

Article

Spatial–Temporal Coupling Characteristics and Interactive Effects of New-Type Urbanization and Cultivated Land Use Efficiency on Food Security

Yihan Zhao ^{1,†}, Yang Peng ^{2,†}, Mengduo Li ¹ and Shuisheng Fan ^{1,2,*}

¹ College of Rural Revitalization, Fujian Agriculture and Forestry University, Fuzhou 350002, China; 52370034015@fafu.edu.cn (Y.Z.); 52570034088@fafu.edu.cn (M.L.)

² College of Economics and Management, Fujian Agriculture and Forestry University, Fuzhou 350002, China; pengyang@fafu.edu.cn

* Correspondence: shuisheng@fafu.edu.cn

[†] These authors contributed equally to this work.

Abstract

Against the backdrop of rapid modernization and tightening agricultural resource constraints, coordinating urbanization and grain production is a key challenge for China. Using panel data from 30 Chinese provinces from 2004 to 2023, this study applies the coupling coordination degree (CCD) model and a panel vector autoregression model to examine the spatiotemporal coupling characteristics and interaction mechanisms among new-type urbanization (NTU), cultivated land use efficiency (CLUE), and food security (FS). The results show that these three systems have gradually evolved toward coordinated development, with major grain-producing regions consistently leading and entering a moderate coordination stage earlier than other regions. Spatially, CCD exhibits significant positive spatial autocorrelation, characterized by stable “High–High” agglomeration in Northeast China and “Low–Low” agglomeration in southern provinces. Dynamic analysis indicates that system fluctuations are mainly driven by internal inertia, while inter-system interactions are also significant; NTU promotes CLUE, and CLUE and FS exhibit bidirectional causality with complex feedback effects. This study argues for promoting urban–rural factor mobility, advancing green and technology-enabled land use, implementing region-specific development strategies, and establishing a “human–land–grain” early-warning mechanism to safeguard food security during urban expansion.

Keywords: new-type urbanization; cultivated land use efficiency; food security; coupling coordination degree; spatiotemporal characteristics; panel vector autoregression model



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1. Introduction

Food security (FS) is a critical cornerstone of national security and a core issue of the United Nations Sustainable Development Goals (SDGs) [1]. China, the major developing nation in the world, provides food for almost 20% of the world’s population on just 9% of the world’s cultivated land, making its food security situation crucial to the international community. Currently, China is in a critical transition period from traditional urbanization to new-type urbanization (NTU), which is people-centered and emphasizes quality and ecology [2,3]. However, fast urbanization processes have inevitably made the conflict between population and land worse, and cultivated land resources are subject to both quantity reduction and quality degradation [4]; consequently, the traditional mode of

extensive cultivated land utilization is no longer sustainable. In this context, alleviating resource constraints brought about by urbanization expansion by improving cultivated land use efficiency (CLUE), and thereby achieving a high level of food security, has become a major strategic issue urgently needing resolution in the process of Chinese modernization.

Unlike traditional urbanization, new-type urbanization (NTU) shifts the focus from land-centered expansion to a people-centered, green, and low-carbon model [5]. It prioritizes ecological livability, intensive efficiency, and urban–rural integration, representing a strategic transition toward quality-oriented development that balances urban growth with resource sustainability. In the process of urbanization, its impact on the ecological environment is not always positive [6], and appropriate policy regulation is therefore required to ensure sustainable urbanization [7]. Additionally, the meaning of CLUE has changed significantly, moving from solely focusing on yield maximization to a green efficiency that takes ecosystem service values and carbon emission restrictions into account [8,9]; non-agricultural employment driven by urbanization may also improve this green efficiency [10]. Meanwhile, the concept of food security has expanded from a single supply–demand balance to cover multidimensional characteristics such as food availability, nutritional structure, system resilience, and sustainability [11].

Although China has made significant achievements in ensuring food security, it still faces severe challenges in the synergistic development of NTU, CLUE, and FS. There is a lag in land use transition during the urbanization process, and the conflict between construction land expansion and cultivated land protection remains intense [12], leading to the loss of high-quality cultivated land and non-grain production of cultivated land [13]. Although the intensity of cultivated land utilization has improved, the excessive use of chemical fertilizers and pesticides has caused serious non-point source pollution, threatening the resilience of the cultivated land ecosystem and restricting the green transformation of CLUE [14]. With the upgrading of residents' dietary structures, the structure of food demand has changed [11], yet the existing agricultural production layout and urbanization pattern have not yet formed a benign interaction, and the imbalance between regional grain production and sales has aggravated the vulnerability of the food supply chain [15].

This evidence suggests that the development of the NTU, CLUE, and FS systems is interconnected, and their development may become unbalanced without proper policy regulation. In these complex situations, coordinating the balanced development of NTU, CLUE, and FS becomes a crucial issue in the processes of urban–rural integration and agricultural modernization. Therefore, what is the degree of coordinated development of NTU, CLUE, and FS—that is, what are their coupling coordination degree (CCD) characteristics? What are the temporal variations and spatial distributions of the CCD of the three systems? What are the interactive effects among these three systems? What policies should be adopted to promote their coordinated development? These questions deserve our attention. Based on these questions, this study uses a coupling coordination model to analyze the CCD among NTU, CLUE, and FS and its spatiotemporal characteristics, and employs a panel vector autoregression (PVAR) model to explore their interaction mechanisms. Finally, policy recommendations are proposed for the coordinated development of NTU, CLUE, and FS.

Despite the growing body of literature, several research gaps remain. Existing studies mostly focus on the bilateral relationship of urbanization and cultivated land or urbanization and food, often failing to systematically incorporate NTU, CLUE, and FS into a unified framework. Consequently, the internal coupling logic and ternary interaction mechanisms among these three systems remain insufficiently explored, particularly regarding the dynamic feedback loops between them. Furthermore, there is a lack of empirical evidence regarding how coupling coordination fluctuates across diverse spatial scales and temporal

stages under the double squeeze of modernization and resource constraints. To bridge these gaps, the marginal contributions of this paper are mainly reflected as follows: (1) Constructing a ternary coupling evaluation index system for NTU, CLUE, and FS, revealing the interaction logic among the three from the perspective of system theory; (2) portraying the spatiotemporal evolution characteristics of the coupling coordination degree of the three major systems at the provincial scale in China, and identifying their spatial agglomeration patterns and regional differences; and (3) using the PVAR model to dynamically analyze the long-term equilibrium relationship and interactive response mechanisms among the three, providing an empirical basis for formulating differentiated regional sustainable development policies.

This paper's subsequent structure is set up as follows: In the second section, pertinent literature is systematically reviewed; in the third section, the methodology, variable selection, and data sources are introduced; in the fourth section, the spatiotemporal coupling characteristics and dynamic interaction effects of the three major systems are empirically analyzed; the conclusions and policy recommendations are then presented.

2. Literature Review

2.1. The Connotation and Influencing Factors of NTU

NTU represents a strategic shift from the conventional extensive urbanization model to a people-centered approach [16], emphasizing the coordinated development of population, economy, society, and ecology rather than mere land expansion [2,3]. Regarding measurement, research has evolved from simple population rates to comprehensive systems incorporating population agglomeration, public service equalization, infrastructure, and urban–rural integration [17]. For instance, Yu [3] developed a multifaceted assessment framework and verified NTU's beneficial contribution to enhancing ecological environmental quality. Zhao & Wang [18] further included green low-carbon indicators, emphasizing the significance of NTU in reducing air pollution and enhancing urban environmental governance capabilities. NTU growth is driven by institutional reform, economic structural changes, urban–rural integration strategies, the rural digital economy, and trade openness. Specifically, household registration reform facilitates the citizenization of rural migrants [19], while the shift from urban-biased to integrated development policies plays a decisive role [20]. Additionally, reducing land finance dependence and upgrading industrial structures remain vital for high-quality NTU development [21]. Recent studies further highlight that the rural digital economy exerts a positive influence on NTU [22], while trade openness serves as a significant driver for its advancement [23].

