively slow adjustment dynamics.

5 Extended analysis and discussion: research on dynamic relationships among produce, social and ecology

5.1 Stationarity tests and optimal lag order selection

Prior to examining the dynamic interactions among Produce, Social, and Ecology by applying the model of PVAR, stationarity tests were performed on all three variables to ensure empirical robustness. To enhance the accuracy of variable stationarity test results, this study employs three distinct testing methodologies, including the LLC test, IPS test and ADF-Fisher test, for comprehensive analysis of variable stationarity. As evidenced by the panel data stationarity test results presented in Table 4, the original data of Produce were non-stationary but became stationary after first-order differencing, while both Social and Ecological were stationary in both their original and differenced forms. These results confirm that all variables are first-order difference stationary ($I(1)$), so their differenced series can be used for PVAR analysis.

Given that the endogenous variable setting order affects PVAR model results, and in accordance with existing research and the analytical framework of this paper, the empirical model specifies the variable sequence as Produce, Social, and Ecology. Moreover, prior

to conducting empirical tests, determine the optimal lag order of the PVAR model is also essential. Following standard econometric practice, the AIC mode, BIC mode, and HQIC mode are employed to determinate the optimal lag order, and the optimal order is determined by the criterion of the most information criteria passing through. As presented in Table 5, the diagnostic results unanimously indicate that the lag order of one is optimal. Therefore, the PVAR(1) model should be established to examine the dynamic interrelationships among Produce, Social, and Ecology.

5.2 PVAR model estimation results

As a theoretically limited model, the PVAR model shares the same constraint as conventional VAR models in that its parameter estimates lack substantive economic interpretation (Ye et al., 2015; Zhu et al., 2019). Therefore, the estimated coefficients alone cannot fully capture the interactions among endogenous variables under spatiotemporal dynamics. Accordingly, this paper only presents the estimation results (Table 6), and will subsequently employ the model's impulse response functions to characterize the impacts of unit standard deviation shocks to specific individual-specific variables on the three endogenous variables of 13 cross-sectional individuals, which can effectively capture the dynamic temporal evolution and more completely reflect the transmission pathways of endogenous variables.

5.3 Impulse response analysis and discussion of the PVAR model

The impulse response functions for 10 lag periods were obtained through Monte Carlo simulations with 1,000 repetitions by applying one standard deviation positive shocks to each endogenous variable in the PVAR model, as shown in Figures 7–9. Here, the vertical axis and horizontal axis represent the magnitude of variable impact and the period of response respectively, the solid line in the middle

TABLE 4 Stationarity tests of produce, social and ecology.

Test	Produce	DProduce	Social	DSocial	Ecological	DEcological
LLC	−0.769 (0.221)	−3.061*** (0.0011)	−5.107*** (0.000)	−2.062** (0.020)	−5.705*** (0.000)	−4.579*** (0.000)
IPS	0.277 (0.609)	−2.988*** (0.001)	−2.758*** (0.003)	−1.35924* (0.087)	−3.130*** (0.001)	−3.238*** (0.001)
ADF-Fisher	0.905 (0.6361)	9.940*** (0.007)	10.374*** (0.006)	5.155* (0.076)	11.731*** (0.003)	11.467*** (0.003)
Conclusion	Non-stationary	Stationary	Stationary	Stationary	Stationary	Stationary

The prefix of “D” before a variable denotes its first difference. *, **, and ***denote statistical significance at the 10%, 5%, and 1% levels, respectively.

TABLE 5 Optimal lag order determination based on different information criteria.

Lag	AIC	BIC	HQIC
1	−18.912	−18.023*	−18.551*
2	−19.002	−17.887	−18.549
3	−19.052*	−17.684	−18.496
4	−18.982	−17.327	−18.310
5	−18.497	−16.513	−17.691

Same as Table 4.

denotes the impulse response values, and the dashed lines represent the confidence interval lines at the 95% confidence level. According to Figures 7–9, as far as the impacts of shocks on itself are concerned, shocks to either the Produce, Social, or Ecology all induce short-term upward fluctuations in their respective functions, and basically gradually converge toward zero around the 3rd to 4th period, with the production function exhibiting relatively larger fluctuation amplitudes. The results indicate that the dynamic evolution of the arable-land production function, social function, and ecological function in the major grain - producing areas all possess strong inertia characteristics.