2.2. The Connotations and Influencing Factors of CLUE

As sustainable agriculture gains prominence, CLUE has evolved from a simple measure of grain or economic output per unit area [24] to a multidimensional indicator of ecological efficiency. This modern view incorporates undesirable outputs like carbon emissions and non-point source pollution [8,9]. The super-efficiency SBM model is frequently utilized to account for these environmental constraints and slack variables [25,26]. For example, Luo et al. [27] and Lu et al. [28] employed this technique to highlight the need for green transformation by revealing the spatiotemporal differentiation characteristics of CLUE under carbon emission restrictions in the Yellow River Basin and the Yangtze River Economic Belt, respectively. CLUE is driven by natural endowments, factor inputs, and institutional frameworks. While soil quality and water resource availability are the basic constraints [29,30], socio-economic factors like land transfer and scale operations [31] significantly optimize resource allocation. Furthermore, rural labor migration creates a favorable mediating effect on efficiency when combined with land transfer [32]. Additionally, changes

in planting structures [33] and the substitution of labor with agricultural mechanization [8] are critical drivers for enhancing the sustainable utilization of cultivated land.

2.3. The Connotations and Influencing Factors of FS

The connotations of FS have expanded from quantitative supply [34] to a comprehensive framework encompassing availability, access, utilization, and stability. Modern FS emphasizes supply chain resilience, nutritional health, and ecological sustainability [35,36]. Allee et al. [37] contrasted the Food Insecurity Experience Scale (FIES) and the Global Food Security Index (GFSI) to highlight the impact of macroeconomic environments on micro-level security. In China, the “Greater Food Approach” further requires building diversified supply systems while addressing the environmental pressures of shifting dietary structures [11]. FS is influenced by shifting demand, supply constraints, and environmental factors. On the demand side, urbanization and rising incomes have increased animal protein and feed grain consumption [38]. On the supply side, the loss of high-quality land and “non-grain” production caused by urban expansion remains a primary threat [39], alongside the hard constraints of environmental carrying capacity [40]. Furthermore, climate change, water scarcity, and an aging agricultural workforce introduce significant uncertainty into production stability [15,41].

2.4. The Relationship Between NTU, CLUE, and FS

The expansion of urbanization may lead to the non-agriculturalization and fragmentation of cultivated land, thereby reducing the production potential of cultivated land [27]. However, some studies argue that NTU creates conditions for land transfer and moderate-scale operations by absorbing rural surplus labor, which facilitates the promotion of advanced agricultural technologies and mechanized operations, thereby significantly improving CLUE [31,32]. Research by Hu et al. [33] also confirms that reasonably planned urbanization can optimize the pattern of cultivated land utilization and promote the concentration of cultivated land resources towards more efficient operating entities. Therefore, the relationship between NTU and CLUE is not a simple negative correlation, but involves a mechanism of positive promotion realized through factor mobility. Although the occupation of cultivated land and the upgrading of dietary structure brought about by urbanization have increased the tension between food supply and demand [38], high-level urbanization can release inefficient rural construction land through population agglomeration. If policies such as the balancing of increases and decreases in construction land (such as land reclamation) are implemented properly, it can actually increase the effective supply of cultivated land and enhance overall grain production capacity through large-scale operations [42,43]. In addition, technological spillovers and infrastructure improvements brought by NTU enhance the resilience of the food supply chain. Liu et al. [44] found that although aging and labor loss pose challenges to agriculture, the capital feedback and socialization of agricultural services brought by urbanization effectively mitigate this negative impact. In the context of limited total cultivated land resources, improving utilization efficiency is the fundamental pathway to ensuring food security. Xie et al. [8] and Ke et al. [9] emphasized that only green efficiency, which accounts for the ecological environment, can ensure the sustainability of grain production. High-efficiency cultivated land utilization directly addresses the needs for stability and sustainability in food security by preserving or raising grain output while lowering inputs of carbon sources like fertilizers and pesticides. Conversely, inefficient and extensive cultivated land utilization, while potentially maintaining yields in the short term, will lead to soil fertility declines and environmental pollution in the long run, ultimately shaking the foundation of food security [26].

In summary, NTU, CLUE, and FS constitute a closely coupled dynamic system. This study moves beyond traditional bilateral analyses by proposing a ternary framework that captures the interaction among these three systems. As illustrated in the theoretical framework diagram (Figure 1), NTU serves as the external driving force reshaping human–land relationships through population and land policy; CLUE acts as the core conversion link, determining the environmental and productive efficacy of factor inputs; and food security provides the ultimate bottom-line constraint and systemic goal. While the existing literature focuses on static bilateral relationships, it lacks a unified perspective on how these three achieve synergistic development through dynamic coupling. By constructing a comprehensive evaluation system for this triad based on this conceptual framework, this study aims to fill the gap in empirical research regarding the spatiotemporal evolution and interactive effects of the NTU–CLUE–FS nexus.

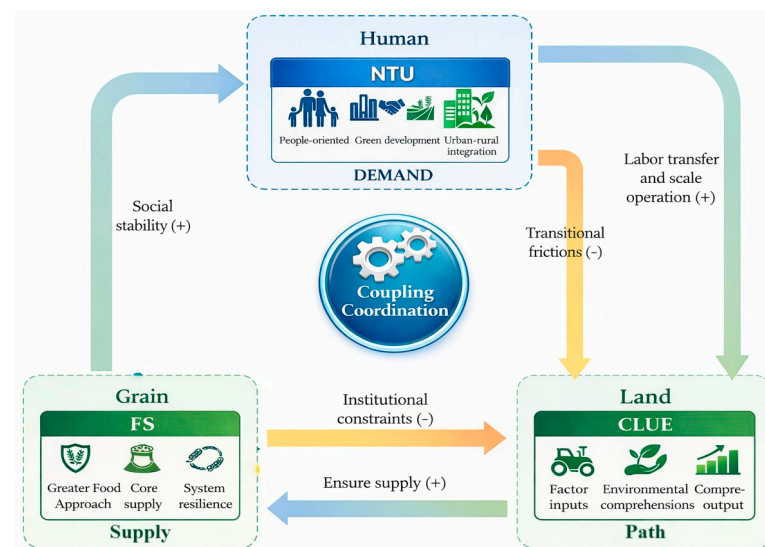


Figure 1. Mechanism diagram of coupling coordination among NTU, CLUE, and FS.

3. Methodology

3.1. Model Methods

3.1.1. Super-Efficiency SBM Model

To scientifically measure CLUE, this paper adopts the super-efficiency Slacks-Based Measure (SBM) model incorporating undesirable outputs. Compared to the traditional DEA model, this method not only overcomes the limitations of being unable to handle input–output slack variables and distinguishing between multiple effective units with an efficiency value of 1, but also incorporates undesirable outputs, such as environmental pollution, into the evaluation system [45]. By further ranking the decision-making units (DMUs) on the efficiency frontier, this model can more accurately reflect the true level of cultivated land utilization under the dual goals of resource conservation and environmental sustainability.

Assume there are n DMUs, and each DMU uses m inputs to produce r_1 desirable outputs and r_2 undesirable outputs. Let $x \in R_+^m$ be the input vector, $y^d \in R_+^{r_1}$ be the desirable output vector, and $y^u \in R_+^{r_2}$ be the undesirable output vector. For the k -th DMU, the inputs, desirable outputs, and undesirable outputs are x_k , y_k^d , and y_k^u , respectively. The super-efficiency SBM model is constructed as follows:

$$\text{Min} \delta = \frac{1}{m} \sum_{i=1}^m \left(\frac{\bar{x}}{x_{ik}} \right) / \frac{1}{r_1 + r_2} \left(\sum_{s=1}^{r_1} \frac{\bar{y}_s^d}{y_{sk}^d} + \sum_{q=1}^{r_2} \frac{\bar{y}_q^u}{y_{qk}^u} \right) \quad (1)$$

Subject to the following constraints:

$$\text{s.t.} \begin{cases} \bar{x} \geq \sum_{j=1, \neq k}^n x_{ij} \lambda_j; \bar{y}^d \leq \sum_{j=1, \neq k}^n y_{sj}^d \lambda_j; \bar{y}^d \geq \sum_{j=1, \neq k}^n y_{qj}^d \lambda_j; \bar{x} \geq x_k; \bar{y}^d \leq y_k^d; \bar{y}^u \geq y_k^u; \\ \lambda_j \geq 0, 1, 2, \dots, m; j = 1, 2, \dots, n, j \neq 0; s = 1, 2, \dots, r_1; q = 1, 2, \dots, r_2; \end{cases} \quad (2)$$

The inequality directions in Equation (2) follow standard SBM assumptions: inputs and undesirable outputs are weakly disposable and thus constrained by $\geq$, while desirable outputs are freely disposable and therefore constrained by $\leq$.

δ is the CLUE value, with $\delta \geq 0$. If $\delta \geq 1$, it indicates that the DMU is effective; if $\delta < 1$, it indicates efficiency loss; $\bar{x}$, $\bar{y}^d$, and $\bar{y}^u$ represent the slack variables for inputs, desirable outputs, and undesirable outputs, respectively; λ_j is the weight vector. The model excludes the k -th DMU itself ($j \neq k$) when evaluating it in order to achieve a super-efficiency comparison.

3.1.2. Coupling Coordination Degree Model

The coupling coordination degree (CCD) model is used in this work to quantitatively describe the synergistic effects and interactive relationship between the three subsystems: NTU, CLUE, and FS. The Coupling Degree (C), Comprehensive Coordination Index (T), and coupling coordination degree (D) are the three primary metrics that make up the model. The degree of connection between systems is measured by the Coupling Degree C, which is computed as follows:

$$C = \left\{ \frac{U_1 U_2 U_3}{\left[\frac{1}{3} (U_1 + U_2 + U_3) \right]^3} \right\}^{\frac{1}{3}} \quad (3)$$

where U_1 , U_2 , and U_3 represent NTU, CLUE, and FS, respectively. The value range of C is $[0, 1]$. When the C value tends to change from 0 to 1, it indicates that the coupling interaction between the three systems is gradually strengthening, and the system is transforming from disordered to ordered; conversely, when C approaches 0, it implies that the interaction between the systems is weak and discrete.

Given that the Coupling Degree only reflects the strength of the interaction between systems and struggles to distinguish the level of coordination, this study further introduces T to evaluate the overall development level of the three systems:

$$T = \alpha_1 U_1 + \alpha_2 U_2 + \alpha_3 U_3 \quad (4)$$

where $\alpha_1, \alpha_2, \alpha_3$ represent the weights of NTU, CLUE, and FS, respectively. This study assumes that the three systems are of equal importance in the coupled coordinated development process, thus setting $\alpha_1 = \alpha_2 = \alpha_3 = 1/3$. This equal-weighting approach aligns with “ternary framework” logic, where high-quality sustainable development depends equally on the success of urbanization, land efficiency, and food security without prioritizing one at the expense of others.

$$D = \sqrt{C \times T} \quad (5)$$

The value range of D is also $[0, 1]$. A larger value indicates a higher level of coordinated development among the three systems. This study divides the CCD into 10 grades, with the specific classification standards shown in Table 1.

Table 1. CCD classification standards.

Coordination Degree (D)	Coordination Level	Coordination Degree (D)	Coordination Level
[0, 0.1]	Extreme Incoordination	(0.5, 0.6]	Barely Coordination
(0.1, 0.2]	Severe Incoordination	(0.6, 0.7]	Primary Coordination
(0.2, 0.3]	Moderate Incoordination	(0.7, 0.8]	Intermediate Coordination
(0.3, 0.4]	Mild Incoordination	(0.8, 0.9]	Good Coordination
(0.4, 0.5]	On the Verge of Incoordination	(0.9, 1.0]	Quality Coordination

3.1.3. Kernel Density Estimation

To deeply reveal the dynamic evolutionary characteristics of the regional distribution of the CCD for NTU, CLUE, and FS, this study employs the kernel density estimation method to visually analyze and compare the distribution morphology, evolutionary trends, and regional disparities of the CCD at both the national and regional levels.

Kernel density estimation methods create continuous probability density curves based on the data itself, without requiring any prior assumptions about the distribution type. The distribution location, morphology, extensibility, and polarization processes of random variables are intuitively reflected by it, which makes it appropriate for examining the spatiotemporal evolution of regional levels of social and economic development. The formula for estimating density functions is as follows:

$$f(x) = \frac{1}{Nh} \sum_{i=1}^N K\left(\frac{X_i - \bar{x}}{h}\right) \quad (6)$$

where x is the observed value of CCD, X_i is the CCD of the i -th province, N is the number of provinces, h is the bandwidth, used to control the smoothness of the density curve, and $K(\cdot)$ is the kernel function. This study selects the widely used Gaussian kernel function, expressed as follows:

$$K(x) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right) \quad (7)$$

3.1.4. Spatial Autocorrelation Model

To explore the spatial correlation and agglomeration characteristics of the CCD, this study introduces spatial autocorrelation analysis methods, including Global Spatial Autocorrelation and Local Spatial Autocorrelation, to reveal its spatial distribution patterns and evolutionary laws.

Global Spatial Autocorrelation is used to determine whether there is a spatial agglomeration phenomenon of CCD within the entire study area. This study employs the Global Moran's I index for measurement, calculated as follows:

$$I = \frac{n \sum_{i=1}^n \sum_{j=1}^j w_{ij} (D_i - \bar{D}) (D_j - \bar{D})}{\left(\sum_{i=1}^n \sum_{j=1}^j w_{ij}\right) \sum_{i=1}^n (D_i - \bar{D})^2} \quad (8)$$

where D_i and D_j represent the CCD of the i -th and j -th provinces, respectively, $\bar{D}$ is the average CCD of the whole country, n is the number of provinces, and w_{ij} is the spatial weight matrix used to characterize the spatial relationship between provinces, which is represented by the inverse distance matrix. This choice is based on the First Law of

Geography, acknowledging that spatial interaction and spillover effects between systems (NTU, CLUE, and FS) are stronger among closer provinces and diminish as distance increases. Unlike a simple binary adjacency matrix, the inverse distance matrix provides a more nuanced representation of the continuous decay of spatial influence across China's vast territory.

The value range of Global Moran's I is $[-1, 1]$. If $I > 0$, it indicates a positive spatial correlation, i.e., High–High or Low–Low agglomeration; if $I < 0$, it indicates a negative spatial correlation, i.e., High–Low or Low–High dispersion; and if $I = 0$, it indicates that the spatial distribution is random.

Global Spatial Autocorrelation struggles to reflect the spatial heterogeneity of local areas. To further identify the agglomeration types and distribution characteristics of CCD in local spaces, this study uses Local Moran's I index for analysis, calculated as follows:

$$I_i = \frac{D_i - \bar{D}}{\sum_{i=1}^n (D_i - \bar{D})^2} \sum_{j \neq i}^n w_{ij} (D_j - \bar{D}) \quad (9)$$

where the meanings of D_i , $\bar{D}$, n , and w_{ij} are consistent with those in Global Moran's I .

3.1.5. Panel Vector Autoregression Model

The panel vector autoregression (PVAR) model is employed to analyze the dynamic interactions among NTU, CLUE, and FS. Compared with the traditional VAR model, the PVAR framework combines the advantages of time-series and panel data, allowing all variables to be treated as endogenous and capturing their mutual feedback effects while controlling for individual heterogeneity and time effects.

To account for non-stationarity and ensure the validity of the dynamic estimation, all variables are transformed into first differences. The PVAR model is thus specified as follows:

$$\begin{bmatrix} \Delta NTU_{it} \\ \Delta CLUE_{it} \\ \Delta FS_{it} \end{bmatrix} = \sum_{j=1}^k \Theta_j \begin{bmatrix} \Delta NTU_{it-j} \\ \Delta CLUE_{it-j} \\ \Delta FS_{it-j} \end{bmatrix} + \alpha_i + \beta_t + \varepsilon_{it} \quad (10)$$

where

$$\Theta_j = \begin{bmatrix} \theta_{11}^{(j)} & \theta_{12}^{(j)} & \theta_{13}^{(j)} \\ \theta_{21}^{(j)} & \theta_{22}^{(j)} & \theta_{23}^{(j)} \\ \theta_{31}^{(j)} & \theta_{32}^{(j)} & \theta_{33}^{(j)} \end{bmatrix}$$

Here, Δ denotes the first-difference operator. ΔNTU_{it} , $\Delta CLUE_{it}$, and ΔFS_{it} represent the growth or change rates of new-type urbanization, cultivated land use efficiency, and food security, respectively. The first-difference transformation is applied to eliminate potential unit roots and mitigate spurious regression problems, thereby ensuring the stationarity of the variables used in the PVAR estimation.