As shown in Figure 7, after applying one standard deviation positive shocks to arable land production function, the arable-land social function exhibits a slight positive fluctuation in the current period, followed by a directional reversal that peaks in the first period before gradually converging to zero starting from the fifth period. Conversely, shocks to the production function induce consistently positive fluctuations in the ecological function, reaching their maximum in the first period and subsequently diminishing until converging to equilibrium by the fourth period. The magnitude of impact analysis reveals that production function exerts greater influence on ecological function than on social function. These findings indicate that enhanced production function in major grain-producing areas promotes ecological function while generating short-term negative effects on social function.

Figure 8 shows that shocks to the arable land social function simultaneously cause negative fluctuations in both production and ecological functions, but with distinct evolutionary trends and impact magnitudes. The production function responds immediately in the current period, then continues downward fluctuations throughout the observation period, indicating that the social function exerts a certain inhibitory effect on production function with lagged characteristics. Unlike the

production function response, the ecological function response peaks immediately in the initial period, then the negative response progressively weakens and finally converges to the steady - state value around the 4th period. Moreover, The response magnitude of ecological function is significantly higher than that of production function, which indicates the social function has an immediate but unsustainable negative impact on ecological function in the short term.

Figure 9 shows that in response to shocks from ecological function, the production function of arable land exhibits no immediate reaction, but subsequently demonstrates an evolutionary pattern of first increasing positively and then gradually decreasing until convergence to zero. This indicates that ecological function improvement may have a positive promoting effect on production function, but with a lagged characteristic. In contrast, the social function shows essentially opposite impulse response characteristics compared to production function, though with smaller impact magnitude. This suggests that ecological function fluctuations lag behind social function, and there may exist potential functional incompatibility between the social function and the ecological function. Effectively balancing socio-economic benefits and ecological conservation in arable land management emerges as a critical determinant for successful multifunctional integration within China’s agricultural systems.

5.4 Variance analysis and discussion

To further quantify the long-term interactions among the production function, the social function, and the ecological function of arable land, this paper extended the analysis with 10-period forecast error variance decomposition. Table 7 reveal the relative contribution of structural shocks to each endogenous variable’s fluctuations.

The variance decomposition results in Table 7 show that in the major grain-producing areas, the arable land production function is affected by 100% of its own fluctuations in the first period. The impacts of production function on the ecological function and the social function become detectable from the second period onward, with the effect intensities stabilizing at 0.113% and 3.061% from the third and fifth periods respectively. These results demonstrate that the production function exerts lagged, long-term, and persistent effects on both social and ecological functions. In the variance decomposition of the social function, the impact of social function on production function becomes apparent in the first period with an effect intensity of 0.116%, while its impact on

TABLE 6 GMM parameter estimates of PVAR model.

Variable	h_Produce		h_Social		h_Ecology	
	Coefficient	t-statistic	Coefficient	t-statistic	Coefficient	t-statistic
L.h_Produce	0.026	0.261	−0.056	−1.472	0.071	1.848
L.h_Social	0.047	0.163	0.043	0.463	−0.045	−0.364
L.h_Ecological	0.357	2.257	−0.025	−0.427	0.066	0.972

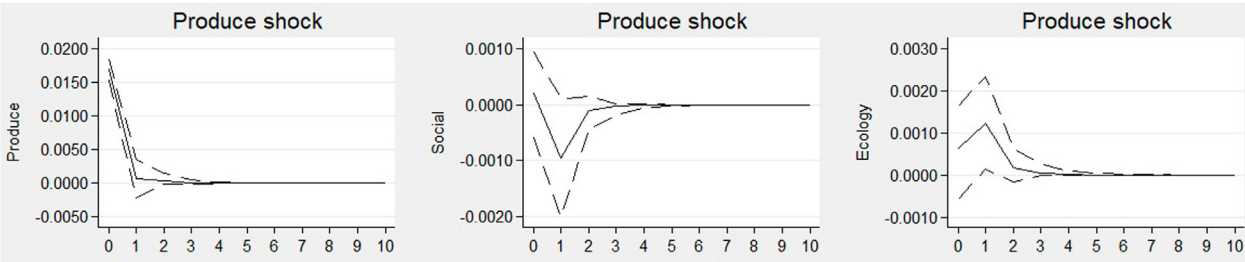


FIGURE 7
Impulse response results with produce as the shock source.