The coefficient matrix Θ_j captures both autoregressive and cross-variable effects among the differenced variables at lag j . Other terms retain their previous interpretations: i denotes province, t denotes year, k is the optimal lag order, α_i and β_t represent province and time fixed effects, respectively, and ε_{it} is the disturbance term.

3.2. Indicator Construction

3.2.1. NTU Indicator System

NTU is a complex engineered system centered on people, covering multiple dimensions such as the population, economy, society, ecological environment, and urban–rural integration. Compared with the traditional urbanization model, which purely pursues urban scale expansion and land development, NTU emphasizes the quality, efficiency, and

equity of development, aiming to achieve the comprehensive development of “people,” the equalization of public services, and the coordinated symbiosis of urban and rural areas [3]. To comprehensively and objectively measure the comprehensive development level of NTU in China’s provinces, this paper draws on the research results of scholars such as Yu [3] and Zhou et al. [46] and constructs a comprehensive evaluation index system containing dimensions such as population development, economic growth, social services, ecological livability, and urban–rural integration. The specific indicators are shown in Table 2.

Table 2. NTU indicator system.

Primary Indicator	Secondary Indicator	Unit	Direction
NTU	Population urbanization rate	%	+
	Urban population density	(person/km ²)	+
	Natural population growth rate	‰	+
	Urban registered unemployment rate	%	-
	Number of students in higher education per 10,000 people	person	+
	Logarithm of per capita real GDP		+
	Logarithm of per capita disposable income of urban residents		+
	Proportion of secondary industry in GDP	%	+
	Proportion of tertiary industry in GDP	%	+
	Harmless treatment rate of domestic garbage	%	+
	Green coverage rate of built-up area	%	+
	Per capita park green area	(m ²)	+
	Per capita road area	(m ²)	+
	Water penetration rate	%	+
	Gas penetration rate	%	+
	Public transportation vehicles per 10,000 people	(standard unit)	+
	Number of beds in medical and health facilities per 10,000 people	(bed)	+
	Urban–rural per capita disposable income ratio	%	-
	Urban–rural consumption level ratio	%	-

3.2.2. CLUE Calculation

CLUE is a key indicator for measuring the output benefits of cultivated land resources under a certain input level. According to the input–output characteristics of the cultivated land use system, this paper constructs an input–output system including factor inputs such as land, labor, and capital, as well as economic, grain, and environmental outputs [8,9,31]. Table 3 presents the various input–output variables. Among them, agricultural carbon emissions mainly originate from the use of fertilizers, pesticides, and agricultural films, agricultural irrigation, and agricultural machinery operations, and are calculated using the most commonly used carbon emission coefficient method.

Table 3. Input–output variables of CLUE.

Type	Variable	Specific Indicator	Unit
Inputs	Land input	Sown area of crops	1000 hectares
	Labor input	Agricultural personnel	10,000 persons
	Machinery input	Total power of agricultural machinery	100 million kW
	Fertilizer input	Fertilizer application amount	10,000 tons
	Pesticide input	Pesticide usage	10,000 tons
	Agricultural film input	Agricultural film usage	10,000 tons
	Irrigation input	Effective irrigation area	1000 hectares
Desirable Outputs	Agricultural output	Gross output value of agriculture	CNY 100 million
	Grain output	Grain yield	10,000 tons
Undesirable Outputs	Environmental output	Agricultural carbon emissions	10,000 tons

3.2.3. FS Indicator System

Food security (FS) measures the ability of a region to provide sufficient, safe, and nutritious food at all times. In alignment with the “Greater Food Approach”, FS in this study is viewed not only through quantitative supply but also through the stability of the entire supply system and the sustainable guarantee of resources [11]. The transition toward this holistic approach requires a shift from focusing solely on “grain” to a broader resource perspective that encompasses production capacity and market resilience. Referring to the frameworks of Zhang et al. [47] and Sun et al. [48], we constructed a multidimensional indicator system in Table 4.

Table 4. FS indicator system.

Primary Indicator	Secondary Indicator	Indicator Description	Direction
FS	Grain yield per unit area	Grain yield per unit of sown area (kg/hectare)	+
	Per capita grain availability	Per capita grain yield (kg/person)	+
	Per capita cultivated land	Per capita cultivated land area (hectare/person)	+
	Grain price fluctuation	Consumer price index for grain (%) $(y_t - y_{1t}) / y_{1t}$	−
	Grain production fluctuation	y_t is the food yield in period t, and y_{1t} is the average food yield calculated by the 3-year moving average method.	−

Specifically, “Grain yield per unit area” and “Per capita grain availability” reflect the core supply capacity emphasized in the Greater Food Approach, while “Per capita cultivated land” represents the fundamental resource endowment. To enhance the assessment of systemic stability and vulnerability, we utilize “Grain price fluctuation” and “Grain production fluctuation” as proxies for market and supply chain resilience. While direct data on provincial grain reserves is often inaccessible, these indicators effectively capture the vulnerability of the food system to external shocks.

3.3. Data Sources

This paper selects panel data from 30 provinces in China from 2004 to 2023 as the research object; due to data availability, Hong Kong, Macao, Taiwan, and Tibet are not included in the scope of the study. The data for NTU mainly comes from the *China Statistical Yearbook* and the *China Environmental Statistics Yearbook*, while the data for CLUE and FS

mainly comes from the *China Statistical Yearbook* and the *China Rural Statistics Yearbook*. All this yearbook data can be obtained from the EPS database (www.epsnet.com.cn). There are a few missing values in the obtained data, which are filled using linear interpolation to create a balanced panel. Output data such as per capita real GDP and total agricultural output were adjusted using 2004 as the base year.

4. Results and Discussion

4.1. Characteristics of the Comprehensive Development Levels of NTU, CLUE, and FS

We calculated all NTU, CLUE, and FS results, and following common practice in academic research, we divided all provinces in China into four regions: East, Central, West, and Northeast. The average NTU, CLUE, and FS levels for each region in different years are shown in Figure 2. The comprehensive development levels of the NTU, CLUE, and FS systems all exhibited a significant upward trend during the study period, indicating that China has balanced the improvement of agricultural production efficiency with the assurance of food security during its rapid urbanization process. Specifically, NTU grew steadily, and the gap between regions gradually narrowed, CLUE demonstrated a characteristic of rapid rise amidst fluctuations—although the Northeast region experienced significant fluctuations in the early stages, its overall efficiency remained leading. Meanwhile, the central and western regions achieved rapid efficiency improvements through technological catch-up, and the efficiency gap between regions showed a convergence trend. Although FS generally presented a gentle upward trend, regional differences were significant; as the main grain-producing area, the Northeast region's food security level and growth rate were far higher than those of other regions, while the eastern region remained at a relatively low level.

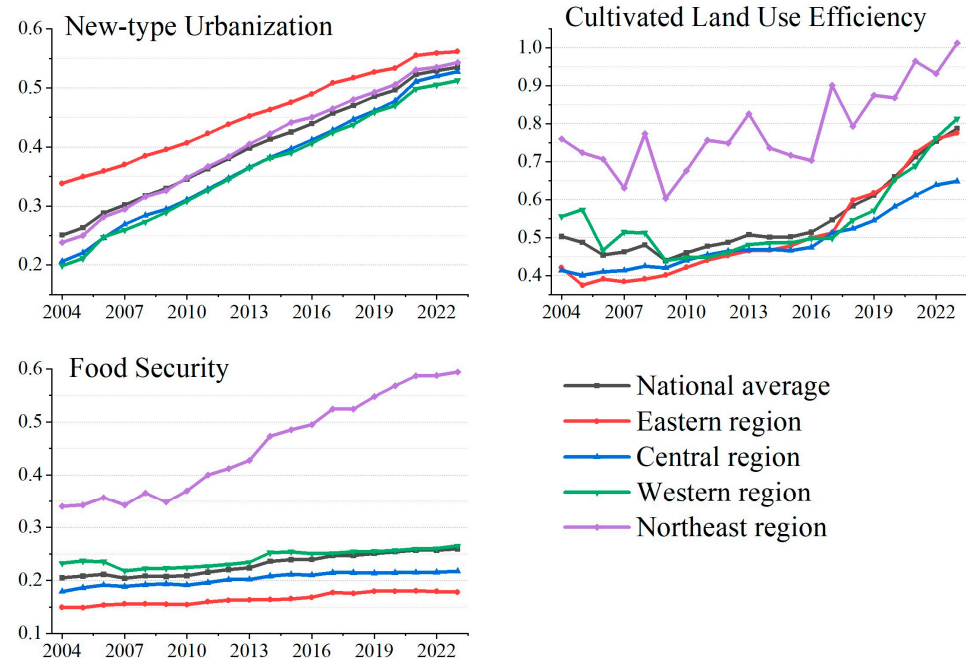


Figure 2. Development levels of NTU, CLUE, and FS in various regions.

4.2. CCD Characteristics of NTU, CLUE, and FS

According to the grain production functional zoning shown in Figure 3, this study divides the country into main grain-producing areas, main sales areas, and production-sales balance areas, and analyzes the CCD levels of different regions. This classification objectively reflects the inherent differences in resource endowments and strategic positioning

for food security across regions, such as the heavy responsibility of stable production in main producing areas versus the resource constraints in main sales areas.

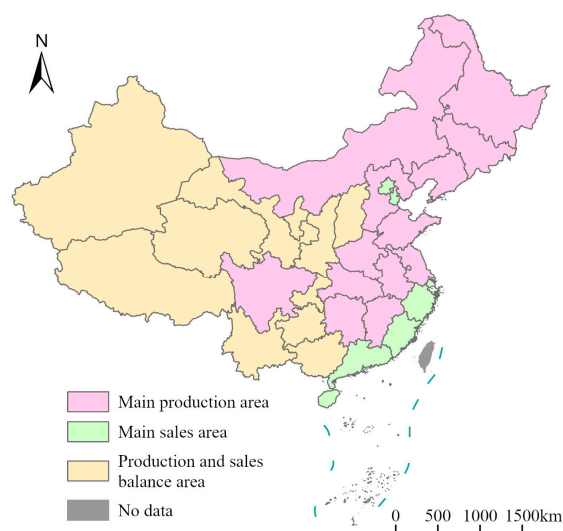


Figure 3. Grain production regions.

As shown in Figure 4, the CCDs of the three main grain functional regions all showed a consistent rising trend, suggesting that while the differentiation features between regions are important, benign interaction between regional systems is continuously strengthening. The main grain-producing areas consistently maintained a leading advantage, with their CCD value climbing from 0.54 at the beginning of the period to 0.71, achieving a leap from “Barely coordination” to “Moderate coordination”. This demonstrates that their resource endowment advantages in ensuring food security and improving cultivated land efficiency are effectively transforming into driving forces for the coordinated development of the system. In contrast, the growth trajectories of the CCD in production-sales balance areas and main sales areas were relatively close and lagging behind, both rising from about 0.52 to about 0.65, completing the transition from “Barely coordination” to “Primary coordination”. This differentiation pattern reflects the constraints of resource endowments on the system coupling relationship. Large-scale agricultural operations and policy inclination helped main producing areas achieve deep integration of the three systems, while main sales areas, which were subject to strict land resource constraints, had a harder time coordinating food security and cultivated land protection as high-level urbanization advanced.

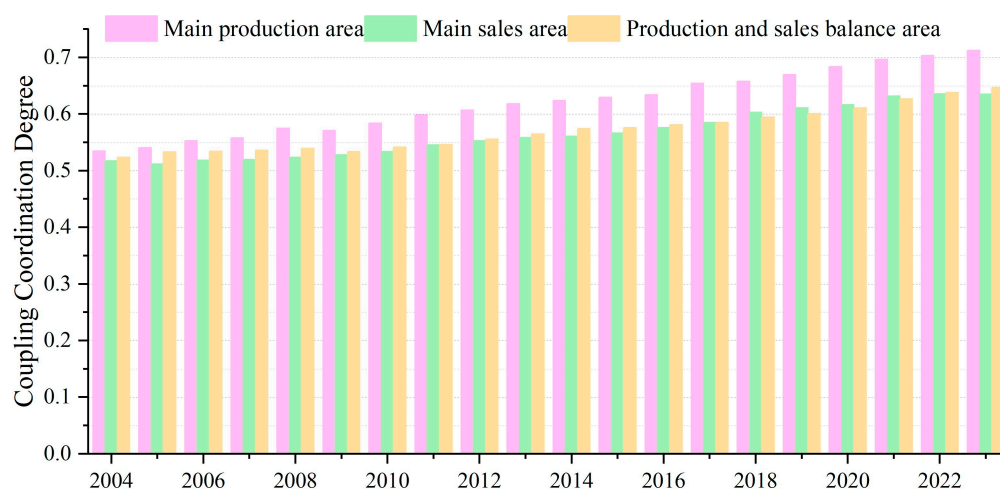


Figure 4. Comparison of CCD in the three major grain production regions.

4.2.1. Temporal Characteristics of CCD

Figure 5 displays the kernel density estimation curves of the CCDs for 30 provinces nationwide from 2005 to 2023, clearly portraying their temporal dynamic evolutionary characteristics. In terms of distribution position, the main peak of the curve continuously shifted to the right, with the center of distribution moving gradually from around 0.5 to approximately 0.65, indicating that the CCDs of NTU, CLUE, and FS in China achieved an overall leap during the study period, and the synergistic development effect became increasingly apparent. In terms of distribution morphology, the curve width gradually diverged and broadened, implying that while the overall coordination degree improved, the absolute differences between provinces did not converge; instead, inter-provincial imbalances expanded due to the rapid evolution of some leading regions. Furthermore, the curves exhibited a clear right-tailing characteristic, indicating that while the advantages of some high-level coordination regions were prominent, the phenomenon of tier differentiation between regions warrants attention.

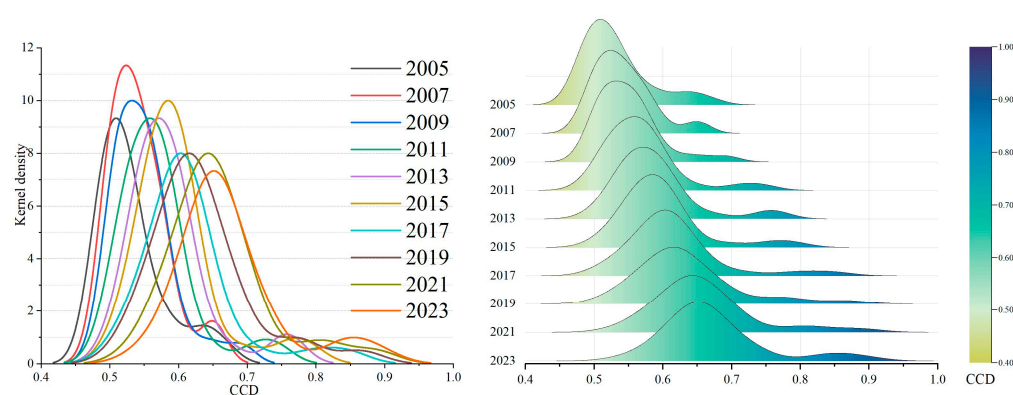


Figure 5. Kernel density curves.

4.2.2. Spatial Characteristics of CCD

To explore the spatial correlation characteristics of the CCDs of NTU, CLUE, and FS on a national scale, this study calculated Global Moran's I from 2004 to 2023. As shown in Table 5, the Moran's I indices for all years within the study period were positive, with values fluctuating between 0.0835 and 0.1507, and all results passed the significance test at the 1% level. This statistical result provides strong evidence that the spatial distribution of the CCDs of the three major systems was not random, but instead exhibited significant positive spatial autocorrelation, that is, provinces with higher (or lower) levels of coupling coordination tended to cluster adjacently in geographical space.

Table 5. Global Moran's I from 2004 to 2023.