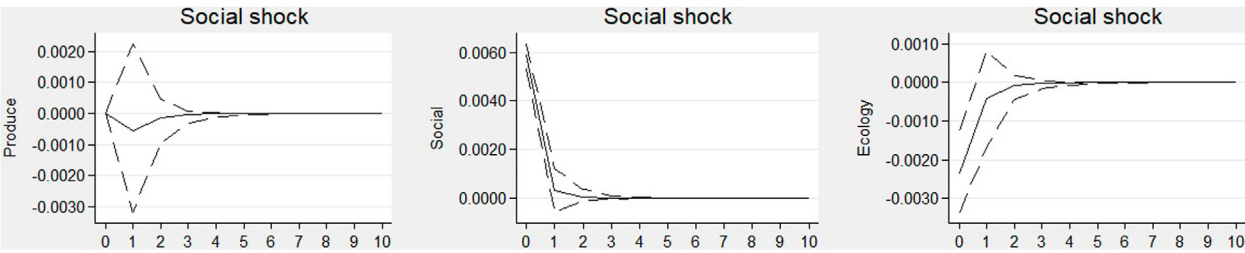


FIGURE 8
Impulse response results with social as the shock source.

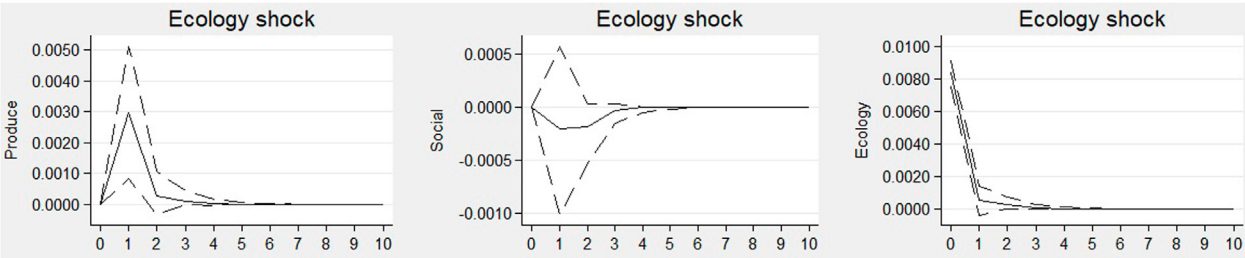


FIGURE 9
Impulse response results with ecological function as the shock source.

ecological function emerges in the second period. Initially, the impacts on both functions are relatively weak, but the effect intensities subsequently show a rapid increasing trend, reaching their peak values of 2.649% and 0.221% respectively by the fourth period. These results indicate that the social function exerts heterogeneous and progressively strengthening effects on the other two functions. Regarding the ecological function, its impacts on both production and social functions emerge

TABLE 7 Variance decomposition of the PVAR Model.

Period	Produce			Social			Ecology		
	Produce	Social	Ecology	Produce	Social	Ecology	Produce	Social	Ecology
1	100.00%	0.000%	0.000%	0.116%	99.884%	0.000%	0.504%	7.136%	92.360%
2	96.858%	0.105%	3.037%	2.618%	97.263%	0.119%	2.420%	7.177%	90.403%
3	96.829%	0.113%	3.058%	2.646%	97.135%	0.219%	2.453%	7.176%	90.370%
4	96.827%	0.113%	3.060%	2.649%	97.130%	0.221%	2.456%	7.177%	90.368%
5	96.826%	0.113%	3.061%	2.649%	97.129%	0.221%	2.456%	7.177%	90.367%
6	96.826%	0.113%	3.061%	2.649%	97.129%	0.221%	2.456%	7.177%	90.367%
7	96.826%	0.113%	3.061%	2.649%	97.129%	0.221%	2.456%	7.177%	90.367%
8	96.826%	0.113%	3.061%	2.649%	97.129%	0.221%	2.456%	7.177%	90.367%
9	96.826%	0.113%	3.061%	2.649%	97.129%	0.221%	2.456%	7.177%	90.367%
10	96.826%	0.113%	3.061%	2.649%	97.129%	0.221%	2.456%	7.177%	90.367%

immediately in the first period, with effect intensities of 0.504% and 7.136% respectively. Subsequently, these effect intensities exhibit fluctuating yet generally increasing trends, ultimately reaching their maximum values of 2.456% and 7.177% by the fourth period. These findings demonstrate that the ecological function exerts immediate, effective, and sustained influences on both production and social functions.

6 Conclusions and implications

The principal findings of this study demonstrate: (1) The production, social, and ecological functions of arable land generally remain at relatively low levels in the 13 major grain - producing provinces, with significant spatial disparities observed across regions. Provincial-level analyses reveal clear trade-offs among different land functions. Furthermore, the three functions exhibit distinct evolutionary trajectories, in which both production and ecological functions show fluctuating upward trends, while the social function demonstrates a steady decline in evolution. (2) The kernel density estimation results demonstrate that while regional disparities among all three arable land functions have shown significant overall improvement, both production and social functions exhibit slight tendencies toward widening gaps, accompanied by evident spatial polarization phenomena. (3) The Markov chain analysis indicates that the three functional states of arable land exhibit limited inter-state mobility with pronounced state persistence in major grain-producing areas. As the functional hierarchy elevates, the difficulty of upward transitions progressively intensifies while the risk of downward transitions consistently escalates. Moreover, neither upward or downward cross - level plunges are observed among the three functions, leading to a slow and gradual dynamic evolution of the inter - provincial disparities in arable land functions. (4) The analysis reveals distinct dynamic pathways among the production function, the social function, and the ecological function, with all three functions demonstrating strong inertial characteristics in major grain-producing areas. Meanwhile, the production function and

ecological function show mutually reinforcing interactions, while both have mutual inhibition with the social function respectively.

The findings collectively indicate that enhancing the multifunctional use of arable land in China’s major grain-producing regions requires both macro-level coordination to holistically advance synergistic optimization and dynamic equilibrium among productive, social and ecological functions, and precise provincial positioning to implement differentiated strategies for comprehensive multifunctional use of arable land. The arable land in Heilongjiang, Jilin, and Inner Mongolia exhibit prominent advantages in production and social functions, necessitating improved vertical and interprovincial horizontal compensation mechanisms to enhance livelihood security and stimulate local grain production enthusiasm while fully leveraging the “Black Soil Protection” policy and drawing upon the experiences of Jiangsu, Shandong, and Henan to continuously strengthen ecological functions. Anhui, Jiangxi, Hubei, Hunan and Shandong should focus on addressing the issue of agriculture yielding to industrial development, resolutely curb the “non-agriculturalization” and “non-grainization” of arable land, strengthen arable land use regulation while cultivating new quality agricultural productivity, emphasize the exploitation of arable land resources and yield potential, while concurrently highlighting and perfecting mechanisms for comprehensive environmental management and ecosystem restoration of farmland, so as to establish a long-term mechanism for sustainable arable land use that combines both incentives and constraints. The provinces of Liaoning, Hebei, Henan, Jiangsu, and Sichuan should consolidate and enhance their comprehensive grain production capacity, promote the integration of agriculture with secondary and tertiary industries, extend the traditional agricultural industrial chain, strive to achieve industrialization, scale, and intensive development of agriculture, and gradually improve the social function of arable land. Moreover, Jiangsu, Henan and Liaoning should intensify the development, introduction and promotion of environmentally-friendly technologies to further improve agricultural ecological quality while maintaining high-level agro-ecological functions.

Meanwhile, Hebei and Sichuan ought to balance arable land conservation with utilization by optimizing development approaches, actively implementing comprehensive soil pollution treatment and remediation projects to reverse soil contamination and ecological degradation trends, thereby enhancing the endogenous motivation for arable land ecological protection. Finally, it is essential to clarify the primary responsibility, reinforce local regulatory responsibilities for arable land protection, and balance the functional trade-offs between farmland protection and land development and utilization. Additionally, by assetizing the value of farmland resources, we can encourage social capital to participate in high-quality agricultural production, thereby fostering a multi-faceted collaborative effort for arable land protection. The ultimate goal is to promote the upward transition of various functions of farmland, achieve complementary and coordinated development of its multiple functions, and comprehensively enhance the comprehensive grain production capacity of farmland to solidify the foundation of food security. The ultimate objective is to promote functional upgrading of arable land, achieve complementary and coordinated development of its multiple functions, and comprehensively enhance integrated grain production capacity to solidify the foundation of food security.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

XX: Conceptualization, Data curation, Formal Analysis, Methodology, Resources, Software, Writing – original draft, Writing – review and editing. FL: Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Validation, Visualization, Writing – review and editing.

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Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This research was funded by the National Natural Science Foundation of China (grant number 72073030), the Humanities and Social Sciences Research Program of the Ministry of Education (grant number 23YJA790044), the Project on Philosophy and Social Sciences Planning in Guangxi (grant number 24JYF002), and the Natural Science Foundation of Hainan Provincial (grant number 624MS076).

Conflict of interest

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