Year	I	Z	p-Value	Year	I	Z	p-Value
2004	0.0878	3.4744	0.0005	2014	0.1151	4.4729	0.0000
2005	0.0835	3.3554	0.0008	2015	0.1202	4.5882	0.0000
2006	0.108	4.1145	0.0000	2016	0.1295	4.8112	0.0000
2007	0.0996	3.7990	0.0001	2017	0.1507	5.5586	0.0000
2008	0.1259	4.6996	0.0000	2018	0.1092	4.2027	0.0000
2009	0.0913	3.6641	0.0002	2019	0.1423	5.1584	0.0000
2010	0.1139	4.3790	0.0000	2020	0.1225	4.5606	0.0000
2011	0.1344	4.9961	0.0000	2021	0.1467	5.2766	0.0000
2012	0.1335	4.9719	0.0000	2022	0.1216	4.5241	0.0000
2013	0.1449	5.2897	0.0000	2023	0.1219	4.5224	0.0000

To further identify the agglomeration patterns and evolutionary laws within space, Figure 6 displays the Local Moran's I index agglomeration distribution for different years. The results show that the local spatial correlation of CCD presents a characteristic of “High in the North, Low in the South.” Specifically, the “High-High” agglomeration area demonstrates high stability in space, being strictly locked in the Northeast region over the long term. This is mainly attributed to the region being the country's main grain-producing area, possessing unique cultivated land resources and high levels of agricultural mechanization, thus achieving high efficiency in cultivated land use while ensuring high levels of food security. This indicates that a solid contiguous area of high-level coordination has formed within this region and has not undergone significant displacement over time.

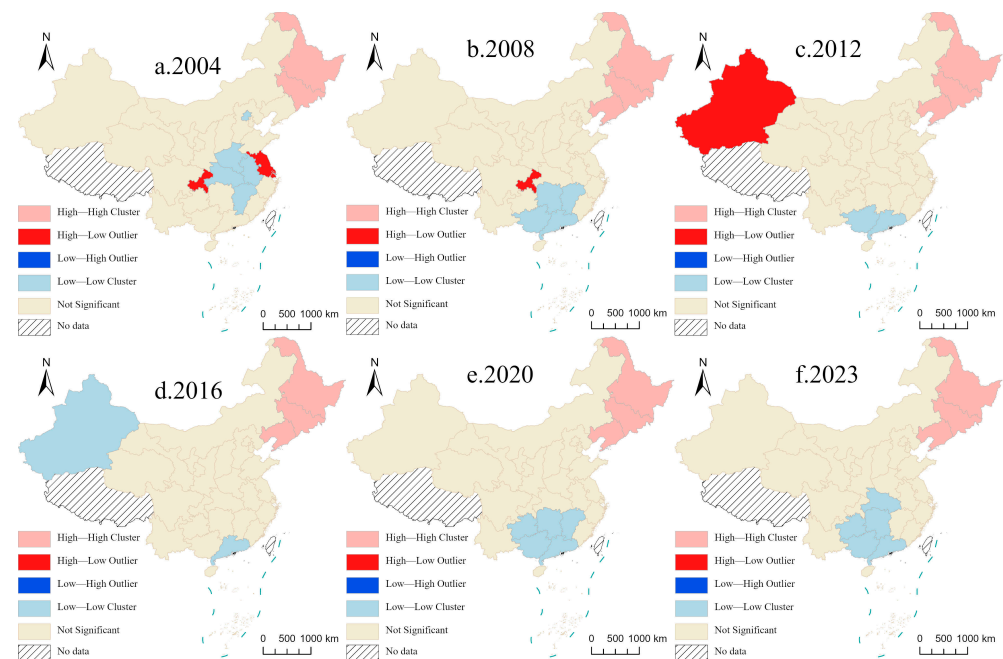


Figure 6. Spatial agglomeration and dispersion patterns of CCD.

Conversely, “Low-Low” agglomeration areas are concentrated in southern provinces and exhibit spatial stickiness, representing a coordination trap. This persistence reflects institutional barriers to factor mobility and fragmented land-use patterns that hinder the spillover of coordination benefits. In these areas, urbanization gains from core cities rarely reach the agricultural sector due to high adjustment costs, complex topography, and inadequate interregional compensation mechanisms, leading neighboring provinces to mutually constrain systemic improvement.

Finally, “High-Low” outliers in Chongqing and Xinjiang show distinct phasic characteristics. While localized policy innovations or capital injections triggered temporary coordination leaps, these features were not sustained. This instability illustrates the difficulty of maintaining policy-driven factor mobility without sustained interregional linkages and technological spillovers. Overall, the clear distinction between high-value and low-value clusters confirms that spatial heterogeneity persists, necessitating integrated regional planning to facilitate cross-border land consolidation and factor flow.

4.3. Interaction Among NTU, CLUE, and FS

4.3.1. Unit Root Test and Cointegration Test

To avoid spurious regression problems caused by non-stationary panel data and ensure the validity and robustness of the empirical results, this paper employs the LLC,

IPS, and ADF-Fisher test methods to conduct unit root tests on the logarithmically treated variables and their first-order difference sequences before constructing the PVAR model.

The test results are shown in Table 6. At the original sequence level, only lnNTU significantly rejected the null hypothesis of the existence of a unit root in all three tests, exhibiting stationary characteristics. In contrast, lnCLUE and lnFS failed to pass the significance test in most LLC and IPS tests, indicating that these two variables may have non-stationary trends at the original level. However, after conducting first-order differencing on all variables, d.lnNTU, d.CLUE, and d.lnFS all rejected the null hypothesis at the 1% or 10% significance level, showing good stationarity.

Table 6. Unit root test results.

	LLC	IPS	ADF-Fisher	Order of Integration
lnNTU	−3.214 ***	−3.9186 ***	−12.3952 ***	I(0)
d.lnNTU	−12.935 ***	−11.9805 ***	−16.9923 ***	stationary
lnCLUE	1.0918	−0.4450	−1.8144 **	I(1)
d.CLUE	−1.5734 *	−5.5679 ***	−9.5171 ***	stationary
lnFS	−1.1868	−1.0024	−3.1426 ***	I(1)
d.lnFS	−12.0346 ***	−9.8684 ***	−8.3901 ***	stationary

Note: ***, **, * denote significance at the levels of 1%, 5%, 10%.

We then conducted the Kao panel cointegration test to examine whether a long-term equilibrium relationship exists between the integrated variables of order one, lnCLUE and lnFS. As shown in Table 7, the results for the bivariate relationship between lnCLUE and lnFS are heterogeneous. Specifically, when lnCLUE is treated as the dependent variable, the Augmented Dickey–Fuller (ADF) *t*-test fails to reject the null hypothesis of no cointegration ($p = 0.2167$). This lack of unanimous evidence across all test statistics suggests that a stable long-term equilibrium relationship cannot be confirmed among the I(1) variables. Given these results, we adopted a conservative econometric approach by utilizing a vector autoregression model with the first differences of all variables instead of a Vector Error Correction Model. This means that our analysis was performed on the rates of change of all variables and ensured the stability of the system and the validity of the subsequent causality, impulse response, and variance decomposition analyses.

Table 7. Panel cointegration test.

Kao Test	lnCLUE, lnFS		lnFS, lnCLUE	
	Statistic	<i>p</i> -Value	Statistic	<i>p</i> -Value
Modified Dickey–Fuller <i>t</i>	−2.047	0.0203	2.5162	0.0059
Dickey–Fuller <i>t</i>	−3.0178	0.0013	2.2234	0.0131
Augmented Dickey–Fuller <i>t</i>	−0.7834	0.2167	2.0988	0.0179

4.3.2. Optimal Lag Order Selection

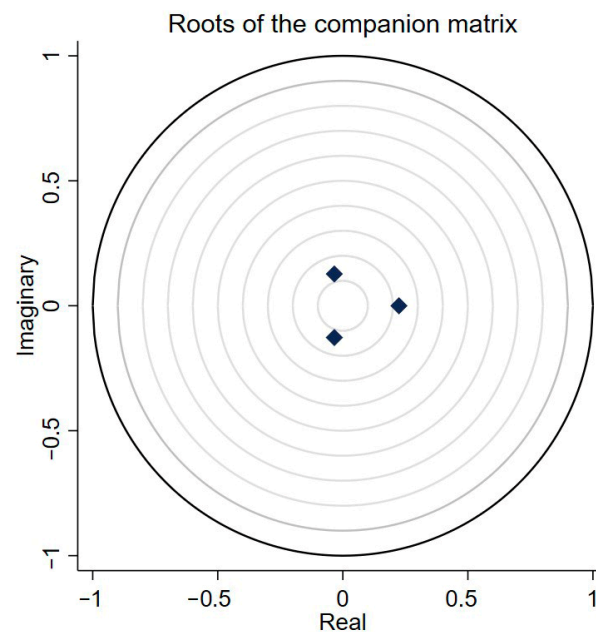
To ensure the validity of the PVAR model estimation, it is necessary to scientifically determine the optimal lag order of the model based on information criteria. Table 8 presents the test results of the MAIC, MBIC, and MQIC criteria for lags 1 to 5. Comparing the values of different orders, it can be seen that as the lag order increases, the statistical values of the three information criteria generally show an upward trend. At lag 1, the values of MBIC, MAIC, and MQIC are all at their minimum, being −212.824, −56.1949, and −119.305, respectively. According to the principle of minimizing information criteria, this study finally determined the optimal lag order of the PVAR model to be order 1.

Table 8. Lag order selection.

Lag	CD	J	<i>p</i> -Value	MBIC	MAIC	MQIC
1	0.808236	33.80514	0.889375	−212.824	−56.1949	−119.305
2	0.613405	23.94414	0.938098	−173.359	−48.0559	−98.5438
3	0.400199	14.77638	0.972453	−133.201	−39.2236	−77.0896
4	0.50743	6.335321	0.994637	−92.3162	−29.6647	−54.9087
5	−6.86439	4.610694	0.86684	−44.7151	−13.3893	−26.0113

4.3.3. Stability Test of Variables

Before conducting Granger causality tests and impulse response analysis, the stability of the PVAR model must be effectively confirmed. Figure 7 illustrates the distribution of the inverse roots of the companion matrix of the PVAR model. The results show that all eigenvalues fall strictly within the unit circle, with none escaping. This geometric characteristic indicates that the PVAR model constructed in this study satisfies the stability constraint conditions, and the system itself is convergent and stationary. Consequently, subsequent Granger causality tests, impulse response function analysis, and variance decomposition can be carried out.

**Figure 7.** Stability test results.

4.3.4. Granger Causality Test

According to the results in Table 9, CLUE significantly constitutes the Granger cause of variations in FS, while changes in FS can further affect the evolution of NTU. At the same time, the test results also indicate that both NTU and FS can significantly serve as Granger causes for CLUE, suggesting that the relationship between the systems is not a simple unidirectional transmission. Instead, there exists a feedback mechanism towards CLUE, meaning that the development status of the former two will, in turn, significantly influence the fluctuations of CLUE. The path from CLUE to FS confirms that efficiency gains are the fundamental driver for grain supply stability, while the influence of NTU on CLUE highlights how urbanization facilitates the labor transfer and scale operations necessary to modernize agricultural production. Concurrently, the impact of FS on CLUE suggests that a stable food security environment encourages long-term land conservation rather than short-term exploitation. Notably, the finding that FS serves as a Granger cause for

NTU indicates that food security acts as a “stabilizer” and “bottom-line constraint” for the urbanization process. A stable material foundation, characterized by consistent food supply and price stability, is a prerequisite for the social stability required to sustain large-scale rural-to-urban population transfers. Conversely, food insecurity or supply volatility may trigger policy adjustments that prioritize rural revitalization and social order, effectively dictating the pace and quality of NTU expansion.

Table 9. Granger causality test results.

Equation	Excluded	chi2	p-Value
h_dlnNTU	h_dlnCLUE	1.6984	0.192
	h_dlnFS	3.5212	0.061
h_dlnCLUE	h_dlnNTU	14.438	0.000
	h_dlnFS	6.0168	0.014
h_dlnFS	h_dlnNTU	1.0023	0.317
	h_dlnCLUE	8.8388	0.003

4.3.5. Impulse Response Analysis

To delineate short-term interactions, Figure 8 presents the impulse response results of each variable to a one-standard-deviation shock over eight periods with a 95% confidence interval and 200 Monte Carlo simulations. While self-shocks across all systems peak initially before approaching zero, cross-system responses reveal more complex dynamics. NTU responds positively to shocks in CLUE and FS, suggesting that efficiency and security gains are effective urbanization drivers. Conversely, CLUE faces a double squeeze, exhibiting significant short-term negative responses to both NTU and FS shocks. This highlights transitional frictions that occur despite the positive causality found in the preceding Granger analysis. NTU shocks likely cause immediate labor thinning and land fragmentation before the scale operations required for efficiency can materialize. Simultaneously, the influence of FS on CLUE reveals institutional constraints where stringent mandates, such as rapid grain land conversion, may disrupt optimized, green-oriented production patterns. These adjustment costs lead to temporary efficiency declines as the system adapts to new regulatory and demographic realities. Additionally, the response of FS to NTU shocks is fluctuating and uncertain, reflecting a conflict between urban technological spillovers and the physical loss of high-quality suburban cultivated land. These findings underscore the presence of institutional constraints and time-lag effects in agricultural modernization. Policy interventions must therefore account for these transitional frictions.

4.3.6. Variance Decomposition

Table 10 presents the variance decomposition results from period 1 to period 5, aiming to quantify the relative contribution of each variable to the variance of the system’s prediction error. The results indicate that NTU and FS exhibit extremely strong self-sustaining characteristics; by the fifth period, their explanatory power for their own variations reaches as high as 97.5% and 96.2%, respectively, suggesting that their development paths are mainly driven by their own inertia and are less affected by external system shocks. In contrast, CLUE has a relatively higher sensitivity to external shocks. Although its own contribution rate still dominates (92% in the fifth period), the contribution rate from NTU reaches 6.8%, and the contribution rate from FS is 1.2%. This result further reveals that within the three major systems, CLUE is in a relatively passive position and is more easily significantly affected by the NTU process, while the influence of FS on it is relatively weaker.

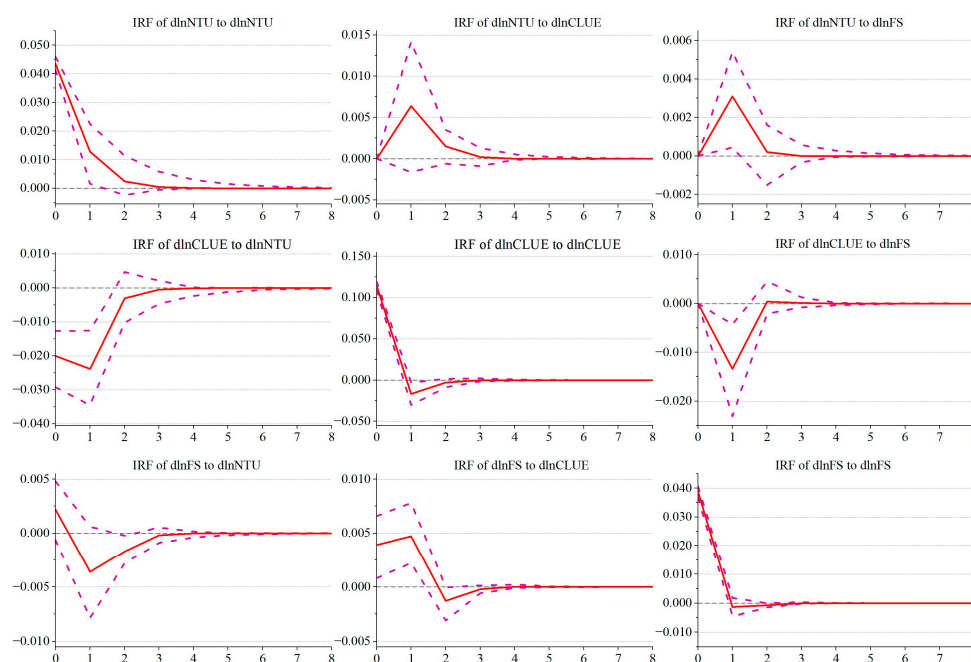


Figure 8. Impulse response of NTU, CLUE, and FS. (Errors are 5% on each side generated by Monte-Carlo with 200 reps).

Table 10. Variance decomposition results.

	Period	dlnNTU	dlnCLUE	dlnFS
dlnNTU	1	1.000	0.000	0.000
dlnCLUE	1	0.030	0.970	0.000
dlnFS	1	0.003	0.010	0.987
dlnNTU	2	0.976	0.019	0.005
dlnCLUE	2	0.067	0.920	0.012
dlnFS	2	0.012	0.024	0.965
dlnNTU	3	0.975	0.020	0.005
dlnCLUE	3	0.068	0.920	0.012
dlnFS	3	0.014	0.025	0.962
dlnNTU	4	0.975	0.020	0.005
dlnCLUE	4	0.068	0.920	0.012
dlnFS	4	0.014	0.025	0.962
dlnNTU	5	0.975	0.020	0.005
dlnCLUE	5	0.068	0.920	0.012
dlnFS	5	0.014	0.025	0.962

4.4. Discussion

The spatiotemporal analysis of the CCD of NTU, CLUE, and FS in this study shows that these three major systems in China have generally moved towards a stage of coordinated development. The CCD of the main grain-producing areas has consistently maintained a leading advantage and was the first to enter the “Moderate coordination” stage, while the economically developed main sales areas and production-sales balance areas have lagged relatively. This indicates that in complex systems involving food security, functional zoning has a constraining effect on system coupling [49], and the spatial correlation of the system’s coordinated development is evident [50]; resource endowments and functional positioning play a decisive role. Main grain-producing areas, benefiting from national policy inclination and the foundation of large-scale agricultural operations, have more effectively transformed resource advantages into synergistic driving forces. In contrast,

main sales areas and production-sales balance areas may face more severe conflicts between rigid land resource constraints and urbanization expansion.

The impulse response and causality data confirm that NTU acts as an external engine for the system, supporting the hypothesis that high-quality urbanization facilitates agricultural modernization. This provides empirical weight to Chen et al. [20] regarding factor allocation optimization. However, our findings add a critical nuance: the observed short-term negative impact of NTU and FS on CLUE—the “double squeeze”—reveals that this engine operates with significant transitional frictions. Unlike the positive transitions described by Wang et al. [42], our results indicate that agricultural efficiency is vulnerable to a decline in effective labor quality in the immediate wake of population transfer. This occurs because rural labor migrates to cities before land transfer and scale operations are fully established, leading to temporary land fragmentation. This implies that the transition from smallholder farming to scale operations involves a period of “efficiency depression” where neither the old nor the new system is fully optimized.

Furthermore, the “double squeeze” on CLUE caused by stringent FS mandates provides a critical perspective on institutional constraints. While Fei et al. [31] and Pei et al. [32] emphasize the mediating role of labor and land transfer, our study suggests that policy-driven land conversion, particularly the rapid shift to food-oriented land use to ensure food supplies, could disrupt existing green-oriented production model transformations and incur short-term adjustment costs. This confirms the view of Hu et al. [33] that lagging utilization patterns exacerbate system friction. For main sales areas, the policy implication is clear: simply accelerating urbanization without providing specific subsidies for the “adjustment costs” of agricultural land-use transitions will likely prolong the period of coordination lag.

5. Conclusions and Recommendations

5.1. Conclusions

Based on provincial panel data in China, this study empirically tested the spatiotemporal evolution characteristics and dynamic interaction effects among NTU, CLUE, and FS using the coupling coordination degree model and the PVAR model. The main conclusions are as follows:

- (1) The overall level of each system has improved, but regional differences are significant. The comprehensive development levels of NTU, CLUE, and FS all show an upward trend. The NTU gap between different regions has gradually narrowed, but the FS gap has gradually widened, and the growth of CLUE presents unstable fluctuations. Over time, the CCD among the three systems has steadily improved, but differences between provinces have gradually expanded, intensifying the unbalanced development of CCD. In addition, main grain-producing areas have moved from “Barely coordination” to the higher coordination level of “Moderate coordination,” while other regions have also reached the “Primary coordination” level. This indicates that with the deepening of NTU, the traditional urban–rural dual structure is disintegrating. Urbanization no longer simply manifests as encroachment on cultivated land but has begun to feed back into agriculture through factor agglomeration effects.
- (2) The spatial correlation of the systems’ CCDs has gradually increased, and high–low agglomeration characteristics exhibit obvious regionality. Global Moran’s I of CCD rose from 0.0878 in 2004 to 0.1219 in 2023, indicating that the spatial correlation of the coordinated development of the three systems is continuously improving. In the distribution of Local Moran’s I agglomeration, the Northeast region presents stable “High-High” agglomeration characteristics, while the southern provinces show “Low-Low” agglomeration. This relatively stable spatial distribution suggests that the

coordinated development of the system is significantly limited by endowments such as agricultural resources and natural conditions.

- (3) The dynamic interaction effects between systems are significant, though fluctuations are primarily driven by internal system dynamics. NTU serves as a Granger cause of CLUE and generates a significant positive response in the long term, confirming that urbanization facilitates agricultural modernization through labor transfer and scale operations. However, impulse responses reveal that CLUE faces a short-term double squeeze characterized by negative responses to both NTU and FS shocks. This highlights transitional frictions such as labor thinning and institutional constraints, where rapid grain-oriented land conversion may disrupt green production transformation. Conversely, the response of FS to NTU shocks remains fluctuating and uncertain, reflecting the conflict between urban technological spillovers and the loss of high-quality suburban cultivated land. Ultimately, addressing these transitional frictions and enhancing the green efficiency of cultivated land rather than merely expanding physical area is the core pathway to ensuring national food security.

5.2. Policy Recommendations

Based on the above conclusions, to achieve the synergistic high-quality development of NTU, CLUE, and FS, the following recommendations are proposed:

- (1) Prioritize the synchronization of land consolidation with labor transfer to mitigate transitional frictions. To address the short-term double squeeze on CLUE, policies must focus on the timing of interventions. Before or during large-scale rural labor migration, local governments should accelerate the standardization of land management rights transfer. By cultivating new types of agricultural management entities and solving land fragmentation early, the system can avoid the efficiency depression caused by labor thinning, ensuring that mechanized operations and modern technologies are implemented before traditional smallholder structures collapse.
- (2) Implement a green-oriented food security strategy to alleviate institutional constraints. Given that rapid grain-oriented conversion can disrupt ecological efficiency, future food security mandates should incorporate green utilization thresholds. This involves increasing R&D investment in green technologies, such as soil testing, formula fertilization, and water-saving irrigation. Especially in ecologically fragile areas, the principle of determining production based on water availability should be strictly enforced. This ensures that the transition to grain-focused production does not come at the expense of long-term ecological output and resource sustainability.
- (3) Execute differentiated regional strategies based on functional positioning. Addressing spatial heterogeneity in coordination, the Eastern region should leverage its capital and market advantages to feed back into main grain-producing areas through technology spillovers. Main grain-producing areas should utilize national fiscal transfer payments to modernize agricultural infrastructure and bridge the efficiency gap. Western ecological functional zones must strictly observe ecological red lines while exploring mechanisms for realizing the value of ecological products, ensuring that urbanization proceeds without compromising the regional ecological carrying capacity.
- (4) Establish a human–land–grain collaborative early-warning mechanism to enhance system resilience. To manage the uncertain impact of NTU on FS, a comprehensive digital monitoring platform is essential. Utilizing remote sensing and big data, authorities should monitor trends of non-agriculturalization and non-grain production in real-time. Integrating food security risks into the early stages of urbanization planning will ensure that high-quality suburban cultivated land is preserved, maintaining a buffer against the physical loss of land during urban expansion.

5.3. Limitations and Prospects

Although this study reveals the coupling mechanism of NTU-CLUE-FS, there are still certain limitations. First, limited by data availability, this study is mainly based on the provincial scale and fails to investigate deeply into the micro-scales of counties or villages, which may mask the specificities of local areas. Second, although green efficiency is considered, the consideration of the impact of natural factors such as climate change on cultivated land utilization is still insufficient. Future research can further utilize multi-source remote sensing data to explore the impact of micro-behavior of farmers on system coupling at a finer scale and deeply simulate the dynamic response mechanisms of the three major systems under different climate scenarios. Third, limited by data availability, grain price and production fluctuations are used as proxies for systemic stability at the provincial level. While these indicators capture supply-chain vulnerability to external shocks, they fail to fully reflect reserve-based emergency response capacities. Future studies should incorporate more detailed data on dietary structure and regional logistics to better represent the multidimensional characteristics of the Greater Food Approach.

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